

IntechOpen

IntechOpen Series
Biomedical Engineering, Volume 33

Telemedicine

Models of Care

Edited by Charles R. Doarn



Telemedicine - Models of Care

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Published in London, United Kingdom

Telemedicine – Models of Care
<http://dx.doi.org/10.5772/intechopen.1008101>
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First published in London, United Kingdom, 2026 by IntechOpen

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British Library Cataloguing-in-Publication Data

A catalogue record for this book is available from the British Library

Telemedicine – Models of Care

Edited by Charles R. Doarn

p. cm.

This title is part of the Biomedical Engineering Book Series, Volume 33

Topic: Bioinformatics and Medical Informatics

Series Editor: Robert Koprowski

Topic Editor: Slawomir Wilczynski

Print ISBN 978-1-83635-316-4

Online ISBN 978-1-83635-315-7

eBook (PDF) ISBN 978-1-83635-317-1

ISSN 2631-5343

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Biomedical Engineering is one of the fastest-growing interdisciplinary branches of science and industry. The combination of electronics and computer science with biology and medicine has improved patient diagnosis, reduced rehabilitation time, and helped to facilitate a better quality of life. Nowadays, all medical imaging devices, medical instruments, or new laboratory techniques result from the cooperation of specialists in various fields. The series of Biomedical Engineering books covers such areas of knowledge as chemistry, physics, electronics, medicine, and biology. This series is intended for doctors, engineers, and scientists involved in biomedical engineering or those wanting to start working in this field.

Meet the Series Editor



Robert Koprowski, MD (1997), Ph.D. (2003), Habilitation (2015), is an employee of the University of Silesia, Poland, Institute of Computer Science, Department of Biomedical Computer Systems. For 20 years, he has studied the analysis and processing of biomedical images, emphasizing the full automation of measurement for a large inter-individual variability of patients. Dr. Koprowski has authored more than a hundred research papers with dozens in impact factor (IF) journals and has authored or co-authored six books. Additionally, he is the author of several national and international patents in the field of biomedical devices and imaging. Since 2011, he has been a reviewer of grants and projects (including EU projects) in biomedical engineering.

Meet the Volume Editor



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Preface

The application of telemedicine is not a new or novel paradigm. It has been part of medical practice for several decades, perhaps centuries, according to some scholars. Regardless, it was not until the pandemic in 2019 that the application and integration became a worldwide phenomenon. As a catalyst for change, concomitant with emerging technologies in telecommunication, computer science, sensors, robotics, and artificial intelligence (AI), the entire world's population is closer to healthcare resources and knowledge than ever before.

This book presents several applications and issues that provide a unique and useful foundation for greater understanding and knowledge to further your efforts in telemedicine. The title, '*Telemedicine – Models of Care*', is intended to showcase various lessons learned from real-world experiences.

This 14-chapter book is organized into three sections. The first is the introduction, where Chapter 1 presents a cogent summary of how telemedicine has evolved over time. Chapter 2 by Mitchell and Holtz presents a discussion from the provider's perspective. While telemedicine is a bidirectional construct, providers must be familiar and comfortable with the protocols and procedures.

Section 2, *Clinical Challenges and Applications*, is an amalgamation of unique clinical settings. Chapter 3 presents ophthalmological issues using virtual models. While much has been published on COVID and telemedicine, Chapter 4 enlightens readers on how telemedicine has transformed care. Using ultrasound devices remotely can significantly impact prenatal care. Chapter 5 addresses this in settings in Indonesia. While the growth of telemedicine in many parts of the world has been hampered by a range of barriers, Chapter 6 examines trends and challenges in Ghana and Nigeria. This section closes out with how telemedicine is applied in pediatric settings in China.

Section 3 focuses on emerging concepts in digital health. It is the largest section and a collection of a wide variety of materials related to AI. Most of this work would not be possible if the work of those before us had not pushed technology forward and developed new and innovative ways to interact with patients. Chapter 8 looks at the role of digital and green transformation in health systems. Chapter 9 addresses the future of digital healthcare in the aftermath of the pandemic. Chapter 10 reviews the digital divide and the barriers to policy and equity in underserved communities. Digital health acceptance is discussed in Chapter 11. The application of AI for our older population is presented in Chapter 12. Chapter 13 addresses the incorporation of AI and telemedicine in Africa. The final chapter, Chapter 14, provides a perspective on the opportunities and challenges that AI brings to telemedicine.

Each chapter provides a wealth of knowledge that further enhances the utility and efficiency that telemedicine and AI can bring to the health sector. While it is not a

panacea for all applications or situations, it does build on the ever-growing foundation from which we can continue to move forward, benefiting the patient and provider.

I acknowledge the wonderful authors and their contributions to this text. I also acknowledge the excellent support from the IntechOpen staff, especially Kristina Kardum Cvitan. Thank you to all who made this book possible.

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Section 1

Introduction

Chapter 1

The Evolution of Telemedicine across Time

Charles R. Doarn

Abstract

The concept of telemedicine is neither new nor novel. It has been a part of healthcare for more than a century, if not longer. The integration of telecommunications into the practice of medicine implies that no one should be without access to healthcare. Communications, as we understand it today, are based on telephony or the internet—both wired and wireless. Yet there were various communication modalities dating into antiquity that were used for medicine. In the modern era, telemedicine has been applied in a plethora of settings, including human spaceflight, military applications, disasters, humanitarian crisis, home health care, and, of course, the rapid increase in utilization during the COVID-19 pandemic. Since the beginning of the twentieth century, healthcare has evolved, and with continuous improvements in telecommunications and computer technology, telemedicine has become a necessary tool in the practice of medicine worldwide; whereby literally every clinical discipline has been impacted. As the first quarter of the twenty-first century comes to a close, the world's population has access to more information and healthcare resources than in all of human history. This chapter provides an overview of the advancement of telemedicine across time and its impact on current practice.

Keywords: telemedicine, spaceflight, disasters, home health care, history, telecommunications, computing, growth

1. Introduction

In antiquity, communications between two points were often accomplished by individuals who literally ran long distances. These individuals were called hemerodromes (day runners or couriers). During the Persian invasion of Greece in the fifth century B.C.E., the Athenian Pheidippides ran between Sparta, Athens, and Marathon to deliver the news and needs of the defenders of Greece, and eventually Greece's victory over the Persians [1]. These runners delivered messages about supplies, injuries, and medical care as it was understood at the time. This early form of communication provided a foundation for sharing knowledge.

It was not until Johannes Gutenberg invented the printing press that communications and knowledge began to become more widespread. Nathan et al. addressed what a doctor might have been like in prehistoric days and antiquity [2]. Galen of Pergamon, one of the most famous physicians in the second-century Rome—physician to Marcus

Aurelius, Commodus, and Septimus Severus—developed the experimental method of medical investigations, much of which was written and communicated through text such as *Galenic corpus* [3–5]. A considerable amount of the practice of medicine was based on Greek and Roman influence until the fourth century, when Islamic culture expanded Greek and Roman philosophies and techniques [6, 7].

Until the fifteenth century, medicine was limited in knowledge and capability, and was the purview of a few, usually the Church in Christendom or in Islam. As the Renaissance and the Age of Discovery unfolded, knowledge and travel for commerce became more widespread, providing an opportunity for growth in medicine, or at the very least, a greater understanding of disease and public health [8]. While the written word from the likes of Leonardo da Vinci, Ambroise Paré, Andreas Vesalius, William Harvey, and Hieronymus Fabricius, helped shape the narrative of the time, it was the ability for more individuals to become learned, and thereby lead humanity into the modern world. Over the course of human history, knowledge has accumulated and has led to new discoveries, which is where the modern world and how telemedicine have evolved.

Over the course of human history, the practice of medicine and education has evolved through need and innovation. Knowledge grew through experimentation and the influences of religion and culture. Technology grew rapidly from the fifteenth century to the present day, and this has accelerated the rapid change and evolution. Change today continues based on needs, challenges, and even events like a global pandemic.

This chapter begins with a historical background from antiquity to the present time. It highlights how telemedicine has been defined and emphasizes various applications or models of care, including spaceflight, military operations, disasters, and clinical applications, including the COVID pandemic. It also touches on research and policy. It concludes with how this historical perspective has impacted current activities and utilization of telemedicine over time.

The literature that is cited is from either firsthand accounts with contemporaries in the field of telemedicine or from literature written about those activities that served as the foundation of modern telemedicine. While there are many examples that can illustrate the impact and evolution of change, it is those that are cited that have established the processes and constructs that are telemedicine today. A complete history of telemedicine was published by Bashshur and Shannon in 2009. A repeat of that work here would be onerous.

2. Defining telemedicine

Telemedicine has been defined by many individuals, organizations, and federal, state, and local government departments or ministries and agencies. Its definition is often attributed to its use. For example, the application in a military setting is not the same as in a large clinical hospital in a major metropolitan area. In scholarly work, it has been defined by Bashshur (1995) [9], Sood et al. (2007) [10], Doarn et al. (2014) [11], and many others. **Figure 1** illustrates how telemedicine fits into a broader vernacular of telehealth, e-Health, mHealth, and personalized health. Regardless of the definition used, it is simply the access to healthcare resources *via* a communication modality, regardless of location. The three modes are synchronous (real-time), asynchronous (store-and-forward), and remote monitoring. In most applications, a hybrid model, which includes all three, is used.

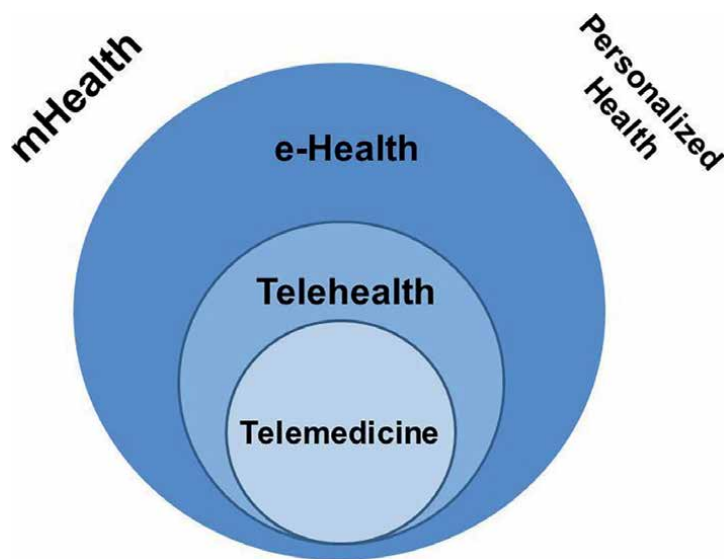


Figure 1.
Telemedicine definitions.

3. Unique applications of telemedicine

The integration of telephony and medicine has often been traced back to the first use of the telephone. The first words uttered by Alexander Graham Bell in 1876 were “*Watson, come here, I want to see you.*” He apparently needed help, as he had spilled acid in his lab, which was just down the hall from where Dr. Watson was [12]. In 1879, The Lancet reported on a pediatric case in which the physician and the child’s mother talked on the phone about her child’s illness [13]. The telephone rapidly became a commodity, and its distribution grew worldwide; from 1876 to 1915, the growth was exponential, and with it a wide variety of applications, including individuals networking with one another, commerce, and, of course, medicine [14].

While we equate telemedicine with the telephone in late nineteenth and early twentieth century, the telegraph was also instrumental in the American Civil War and with the development of wireless communications by Gulielmo Marconi in 1894 [15]—about the same time as Wilhelm Conrad Röntgen discovered X-rays [16]—communications between two points could be done in real-time. Additional innovations that enhanced medical care included better education and, of course, the 1918 pandemic. These innovations changed the lives of most of the entire world. It would take another 100 years of so for communications and computer technology to reach most of the world’s population.

Sir William Osler, a founding physician of Johns Hopkins Hospital in Baltimore, Maryland, and the eventual establishment of Johns Hopkins School of Medicine, created the medical residency and new ways of teaching medical students [17]. At the turn of the twentieth century, American medicine was woefully behind that of Europe. Standards for medical education and training, clinical examination protocols, and public health standards were lacking. The 1918 pandemic and the First World War brought worldwide tragedy and suffering [18, 19]. While World War II and the Cold War were on the horizon, medical care capabilities and public health improved. Technology in communications, the development of standards, aviation, and early computer technology changed the course of humanity.

The examples stated above lay out a timeline from antiquity to the present time as an illustration of how technology has changed and created a more robust healthcare capability, which continues to influence the commercial sector, the health sector, the legislative sector, and variability in the law; which simply implies that equity and equality are not universally the same.

Telemedicine and its evolution are linked to the aforementioned events and discoveries. The following is a summary of many applications beginning in the mid-twentieth century. It is not intended to be a lengthy treatise on the applications.

3.1 Human spaceflight

At the end of World War II, there was a push by both the United States (U.S.) and the Union of Soviet Socialist Republics (USSR) to achieve superiority in space. Much of the accumulated knowledge of rocketry was transitioned from Germany at the end of World War II, where key individuals were taken to the U.S. through Operation Paperclip, and others were taken to the USSR [20]. As the Cold War ensued, the objective was to achieve human spaceflight. By the late 1950s, the USSR launched a canine named Laika (see **Figure 2**), who was monitored from the ground *via* wireless telemetry [21]. While Laika did not survive the Sputnik II mission, the telemetry of biomedical information from space to ground ushered in a new era of telemedicine.

Beginning in the early 1960s, as Soviet cosmonauts and American astronauts were launched into space, their physiological status was monitored from their spacecraft, space suits, and from the surface of the moon (c 1969) by medical personnel at mission control centers in Moscow, Russia, and Houston, Texas [22, 23]. During the height of the Cold War, Soviet and American scientists, researchers, medical personnel, and engineers often collaborated. This collaboration led to a number of groundbreaking efforts both nationally and internationally.

Telecommunications assets and computer technology during this period grew to meet the demands for monitoring astronauts and cosmonauts in space on the surface of the moon.

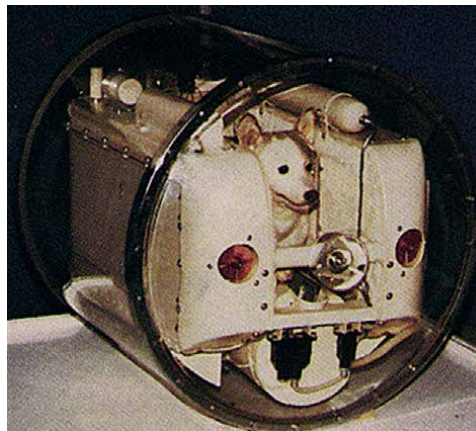


Figure 2.
Laika in containment harness of the rocket (c 1957).

3.1.1 National efforts

Preparation for spaceflight requires extensive system development, design, crew selection, and crew and ground support training. Often, testbeds or simulations are developed to evaluate and perfect technologies and protocols. In preparation for NASA's first space station, Skylab, a medical system was developed, and components were evaluated in ground-based testbeds. This program was the Space Technology Applied to Rural Papago Advanced Health Care (STARPHAC) and began in the early 1970s. Using wireless communications and a mobile medical facility, patients on the Tohono O'odham (formerly Papago) Reservation in the Sonoran Desert in Southern Arizona were seen by physicians and medical personnel in Sells, Arizona [24, 25].

In addition, NASA has used underwater habitats to evaluate technology, support training, and research initiatives in the Aquarius habitat (See **Figure 3**) as part of NASA Extreme Environment Mission Operations (NEEMO). During several missions, crews evaluated telerobotic surgery capabilities in 2005–2007 [26, 27]. This evaluation included wireless manipulation of surgical instruments separated by more than 1500 miles. These research efforts paved the way for enhancements in robotic telesurgery and autonomous care in terrestrial medicine [28].

At the Institute for Biomedical Problems in Moscow, a testbed, Mars 500, has been used to evaluate crews in isolation periods often exceeding 12 months, using telemedicine [29, 30]. This testbed provided Russian researchers to interact with the isolated crew members, who were literally in the next room.

While this is only a small snippet of what has been done on ground-based research, it builds on previous work and lays a foundation for further research that has enhanced and continues to enable healthcare worldwide with the application of telemedicine.



Figure 3.
Aquarius Habitat of the coast of Key Largo, Florida.

In each of these cases, telecommunications and computer technology continued to evolve.

3.1.2 U.S./USSR Joint Working Group on space biology and medicine

In the early 1970s, the U.S. and the USSR established the Joint Working Group (JWG) on Space Biology and Medicine [31]. This JWG had a number of scholarly and research initiatives. One of which was conducting a joint docking mission—the Apollo-Soyuz Test Project (c 1975) [32] and the second was applying telemedicine in the aftermath of a devastating earthquake in Soviet Armenia (1988). Medical personnel and officials from the U.S. and USSR established a spacebridge using a dual satellite hop to evaluate the injured in Armenia in the months after the disaster [33]. This telemedicine system was further extended to Ufa, Russia to address burn victims after train collision.

The foundation of this spacebridge project led to two more projects between the U.S. and the USSR/Russia in 1993 and 1994 [22, 31, 34]. Both of these telemedicine efforts were enhanced with improvements in communication and information technology. They used satellite communication assets, including large ground terminals and expensive bandwidth. The third project, Spacebridge to Russia in 1994, used the internet and voice-over-Internet protocol to support synchronous video conferencing and the emerging World Wide Web [35]. **Figure 4** illustrates the use of Netscape 1.0 for (a) image storage and display, (b) video conferencing, (c) audio files, and (d) patient management. This web-based platform in 1994 was one of the world's first large-scale telemedicine efforts using the world wide web, the internet, and international synchronous telemedicine [36].

These projects help define international telemedicine efforts and on several occasions were applied in conditions or situations that were originally intended. This included the Spacebridge to Armenia applied in a train collision in Ufa, Russia, and the Spacebridge to Moscow, which was applied during the political uprising in 1993 in Moscow. The point here is that an existing and operational telemedicine program can be rapidly transitioned to a disaster if needed. This early work led to enhancements in international relations for the International Space Station (ISS) medical framework [37], enhancements in medical monitoring on the Mir Space Station [38] and

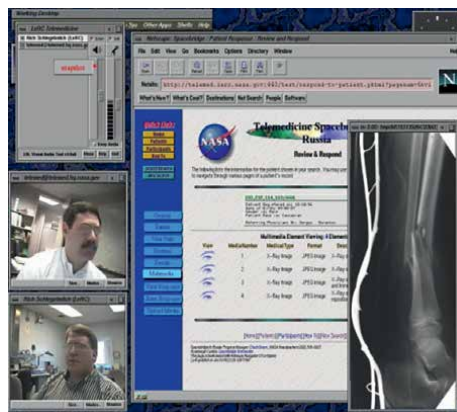


Figure 4.
Spacebridge to Russia graphical user interface.

the development of the Multinational Telemedicine System for NATO in 2017 [39]. This multinational (Finland, Moldova, Romania, Ukraine, and the U.S.—Russia was removed from the project) effort uses the construct that the ISS uses between nations to support medical operations.

Telemedicine applications and technologies from space agencies, countries, or programs have been broadly applied. Deitrich et al. highlight space technologies applied in global health [40]. The Indian Research Organization supports telemedicine across all of India [41]. Grigoriev et al. discuss contributions of space medicine in public health with Russia [42]. Wang et al. discuss advancements in aerospace medicine and application of telemedicine in the Chinese space program [43].

3.2 Military

The military began using telemedicine in support of warfighters in the U.S. and for Veterans in the early 1990s; most of which was in support of radiology [44, 45]. Crowther and Poropatich reported cases from Somalia and Croatia where telemedicine was used by the U.S. Army to transmit information and images in 1993 [46]. Not only was telemedicine further developed for integration in various echelons of care, but it was and continues to be applied in various clinical settings [47], peacekeeping operations [48], and humanitarian missions [49]. The U.S. Navy deployed teleradiology in the early and telemedicine on ships at sea 1990s [50, 51].

In the early 1990s, the U.S. Army established the Medical Diagnostic Imaging Support System (MDIS) through the Army Medical Research and Materiel Command's Medical Advanced Technology Management Office (MATMO) [52, 53]. Located at Ft. Detrick, Maryland, MATMO became the Telemedicine and Advanced Technology Research Center (TATRC) [54]. The U.S. Army's effort here resulted in a wide variety of telemedicine initiatives and technologies that enabled more effective healthcare for the warfighter through successive military campaigns from 1990 to the present time [55–59]. **Figure 5** illustrates the transport of injured warfighters from the battle space to Landstuhl, Germany, for definitive care.

The application of telemedicine in the military and the tempo of care necessary to address injuries have changed the face of trauma medicine in support of the military and civilian care in the U.S. and worldwide [60, 61]. The Force Health Protection Strategy that supported the military engagement in Afghanistan made improvements

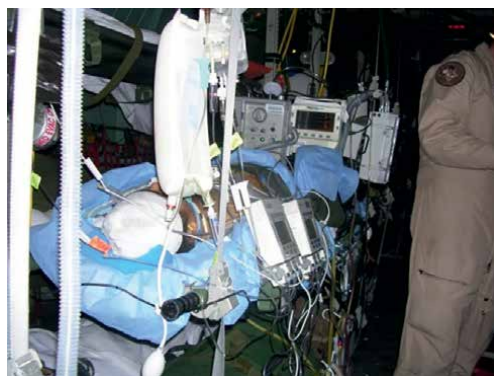


Figure 5.
Military transport of the injured to definitive care.

in health and preventive medicine [62]. Telemedicine has recently been used in Ukraine as well as other conflicts [63].

While the military did not fully embrace telemedicine until the early 1990s, it has been widely adopted worldwide and is embedded in all military planning. The challenge and barriers of delivery are communications, location of assets (warfighters and medical support systems), and infrastructure. Zajtchuk and Gilbert addressed this in 1999 [64] and while it has greatly improved, all barriers have not been ameliorated. Over time, telecommunications assets provided by the Signal Corps of the military, have grown in capability.

3.3 Disasters

In a natural disaster or one directly caused by humans, telecommunications is paramount in (a) understanding the conditions on the ground and (b) developing responses to address suffering of the injured or ill, (c) addressing morbidity and mortality, and (d) developing and implementing plans for response. Disasters disrupt normal life. Infrastructure is often completely destroyed. **Figure 6** illustrates the presidential palace building after the earthquake in 2010. Earthquakes, hurricanes, tsunamis, torrential rain, flooding, tornadoes, chemical spills, terrorism, and war cause all manner of challenges for individuals to receive adequate medical care. Telemedicine has been applied across the globe for nearly 100 years. Litvak et al., in their scoping review, address telemedicine use in disasters [65]. Very early in the U.S. Space Program with NASA, Hibbard reported on telemedicine and disasters in 1970 [66]. In the decades that followed, NASA would develop telemedicine for spaceflight but also apply it terrestrially with early satellites, including ATS-6 [22], STARPHAC [67], the Spacebridge Projects [68], and the Chilean mine mishap in 2010 [69–71].

NATO, through its Science for Peace and Security Program, funded the development of a multinational telemedicine system for disaster response. The system was established and evaluated in Lviv, Ukraine, in 2017 [39, 72]. As the Earth continues to be impacted by nature and events caused by humans, telemedicine will be a tool that



Figure 6.
National place in Haiti after the 2010 earthquake.

will enable more rapid response in all humanitarian crises and will likely include more expansive technologies, including robotics and artificial intelligence [73–75].

3.4 Education

Pedagogical interaction, education, and training are at the heart of any society. As mentioned earlier, knowledge was limited to only the elite or religious leaders until the printing of materials was more widespread. Today, information is literally at our fingertips through our mobile phones. This has increased access to information and expertise that was not possible a few generations ago. Billions of phones have been manufactured and distributed worldwide. Search engines, like Google, Yahoo, Baidu, Bing, Yandex, and DuckDuckGo, are just a few of the 1500 or so search engines worldwide. As the algorithms used in these tools become more powerful, faster, and embedded with artificial intelligence, education in medicine and health, as well as other disciplines, will greatly improve. Recent innovations in ChatGPT may add value. Arif et al. address this in the discussion of the future of medical education [76]. Strzelecki posits that ChatGPT might replace commercial search engines [77].

Enhancements in telecommunication, computer technology, imaging, storage, data mining, and informatics enable better education. In 1976, microwave communications was introduced to Appalachia in the U.S., thereby permitting access to knowledge and medical care that was not possible before [78]. Continuing medical education in Newfoundland, Canada, was enhanced *via* a telemedicine link [79].

Medical education and training of healthcare personnel can be standardized, easily accessible, and even tailored to meet specific needs *via* telemedicine tools. Today, these tools support educational and business exchanges for convenience and cost savings.

3.5 Clinical applications

In the preceding paragraphs, you can see that telemedicine has been applied in human spaceflight, the military, humanitarian efforts, and education. Throughout



Figure 7.
Nineteenth-century physician with twenty-first century technology.

the world, telemedicine has been applied in every clinical discipline, including remote surgery. Bashshur et al. discuss telemedicine in primary care [80] and chronic disease management [81]. He further states that telemedicine initiatives are essential for healthcare reform [82]. **Figure 6** depicts a nineteenth-century physician visiting a patient with his black bag. Today, the physician can also visit patients wherever they are with twenty-first-century technology.

The development over the past century has permitted the application of telemedicine in everyday life worldwide. The pandemic created a perfect storm for telemedicine to become more widely accepted and applied in all environments (**Figure 7**) [83].

4. Research

Telemedicine has been researched across the entire world. There have been think tanks in the U.S., Europe, India, the Middle East, and everywhere that healthcare can be enhanced. These assemblages have brought together a wide range of subject-matter expertise to develop pathways for research initiatives. We have seen tremendous growth in the number of research articles since 2019 and the beginning of the pandemic. **Table 1** illustrates the number of publications in PubMed from 1900 to the present time. The search was done on PubMed only (<https://pubmed.ncbi.nlm.nih.gov/>); terms included <telemedicine>, <telehealth>, <COVID>, <telemedicine and COVID>, and <telehealth and COVID>. The search was limited to the time periods

Decade	Telemedicine (TM)	Telehealth (TH)	COVID-19	TM and COVID-19	TH and COVID-19
1900–1970	1	1	0	0	0
1971–1980	27	28	0	0	0
1981–1990	30	38	0	0	0
1991–2000	4153	4172	0	0	0
2001–2010	9077	8984	0	0	0
2011–2019	23,243	24,332	47	2	2
2020	8079	8787	92,272	3715	4044
2021	8610	9870	142,014	4564	5269
2022	7494	9091	131,639	3497	4339
2023	6379	7845	90,135	2408	2999
2024	7179	8427	59,431	1944	2276
2025	3541	4247	22,099	663	785
Totals	69,066	76,359	472,839	14,435	16,998

Table 1.
Growth of telemedicine, telehealth, and COVID-19 with telemedicine and telehealth from 1900 to the present (source: PubMed).

delineated in the table. It is only being used to illustrate the growth. The number of research articles changes daily. Nevertheless, the growth in all five categories has been significant since the beginning of the public health emergency.

Much of the funding for telemedicine and telehealth was a direct result of funding from entities such as the U.S. Government. When the internet and computer technologies began to rapidly change in the 1990s, more research was conducted, and scholarly output increased. While the integration and application of telemedicine were slowly adopted, it was the pandemic and the public health emergency that served as a catalyst for change. This seismic shift would not have been possible if not for the work done in the 100 years or so before the pandemic. This work includes the refinement in telecommunications, computer storage, computing power, video-teleconferencing tools, and great access. COVID-19 basically helped rewrite what it meant to have access to healthcare expertise, knowledge, and education.

5. Policy

Legislation, guidelines, and policy are driven by many factors, including political leadership, societal needs, environmental conditions, and technology. In 1948, the newly formed United Nations established the U.N. Declaration of Human Rights [84]. Furthermore, the U.N. established the Millennium Development Goals (MDGs), which concomitant with telemedicine and telehealth, can lead to improvement in health outcomes [85, 86]. Many countries instituted a variety of laws, and departments and ministries of health have developed policies and guidelines that govern how telemedicine can be conducted, regulated, and funded (reimbursed). For example, in the European Union (EU), digital health and ethics were of concern, so the EU adopted 16 ethical principles that address digital health [87]. In the U.S., the Health Insurance Portability and Accountability Act was codified into law in 1996 [88], and the Health Information Technology for Economic and Clinical Health Act, a provision of the American Recovery and Reinvestment Act, became law in 2009 [89]. Each of these has been impacted by technology and continues to be relevant in healthcare.

In 1993, a number of telemedicine experts established the American Telemedicine Association (ATA) in Washington, DC. The International Society for Telemedicine and e-Health was established in 1997 and re-established in 2003 in Switzerland. The ATA established a significant number of guidelines through special interest groups that cover a wide variety of clinical disciplines [90]. In addition, the G8 was instrumental in developing 21 recommendations to a G8 subproject (Global Health Applications Subproject). Representatives from Australia, Canada, France, Germany, Italy, Russia, the UK, and the U.S. developed a comprehensive report, and Lacroix et al. published an executive summary [91].

As we often see worldwide, policy is often driven by political leadership, which can be in direct contrast to earlier policies. Pollack-Porter et al. address the importance of policy change in public health. She states that changes in policy have a significant impact on health [92]. The COVID-19 pandemic served as a catalyst for change worldwide [93, 94].

6. Conclusions

As the chapter title indicates, the evolution of telemedicine across time has increased a greater awareness of the potential to reach all of the world's population

regardless of location. From space to the terrestrial applications, telemedicine and the various models of care have improved public health and life in general.

This has been made possible by the tireless efforts of researchers in the field of medicine, communications, computer technologies, sensors, robotics, AI, education, and our insatiable desire to change. Protocols and procedures have enabled individuals in extreme environments to gain access to care. While challenges do remain, it is incumbent upon all of us to understand how we got here—the evolution of telemedicine—as a tool for change. The merging of technology and health across all of life, often called OneHealth, will provide a strong framework for meeting the MDGs and providing access to health and education for all [95].

The above material provides an evolutionary tale of how communications from antiquity to the internet we have today have made the world closer than ever before. Each step over the past few millennia has proven to impact human society in many ways. For example, very early on, communications in the nineteenth-century, across oceans or landmasses, took weeks; telecommunications, including telephony and the internet, now make sharing information and knowledge in real-time possible. One of the first uses of the World Wide Web for telemedicine in 1994 was the aforementioned Spacebridge to Russia, which was a direct result of the national space programs [34]. This project utilized web-based video-teleconferencing, which continued to grow into tools like Zoom and Teams, used by governments, industry, academia, schools, and, of course, the healthcare sector worldwide.

Never before has the world's population been so informed and close as it is in this time period. It is not just one event but a litany of events by thousands of individuals over thousands of years that have brought us here. Our challenge now is to keep evolving and innovating so that no one is left behind. This will remain a key challenge moving forward.

Research continues, clinical practice evolves, and outcomes are changed, and scholarly output, which drives policy changes and can ameliorate the barriers. Jafarzadeh et al. address this in their 2022 article relating to further evaluation of telemedicine efficiency [96].

While one does not have a crystal ball, we can clearly see growth in research and applications, often faster than we want, in AI, robotics, and communications. The point here is that it once took centuries now to occur in days!

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Perspective Chapter: Affordances of Telemedicine – Provider Perspectives on Social Presence and Support in Virtual Care

Katharine M. Mitchell and Bree Holtz

Abstract

Telemedicine's rapid integration into healthcare delivery has transformed how providers and patients interact. While much attention has been given to clinical efficacy and access, fewer studies have examined how telemedicine technology features shape the social dynamics of provider-patient communication. This chapter explores provider perspectives on how specific telemedicine affordances modality, interactivity, and navigability influence social presence and the delivery of social support. Drawing on qualitative interviews with providers across specialties, this work introduces a framework linking technological features to communication outcomes in virtual care. Findings highlight both benefits and barriers to empathy, engagement, and support, and suggest future directions for platform design, training, and research.

Keywords: social presence, social support, digital affordances, provider-patient interaction, telemedicine

1. Introduction

Telemedicine has experienced unprecedented growth in recent years, catalyzed by the COVID-19 pandemic and supported by shifts in health policy, infrastructure investment, and evolving patient expectations [1]. What began as an auxiliary tool for reaching patients in remote areas has now become a foundational mode of care delivery across numerous specialties. In this transformation, healthcare systems and providers have emphasized outcomes such as accessibility, cost-efficiency, and clinical effectiveness [2]. Yet far less attention has been paid to the relational dynamics of care: how providers connect with, support, and communicate with patients in the absence of physical presence [3].

Virtual care reconfigures the sensory and emotional landscape of medical encounters. A patient may now interact with their provider from a bedroom, parked car, or

workplace breakroom; contexts that blur traditional professional boundaries and alter how care is perceived and delivered [4, 5]. For providers, the shift to a screen-mediated interaction raises new challenges and opportunities: How do they express empathy without proximity? How do they read a patient’s anxiety through pixelated expressions? How does the interface itself, the presence or absence of features like chat, video, screen share, shape their ability to support patients? [6–8].

In traditional clinical encounters, social support whether emotional reassurance, validation, or clear information, is often conveyed through subtle gestures: eye contact, body orientation, pauses, tone of voice [9, 10]. These cues can be filtered or lost in telemedicine, depending on the design and functionality of the platform [11, 12]. And yet, patients’ needs for such support are not diminished by the medium; they may, in fact, increase in virtual settings where disconnection and uncertainty are more likely.

Affordance theory offers a useful lens to examine this phenomenon. It emphasizes how the design and capabilities of a tool (in this case, a telemedicine platform) shape user behavior and perception [8]. When paired with social presence theory [7] and frameworks of social support, affordance theory helps illuminate how healthcare providers navigate technological constraints to maintain relational care (**Figure 1**).

This chapter seeks to explore how healthcare providers understand and experience telemedicine affordances in relation to their ability to deliver social support to patients. By centering provider perspectives, this inquiry contributes to a deeper understanding of how digital health systems can either facilitate or undermine core elements of human care. It also offers practical insights for the future design of telemedicine platforms that better support presence, empathy, and trust.

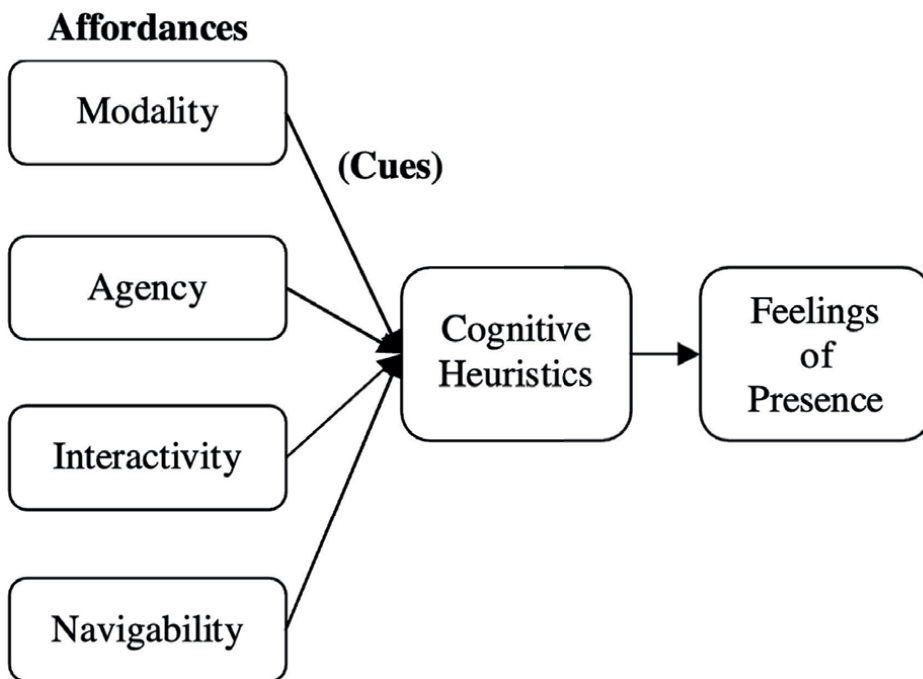


Figure 1.
Affordance cues, Sundar et al. [13].

2. Theoretical framework

To understand the influence of telemedicine technology on provider-patient interaction, we turn to three theoretical constructs: social support theory, technology affordances, and social presence theory (See **Figure 2**) [14]. Social support theory is foundational to effective healthcare communication. It identifies types of support that patients may seek or receive, typically divided into two broad categories: problem-focused and emotion-focused support [15]. Problem-focused support includes instrumental help (e.g., scheduling, prescriptions) and informational support (e.g., guidance, explanations). Emotion-focused support includes emotional validation (e.g., empathy, compassion) and esteem support (e.g., affirming the patient's competence or strength). Each of these plays a unique role in patient outcomes and satisfaction.

Affordance theory describes the possibilities for action that a technology allows or suggests [8]. In the context of telemedicine, these affordances include what providers can do with video, audio, chat, screen sharing, and navigation tools. These features structure the interaction and influence what types of communication and support are most natural or challenging.

Social presence theory examines the degree to which technology allows people to feel as if they are “with” one another. High social presence fosters trust, empathy, and openness; low social presence may lead to miscommunication or feelings of detachment [16].

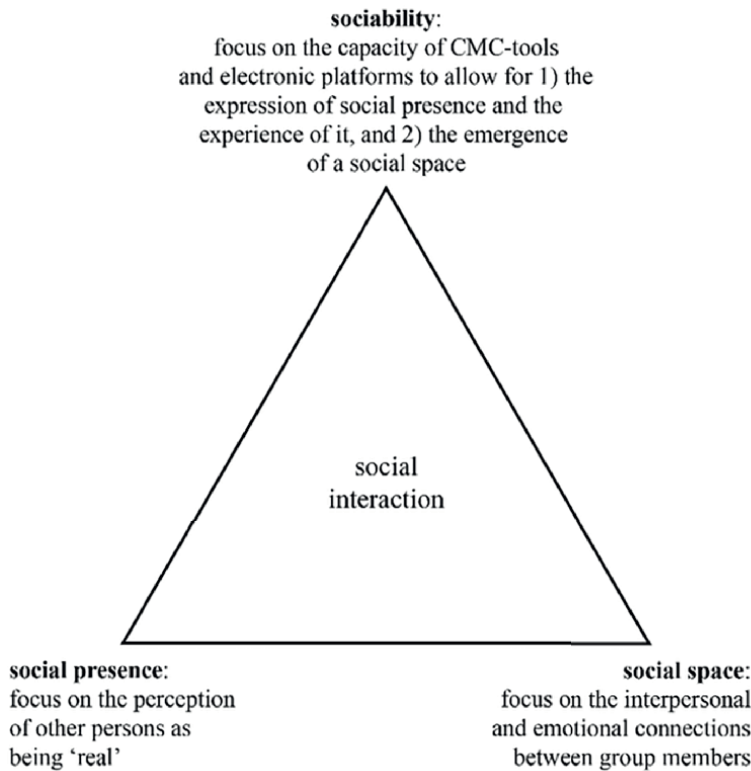


Figure 2.
Social presence triangle, Kreijns et al. [14].

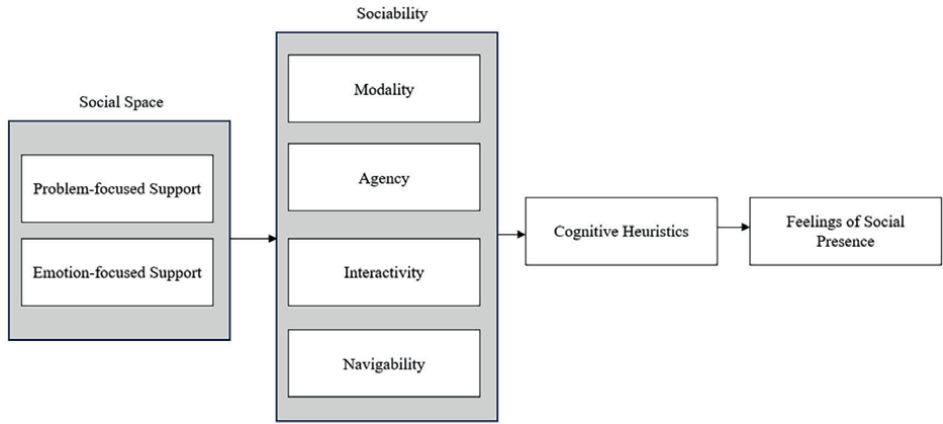


Figure 3.
Social support, affordance, and social presence theories combined framework.

Applying these frameworks together allows us to analyze how telemedicine platforms shape communication behaviors and relational outcomes (See **Figure 3**).

3. Methods

We used qualitative interviews to better understand how providers interpret and navigate the features of telemedicine platforms especially in terms of how those features shape their ability to connect with patients. A total of 17 interviews were conducted with clinicians across a range of specialties, including psychiatry, pediatrics, internal medicine, and primary care. Participants had diverse patient populations and varying levels of experience with telehealth, but all had conducted at least 10 virtual visits.

Our interview guide focused on the real-world use of digital tools during clinical care. We asked questions such as: “What makes a telemedicine encounter feel emotionally connected?” “What features of the platform help or hinder that connection?” and “How do you know when a patient feels supported during a virtual visit?” We also asked them to compare virtual and in-person visits in terms of presence, communication flow, and emotional resonance.

These interviews, conducted between January and April 2023, were held via Zoom or telephone, recorded, transcribed, and coded using thematic analysis. Our analytic process was guided by the frameworks of social support theory, social presence, and affordance theory. We looked for recurring patterns in how providers described the affordances of technology such as video resolution, chat functionality, or screen sharing and how these helped or hindered emotional connection with patients. The findings reflect an interplay between technological design and relational practice.

Transcripts were analyzed using a thematic approach. We began with a round of open coding to identify initial patterns, followed by focused coding to refine themes around modality, interactivity, and navigability. Codes were iteratively compared and grouped based on conceptual overlaps and their relevance to social support and presence. To ensure analytic rigor, two researchers independently coded a subset of transcripts and discussed discrepancies to reach consensus on the final coding framework [17].

4. Findings

This chapter explores how specific affordances of telemedicine, modality, interactivity, and navigability, shape providers' ability to offer social support and maintain social presence. Providers reflected not only on the functionality of these affordances but also on their emotional and relational impact. Their insights revealed that while telemedicine can extend connection in meaningful ways, it also introduces new challenges that must be navigated with care and intention.

In the following subsections, we explore how providers understood and navigated these three affordances in their daily practice. Each section highlights specific examples of how platform features functioned as both facilitators and barriers to the delivery of social support.

4.1 Modality affordances: Seeing and feeling through the screen

For many providers, video was more than a technical feature, it was the primary conduit for empathy. High-resolution video made it possible to pick up on nonverbal cues that are essential to understanding a patient's emotional state. As one provider explained,

The better the quality of the video, you know, [the better] you can read the patient's body language and facial expressions (P1, M35). (Note: P is the participant number, M/F is their gender, and the participants age)

Providers also described video as an unexpected window into patients' lives. Seeing a patient's home environment offered rich context that could enhance care and deepen the relational dynamic.

In a telemedicine [visit], you see even what you can't see in person. I mean, most of the time when they're doing it from their home, you can kind of get a gauge of what their background looks like, what their home life looks like. Is, you know, is it kept? I think you can almost see in their lives quite a bit more [than in person] and maybe make you more empathetic (P3, F31).

However, this intimacy could come at a cost. Some providers reported patients' environmental factors being distracting.

Sometimes the informal nature that the environment creates. For some patients, they don't take it as serious and are very distracted within the interview, the TV on in the background, or and then patient confidentiality (P1, M35).

Although the features of telemedicine technology afford visibility and synchronicity in a way that feels comparable to in-person interactions, the mediated nature of interacting through a technological device was noted by multiple participants to create feelings of distance. These feelings of distance appear to be outcomes of the inability to physically touch their patients but is also a result of a loss of humanness or abstraction. For example, one participant commented on the lack of touch, saying:

I feel like when the component of human touch is involved, and with the physical exam, the patients tend to have more comfort that they're being taken care of in a way. Having that [touch] component in person does help with that. They tend to feel a little bit better that 'someone's looking at me,' 'someone's checking me out,' 'someone's telling me that I'm okay or not okay.' (P21, M32)

The visual modality of telemedicine served as both a bridge and a barrier to emotional connection. Providers valued video's ability to convey nonverbal cues, offer insight into patients' home environments, and foster empathy through contextual visibility. Yet, this increased intimacy could introduce distractions or blur professional boundaries. The absence of physical touch and the mediated nature of communication through a screen contributed to a subtle sense of abstraction or distance, reminding providers and patients that something fundamental about in-person care was missing. While video afforded many relational benefits, its limitations tempered the sense of full presence.

4.2 Interactivity affordances: Co-creating care in real time

Interactive features like screen sharing, chat, and digital co-navigation were seen as vital tools for collaborative care. These features allowed providers and patients to engage in real-time problem solving, clarify medical information, and build a shared sense of agency.

I think that's something that patients are usually really appreciate. When a doctor takes time to go through specific lab results or imaging and point to things and say, you know, this is something important, or you know, I've looked at this, and everything is normal, and you know it all, everything looks as it should. Yeah, I think it's more comforting, I think, to the patient. It helps with support. (P5, M59)

This reciprocal communication was noted by other participants to have a positive impact on the interaction. For example, "It [screen share] definitely improves the interaction. It gives you something tangible to look at and talk about. Helps them feel involved" (P2, F48).

Interactive features such as screen sharing and chat enriched telemedicine visits by transforming patients from passive recipients into active participants. Providers emphasized how these tools supported real-time collaboration, enhanced comprehension of medical information, and helped patients feel more engaged and reassured. By offering something concrete to focus on like lab results or imaging these features fostered transparency, comfort, and a greater sense of shared understanding. Ultimately, interactivity was not just functional but relational, deepening the quality of connection between provider and patient.

4.3 Navigability affordances: Balancing efficiency and emotional presence

Telemedicine technology affords users movability, or the ability to move around among multiple screens while appearing to continue eye contact with the patient. For example, one participant noted:

I do think that I myself am very distracted when I'm on there, I'm like, 'Oh, let me check [this other thing]'. Like they're talking about something, and I'm like, 'Okay, well, I can like, go look at their labs while they're talking'. [This can be done] virtually

because it's like they won't see me, and they will not know. And I like we'll just go look at their logs, and like, they'll be going to certain things while they're talking. To be honest, which is terrible, but it's like it's possible to do without looking bad. (P10, F37)

One participant noted that eye contact is just different in telemedicine, “Especially now with technology, you know, most people are pretty used to that screen [viewing]. So, you know, they kind of realize that they might be looking at you, although it doesn't look like they're looking at [them]” (P3, F31). However, that same participant noted that the affordance may actually have a negative impact on social support. They said:

Trying to connect but I would say that maybe this is just me but it's easier for me to I'm sure it looks more to them that I'm just looking at the computer and typing as they talk when it's more to them that I'm just looking at the computer and typing as they talk when it's virtual. Cause I'm not making eye contact into the camera. So maybe a little less personable. (P3, F31)

The navigability of telemedicine platforms allowing providers to move seamlessly between screens and information sources was seen as both a strength and a drawback. While this flexibility enabled multitasking, such as reviewing labs during patient conversations, it also risked diminishing the perception of attentiveness. Providers acknowledged that the lack of direct eye contact, caused by shifting focus between screens or cameras, could make interactions feel less personal. As a result, while navigability supports efficiency, it may inadvertently weaken the sense of connection and emotional presence during virtual care.

4.4 Enhancing vs. hindering presence

While each affordance (modality, interactivity, and navigability) offers distinct relational opportunities, providers consistently circled back to a shared concern: how present they felt with their patients (see **Table 1**). This theme of *presence* emerged as both a goal and a challenge across all features of telemedicine technology. High-quality video and interactive features can simulate in-person presence, enabling providers to perceive and respond to emotional cues. However, disruptions in flow, poor lighting, and technical glitches reduce authenticity. Some providers reported

Affordance	Description	Theme
Modality	Video affords visibility into patients' emotional cues and home context	Seeing and feeling through the screen
	Lack of physical presence and human touch reduces connection	Loss of touch
Interactivity	Screen share supports engagement and clarity	Collaborative navigation
	Reviewing visuals with patients enhances trust	Emotional reassurance
Navigability	Providers navigate between screens unseen, sometimes creating disengagement	Silent multitasking and distraction
	Difficulty with camera-based eye contact can reduce perceived presence	Eye contact challenges

Table 1.
Summary of key affordances.

that asynchronous aspects (e.g., delayed responses, lack of shared space) made communication feel transactional rather than relational.

The degree of presence experienced was also shaped by how well the provider adapted to the virtual setting. Some clinicians adjusted their voice modulation, gaze, and posture to better simulate in-person interaction. Others admitted to feeling constrained, especially when unsure if they were “coming across” as warm or engaged. Presence was described as fragile easily enhanced by well-designed features but just as easily broken by lag, audio issues, or poor user experience.

5. Implications

These findings illustrate how seemingly simple features such as video resolution, screen-sharing, and interface navigation act as powerful affordances that shape not just the logistics of care, but also its emotional tone and relational dynamics. Drawing on affordance theory, we see how the technological environment is not neutral: it enables, constrains, and reshapes what it means to be present, to connect, and to support. Modality, interactivity, and navigability are not merely technical characteristics they are relationship-mediating forces in digital care environments.

5.1 Design implications

To better support social presence, developers should consider embedding visual and interactive tools that mimic co-presence. This includes shared whiteboards, gesture recognition, and AI-enhanced facial tracking to simulate eye contact. Interfaces should be streamlined to minimize cognitive overload and distractions.

Providers emphasized the need for customizable interfaces that allow each specialty to highlight relevant features. For example, behavioral health might prioritize facial cues and silence detection whereas primary care might emphasize chart annotation and medication visuals. Developers should involve clinicians in the design process to ensure practical, real-world functionality. Design must also account for diverse patient technology literacy levels and ensure accessibility across devices.

5.2 Training implications

Providers would benefit from training on digital bedside manner learning to modulate voice, pace, and nonverbal behaviors in front of a camera. Training should go beyond technical proficiency to include communication strategies that foster connection. Role-playing difficult conversations via video, peer feedback on telepresence, and simulation-based learning can help. Providers also expressed a desire for “etiquette guides” that outline best practices, such as where to position the camera, how to manage silences, and ways to express empathy virtually. Institutions should incorporate modules that demonstrate how to use platform features for emotional support, not just clinical efficiency.

6. Conclusion

As telemedicine becomes a permanent fixture in healthcare delivery, it is essential to move beyond questions of efficiency and access to consider the quality of

communication and connection within virtual care. This chapter has examined how healthcare providers experience and interpret the features and affordances of telemedicine technology in relation to their ability to deliver social support an often overlooked, yet vital, component of patient care.

The findings demonstrate that specific affordances, modality, interactivity, and navigability, play a significant role in shaping the social presence of providers and the types of support they can offer. High-resolution video, screen-sharing, and chat tools can enhance empathy, clarity, and shared understanding, while poor design, technical glitches, or unintuitive interfaces can erode trust and connection. Providers are actively adapting to these challenges, developing new forms of “digital bedside manner”, and drawing on both their clinical skills and communication intuition to bridge the physical and emotional distinctions introduced by the screen.

Importantly, the chapter underscores that telemedicine does not merely digitize healthcare; it reconfigures it. The tools and interfaces we use actively shape the care experience. When platforms are thoughtfully designed and supported with provider training, they can foster meaningful relationships, deepen patient engagement, and reinforce patient-centered values. When they are poorly designed or implemented without consideration of communication dynamics, they risk reinforcing barriers to care.

This analysis also has implications beyond individual encounters. It invites designers, administrators, policymakers, and educators to consider how technologies can be leveraged not just for operational efficiency but for relational excellence. Equipping providers with the tools and training to offer social support in virtual environments is not an optional enhancement it is a requirement for equitable and compassionate care in the digital age.

Future research should also explore how different populations experience telemedicine, particularly in terms of equity, cultural relevance, and trust. There is a need to integrate patient perspectives more fully and to test interventions that improve telepresence and support delivery across diverse clinical contexts. In sum, the future of telemedicine will not be defined solely by bandwidth, access, or reimbursement. It will be defined by our ability to preserve what makes care human even when it's delivered through a screen.

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Section 2

Clinical Challenges and Applications

Eyes on the Future: Integrating Virtual Care Models with XR and Digital Innovation in Ophthalmology

Giselle Ricur, Shalini Shah, Sarah Tajran and Eduardo Alfonso

Abstract

The Bascom Palmer Eye Institute (BPEI) at the University of Miami has pioneered the integration of digital health innovations and medical extended reality (MXR) to transform ophthalmic care and education. This chapter reviews BPEI's journey in adopting teleophthalmology, artificial intelligence (AI)-assisted diagnostics, and immersive MXR technologies, encompassing virtual reality (VR), augmented reality (AR), and mixed reality (MR), to enhance access, clinical precision, and trainee engagement. The Virtual Eye Care (VEC) program exemplifies a comprehensive telehealth ecosystem that has expanded patient access through synchronous, asynchronous, and hybrid care models, supported by a centralized VEC HUB optimizing workflows and patient triage. Between 2020 and 2025, BPEI delivered over 36,000 virtual visits, with high patient satisfaction and minimal appointment wait times. Meanwhile, MXR-based platforms are serving as ophthalmic screening solutions in eye clinics, as well as educational tools. The Bascom Palmer Verse metaverse platform and VR surgical simulators are revolutionizing ophthalmic training by providing immersive, risk-free environments that improve skills acquisition and knowledge retention. These technologies also empower patient education and remote monitoring. Challenges remain in regulatory compliance, data security, and equitable technology deployment, yet BPEI's iterative, patient-centered approach offers a scalable model for other academic institutions. Looking forward, continued collaboration among healthcare providers, educators, technologists, and policymakers will be essential to embed digital health and extended reality as integral components of ophthalmic care. This paradigm shift promises to enhance diagnostic accuracy, streamline clinical workflows, and ultimately improve patient outcomes while advancing the next generation of ophthalmic clinicians.

Keywords: ophthalmology, teleophthalmology, virtual eye care, hybrid models of care, ophthalmic education, medical extended reality, virtual reality, telemedicine

1. Introduction

The University of Miami (UM) has been a pioneer in virtual care for over two decades, consistently integrating emerging technologies to enhance healthcare delivery and medical education. This commitment dates to 1968 with the development of Harvey®, the first computer-enhanced mannequin simulator, created at UM to advance clinical training [1]. Within the Miller School of Medicine, the Bascom Palmer Eye Institute (BPEI) has established itself as a global leader in ophthalmic care and education, distinguished by its early and sustained adoption of innovative technologies in clinical practice and translational research [2].

Since 2020, the UM Health System has significantly expanded its telehealth capabilities, with teleophthalmology emerging as a critical tool for enhancing access to clinical care at BPEI. In response to the COVID-19 pandemic, BPEI rapidly deployed virtual triage and consultation services, enabling patients to receive timely ophthalmic evaluations from the safety of their homes [3]. This evolution not only addressed immediate public health needs but also laid the foundation for a robust, scalable virtual eye care infrastructure. Today, teleophthalmology continues to play a vital role in reducing geographic and logistical barriers to care, particularly for underserved populations across South Florida and beyond.

As the healthcare landscape continues to evolve, it is imperative to leverage digital tools for improved patient outcomes and more effective educational methodologies. Advances in digital health and extended reality (XR) which includes virtual reality (VR), augmented reality (AR), and mixed reality (MR)—are opening new frontiers in how healthcare professionals interact with patients and how medical training is delivered [4, 5].

Digital health innovations are reshaping patient care by offering immersive, interactive experiences that enhance understanding, engagement, and adherence. For instance, the onset of remote patient monitoring programs with biosensors, wearables, and apps enable patients to self-monitor their conditions, increasing their level of participation in the care process. VR-enabled devices can not only enhance remote monitoring but can also be used in-office or in community settings, transforming the manual ophthalmic work-up of a patient into an automated, precise, and more engaging experience for users while optimizing clinical workflows and resources [6, 7]. Additionally, VR can simulate surgical procedures, while AR can overlay complex anatomical structures in real time, empowering patients to better comprehend their diagnoses and treatment plans. This transparency fosters greater patient satisfaction and promotes a collaborative, empowered approach to healthcare [8].

In ophthalmic education, XR technologies are transforming how future eye care professionals are trained. Traditional pedagogical models are being augmented with immersive simulations that allow trainees to practice procedures in a risk-free environment and experience a broad spectrum of clinical scenarios [9–11]. By integrating these advanced tools into curricula, institutions like BPEI can elevate instructional quality, improve knowledge retention, and better prepare clinicians for the complexities of real-world practice.

This chapter explores the integration of digital health innovations and extended reality at BPEI, with a focus on their impact on patient care and ophthalmic education. Through a review of our institutional journey and outcomes, we aim to highlight the transformative potential of these technologies for patients, practitioners, and trainees alike—ultimately paving the way for a more effective, accessible, and engaging future in ophthalmology.

2. Defining digital health innovations in ophthalmology

Digital health innovations in ophthalmology encompass a broad spectrum of technologies designed to enhance both patient care and clinical practice. These include telemedicine platforms, artificial intelligence (AI)-driven diagnostics, mobile health applications, and cloud-based electronic health records (EHRs), all of which contribute to a more connected, efficient, and patient-centered model of care [12, 13].

A notable advancement is the implementation of cloud-based EHR systems, such as Epic (Epic Systems Corporation, Wisconsin, USA), which is utilized at the University of Miami. At the BPEI, clinicians access Epic's ophthalmic module, Kaleidoscope, which streamlines documentation and facilitates interdisciplinary communication. Through the *MyUChart* patient portal, individuals can view their health records, enhancing transparency and fostering a more collaborative relationship between patients and providers.

Mobile health applications and biosensors are also transforming how patients engage with their eye health [14]. These tools offer real-time, personalized insights into ocular wellness, enabling users to monitor vision changes, detect early signs of disease, and participate in preventive care from the convenience of their smartphones. Many apps incorporate vision tests, symptom checkers, and AI-assisted diagnostics, empowering patients to seek timely medical attention [15]. Some applications also integrate with wearable devices to track screen exposure, eye strain, and environmental factors, while others support teleophthalmology by allowing users to submit ocular images for remote evaluation. Although not yet standard at BPEI, such apps can improve adherence by reminding patients to take medications, schedule exams, or track symptoms.

Innovative imaging technologies further enhance diagnostic precision. The integration of optical coherence tomography with high-resolution retinal imaging enables non-invasive, early detection of ocular diseases. AI-assisted algorithms are increasingly embedded in these platforms, improving diagnostic accuracy and enabling personalized treatment strategies. As the United States Food and Drug Administration continues to approve these tools for clinical use, their role in optimizing eye care is expected to expand significantly [10, 16, 17].

These advancements have catalyzed the emergence of a new interdisciplinary field dubbed Oculomics, that explores the relationship between ocular biomarkers and systemic health, using advanced imaging and AI to identify indicators of diseases such as cardiovascular conditions, cancer, neurodegenerative disorders, and metabolic syndromes [18–20]. By analyzing retinal structures or tear fluid composition, clinicians can detect systemic diseases at earlier stages—often before symptoms arise. This approach promises to support risk stratification, early intervention, and personalized care, all through non-invasive, ophthalmic imaging.

Ultrawide-field fundus imaging represents another leap forward, capturing a broader view of the retina in a single image and enabling earlier detection of peripheral retinal pathologies. The development of portable and handheld fundus cameras has further democratized access to diagnostics, allowing high-quality imaging in emergency departments, hospital bedsides, and community outreach settings [21–23]. At BPEI, these tools have been instrumental in initiatives such as mobile vision vans, health fairs, and collaborations with organizations like the Major League Baseball's Miami Marlins, where athletes were screened using portable digital technology prior to spring training.

By integrating these digital innovations into clinical workflows and outreach programs, ophthalmologists and other vision care providers can extend the reach of care, improve early detection, and enhance long-term outcomes—particularly for underserved populations. These technologies collectively represent a paradigm shift in how eye care is delivered, monitored, and experienced.

3. Medical extended reality (VR, AR, MR) and its role in eye care

XR, an umbrella term encompassing VR, AR, and MR, is redefining the landscape of healthcare delivery and education. In ophthalmology, these immersive technologies are being leveraged to enhance diagnostic precision, surgical training, and patient engagement.

Medical extended reality (MXR) has emerged as a dynamic interdisciplinary field at the intersection of immersive technology and clinical practice. Recognizing the need for a standardized framework to guide its development, Spiegel, et al. at Cedars-Sinai proposed a taxonomy to categorize MXR applications and support future research and implementation strategies [24].

- *Virtual reality* creates fully immersive digital environments that simulate real-world scenarios. In ophthalmology, VR has been used in surgical training, allowing clinicians to practice complex procedures in a risk-free, controlled setting. This experiential learning enhances skill acquisition and reduces the likelihood of errors in clinical practice. Additionally, VR can be employed to reduce patient anxiety by familiarizing individuals with surgical environments prior to procedures, thereby improving overall comfort and satisfaction. Lately, VR has experienced increased adoption for performing clinical screenings, comprehensive eye exams, and remote monitoring, changing the paradigm of how ophthalmic examinations are performed.
- *Augmented reality* overlays digital information onto the physical world, enhancing real-time perception and decision-making. In ophthalmic surgery, AR can assist clinicians by projecting anatomical landmarks or procedural guidance directly onto the surgical field. For example, AR can help visualize optimal incision paths during cataract extraction or retinal repair, improving surgical precision and outcomes.
- *Mixed reality* blends elements of both VR and AR, enabling users to interact with both physical and digital objects simultaneously. This hybrid approach facilitates collaborative training environments where learners can manipulate virtual tools while engaging with real-world instruments and peers, fostering deeper understanding and teamwork.

Together, these XR modalities are transforming how ophthalmologists are trained, how procedures are performed, and how patients experience care. By integrating XR into clinical workflows and educational programs, institutions can enhance diagnostic accuracy, streamline training, and promote a more patient-centered approach to care.

At BPEI, several VR-enabled solutions have been piloted to modernize ophthalmic diagnostics. Notably, the Olleyes VisuALL™ S (Olleyes Inc., Summit, NJ) and the VF

Heru Prime (Heru, Inc., Miami, FL) applications—deployed on wearable VR headsets such as the Pico Neo 3 Pro Eye (ByteDance, Beijing, China)—are revolutionizing comprehensive eye exams. These portable, user-friendly systems enable automated visual field testing and other assessments without the need for traditional, space-intensive equipment. Clinicians can evaluate visual acuity, contrast sensitivity, and field defects efficiently, even in non-traditional settings, thereby improving access for elderly or mobility-impaired patients.

Recent studies highlight the clinical validity of VR-based diagnostics. One study reported a mean VR visual field test duration of 344 seconds, significantly reducing testing time without compromising accuracy [25]. Another demonstrated strong concordance between VR perimetry and the Humphrey Visual Field Analyzer (HVFA), with a Spearman's correlation coefficient for mean deviation (MD) of $r_s(41) = 0.871$, $p < 0.001$ [26].

Beyond patient benefits, VR-based testing enhances clinical efficiency. Traditional visual field assessments often require dark rooms, technician oversight, and extensive setup. In contrast, VR platforms support bedside testing in emergency departments, hospitals, and outreach settings. For example, a VR-based model for detecting relative afferent pupillary defects achieved an accuracy of 0.97, sensitivity of 0.94, and specificity of 1.00 [27].

These technologies also streamline workflows by reducing supervision requirements and enabling multitasking. Integrated AI and cloud-based analytics allow for real-time data processing, longitudinal tracking, and rapid treatment planning. As a result, institutions can improve throughput, reduce bottlenecks, and elevate the overall quality of care.

Technology is also highly useful in education, such as hands-on surgical training. Improvements in skill scores and decreases in technical errors were significantly associated with using a high-end VR simulator for intraocular surgery training, such as the EyeSi Surgical simulator (Haag-Streit, UK) [28]. These immersive training tools provide a safe, repeatable environment where trainees can refine their techniques without risk to patients, accelerating the learning curve and standardizing skill acquisition across institutions. At BPEI, first, second, and third-year residents all have the opportunity to train on the use of virtual reality surgical simulators like the EyeSi or the HelpMeSee Eye Surgery Simulator (HelpMeSee, NJ, USA) during their rotation at the Bruce W. Carter Department of Veterans Affairs Medical Center in Miami, Florida. We believe that the use of MR in surgical simulations represents a paradigm shift in ophthalmic education, bridging the gap between theoretical knowledge and practical expertise.

In summary, XR technologies are not only enhancing the precision and accessibility of ophthalmic diagnostics but are also reshaping the educational and experiential dimensions of eye care. As these tools continue to evolve, their integration into mainstream practice will be pivotal in advancing both clinical excellence and patient empowerment.

4. BPEI's virtual eye care program: Bridging the digital divide in ophthalmology

BPEI has pioneered a transformative approach to virtual ophthalmic care through its VEC program—an initiative designed to enhance access, efficiency, and patient experience through secure, technology-enabled services. Introduced to the BPEI Board of Governors in early 2022, the program was envisioned as a foundational step

in expanding digital health capabilities under the guiding principle of “*Eye Care, everywhere.*” This vision emphasizes a connected ecosystem that integrates health and social care, education, research, and partnerships with technology-driven enterprises.

BPEI’s digital ecosystem is inherently collaborative, linking patients, providers, academic institutions, and industry leaders. By mapping the patient journey, digital innovations are strategically embedded at critical touchpoints—diagnosis, treatment planning, follow-up, and fulfillment—ensuring personalized and accessible eye care.

The VEC strategy, initially outlined for Fiscal Year 2022–2023, incorporated synchronous, asynchronous, and hybrid care models aligned with three core objectives:

- *Improving access:* Reducing wait times and eliminating geographic barriers through virtual consultations.
- *Enhancing clinical accuracy:* Utilizing digital slit lamps, imaging devices, and integrated EMR systems to support real-time assessments.
- *Educating providers:* Implementing XR-based simulations, training modules for residents and fellows, and virtual etiquette protocols to optimize patient-provider interactions.

The implementation followed a structured, iterative approach involving stakeholder engagement, continuous monitoring, and strategic evaluation to optimize outcomes. What began as isolated virtual consultations has evolved into a comprehensive telehealth ecosystem. Like many institutions globally, BPEI experienced a pivotal shift during the COVID-19 pandemic, which accelerated the adoption of telemedicine.

In March 2020, BPEI designed a novel virtual triage program to mitigate exposure risks during lockdowns called Rapid Virtual Eye Care® (RVEC). This on-demand, synchronous video or audio-only service enabled patients with acute ophthalmic concerns to receive timely consultations from home. Since its formal launch in October 2020, virtual visit volume increased from approximately 50 per month to over 350 monthly visits within 3 years [3]. Today, the RVEC program serves as the digital front door to BPEI’s ophthalmic services, offering 24 to 72-hour access to more than 500 patients monthly. This growth is attributed to several key enablers: dedicated leadership, the creation of virtual coordinator roles, the integration of self-scheduling features on the BPEI website, and a robust digital marketing campaign. These efforts were supported by continuous feedback mechanisms and iterative improvements, as described by Townsend et al. [3].

In 2022, BPEI formally established the VEC department, launched a Tele-Ophthalmology Research Fellowship, and expanded its engagement with medical extended reality technologies—solidifying its commitment to digital transformation in eye care. Between 2020 and 2025 to date (07/31/25), BPEI recorded over 36,000 virtual visits, including 18,362 RVEC consultations (**Figure 1**). In fiscal year 2024–2025 alone, 9047 visits were completed, with 5341 patients utilizing RVEC services. Patient satisfaction remains a cornerstone of the program, reflected in a 93.73 Press Ganey Top Box score for “willingness to recommend.” Additionally, the average lead time to the first available RVEC appointment was just 0.41 days, underscoring the program’s efficiency and accessibility.¹

¹ Source: BPEI-Virtual Eye Care Dashboard. MS Power BI, 2025. Last access: July 31st, 2025.

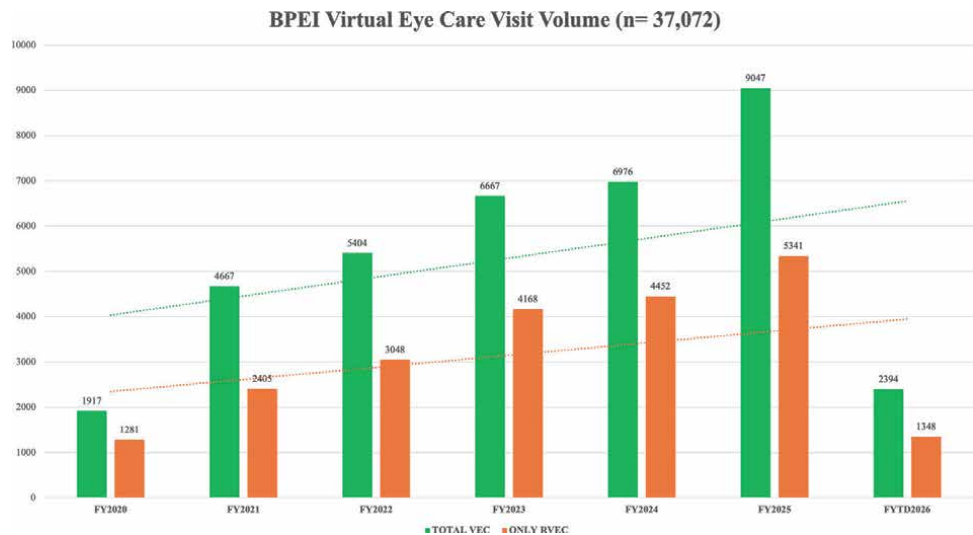


Figure 1.
Annual total Virtual Eye Care (VEC) and Rapid Virtual Eye Care (RVEC) visit volume from 2020 to 2025.

BPEI’s strategic embrace of telehealth exemplifies how digital innovation can bridge care gaps, enhance patient engagement, and deliver high-quality ophthalmic services at scale.

5. Lessons learned

The long-term success of the VEC program at BPEI can be attributed to several strategic innovations and operational frameworks. In addition to the foundational elements outlined by Townsend et al., two critical components have emerged as key drivers of sustained impact: the establishment of the VEC Hub and the development of hybrid care models [3].

5.1 The VEC Hub: A centralized support framework

The VEC Hub was conceptualized as a centralized infrastructure to support virtual consultations and expand access to specialized ophthalmic care beyond traditional clinical settings. This model relies on a multidisciplinary team of allied health professionals trained to manage the administrative, technical, and clinical aspects of virtual encounters.

The Hub’s structured intake process ensures that patients receive comprehensive evaluations prior to provider engagement. This includes medication reconciliation, pharmacy verification, symptom documentation, pain assessment, social history review, ophthalmic-specific questionnaires, health and safety screenings, allergy checks, and technical support. By standardizing these pre-consultation workflows, the VEC Hub enhances the quality and consistency of virtual care delivery.

Furthermore, the seamless integration of Zoom (Zoom Communications, Inc. San Jose, CA) and Epic platforms enables real-time documentation and continuity of care, while optimizing provider efficiency and remote patient management.

5.2 Hybrid models of care: Evolving definitions and applications

The concept of hybrid virtual care has evolved significantly, particularly in response to the COVID-19 pandemic. Initially, “hybrid” referred to the integration of multiple telecommunications technologies—such as VoIP, satellite, and microwave systems—to facilitate remote interactions. These systems enabled synchronous (real-time) and asynchronous (store-and-forward) communication between patients and providers [29, 30]. As the pandemic reshaped healthcare delivery, the definition of hybrid care expanded to encompass a blend of in-person and virtual services [31]. This model allows for flexible, patient-centered care pathways that preserve the benefits of face-to-face interactions while leveraging the convenience of telehealth. For example, a patient may undergo an initial in-person examination followed by virtual follow-ups to monitor progress or manage chronic conditions.

This approach not only improves access and continuity of care but also reduces the burden on healthcare facilities and staff. By tailoring visit formats to individual patient needs, hybrid models enhance satisfaction and clinical outcomes. In ophthalmology, where diagnostics often rely on specialized imaging, hybrid care has proven particularly effective. At BPEI, a comprehensive workflow has been implemented that begins with a virtual consultation to assess patient needs and order necessary tests. Patients then attend in-person visits at one of BPEI’s South Florida locations for imaging and diagnostics. Importantly, they are not required to wait for immediate provider review; instead, results are discussed during a follow-up “tele wrap-up” appointment conducted virtually.

This model offers several advantages: it minimizes travel and wait times, enhances patient comfort, and allows for more thoughtful, unhurried discussions of clinical findings. Providers can also schedule future hybrid visits, enabling patients to complete testing in person while continuing to benefit from virtual consultations.

As an example, in October 2023, the Cornea Service at BPEI piloted a new hybrid service line called the Tele Dry Eye Clinic (Tele DEC) to address the high volume of patients with dry eye-related disorders that were straining the system. By integrating a virtual screening process with on-site testing and virtual follow-up visits, the clinic successfully streamlined workflows, enabling smooth and efficient care delivery. Since its official launch, Tele DEC has served 1186 patients—an interannual increase of 52.24% in patient volume.² In addition, patients identified as candidates for meibomian gland therapy were referred for treatment to the newly established Lid Margin Clinic, which has become a new source of net income. This treatment algorithm, or new model of care, has been extremely well received due to its efficiency and rapid patient access. Consistently high Press Ganey scores reflect strong patient satisfaction in a field where, despite numerous treatment options, true satisfaction has traditionally been elusive.

By integrating virtual and in-person care in a seamless, patient-centric manner, BPEI’s hybrid model exemplifies a forward-thinking approach to ophthalmology. It demonstrates how technology can be harnessed to deliver high-quality, accessible, and efficient care tailored to the unique needs of each patient.

² Source: BPEI-Virtual Eye Care Dashboard. MS Power BI, 2025. Last access: July 31st, 2025.

6. MXR: Elevating ophthalmic training

The rapid evolution of digital health and extended reality technologies is transforming ophthalmic education, offering immersive, adaptive, and accessible learning environments. At the UM's Miller School of Medicine, the BPEI has embraced MXR to enhance clinical training, improve student engagement, and expand educational reach.

6.1 Creating the learning environment: The Bascom Palmer Verse

To meet the growing demand for innovative, on-demand, and risk-free training environments, BPEI launched the Bascom Palmer Verse (BPEIVerse) in 2022 [32]. Developed in collaboration with students and faculty from the University of Miami's Virtual Experience Simulation Lab, this immersive metaverse platform replicates the physical layout of BPEI and includes an amphitheater, auditorium, exam rooms, surgical suite, and a collaborative networking patio (**Figures 2–4**). This digital twin offers a new learning scenario, hosted on a metaverse solution primarily used for education and enterprise collaboration called Engage XR (Engage XR, London, UK, <https://engagevr.io>). These types of virtual network environments allow for real-time interaction between students and faculty, in highly visual and engaging scenarios, enabling enhanced experiential learning opportunities for all users.

The BPEIVerse's vision is to enable trainees to practice complex surgical techniques, refine diagnostic skills, and engage in simulated patient encounters in a safe, interactive environment. It supports real-time feedback and peer collaboration, aligning with BPEI's mission to advance ophthalmic knowledge through compassionate care and innovative education. The platform has received public recognition, being named a finalist for Best Healthcare and Wellness Solution (2024) and Best Education Solution (2025) at the annual 2024 and 2025 Auggie Awards, respectively.



Figure 2.
Bascom Palmer Verse auditorium. Image acquired with a Meta Quest Pro (Meta, Menlo Park, CA) and downloaded from the UM's account on Engage XR platform (<https://app.engagevr.io>).



Figure 3. Bascom Palmer Verse amphitheater. Image acquired with a Meta Quest Pro (Meta, Menlo Park, CA) and downloaded from the UM's account on Engage XR platform (<https://app.engagevr.io>).



Figure 4. University of Miami's Miller School of Medicine second-year students' avatars participating in the Bascom Palmer Verse. Image acquired with a Meta Quest Pro (Meta, Menlo Park, CA) and downloaded from the UM's account on Engage XR platform (<https://app.engagevr.io>).

6.2 Integrating VR into clinical training

BPEI has incorporated VR-based ophthalmology rotations into its curriculum, allowing medical students to develop diagnostic proficiency and clinical

decision-making skills in a simulated environment. A 1-week rotation includes peer-led, case-based VR presentations and simulated slit-lamp examinations to build confidence and reinforce learning (**Figures 4 and 5**).

Additionally, MXR workshops introduce third and fourth-year medical students to VR tools (Olleyes, Heru) used in clinical imaging, including modules for visual acuity, perimetry, pupillometry, color vision, contrast sensitivity, extraocular motility, and cover-uncover testing (**Figure 6**).

6.3 User experience and challenges

Initial implementation of the BPEIverse training program demonstrated high levels of student engagement and faculty adaptability (**Figure 7**). However, technical challenges such as cybersickness and usability issues were noted during the VR sessions, highlighting the need for continued refinement and progressive monitoring (**Figures 8 and 9**).

Despite these limitations, the inaugural students reported increased comfort presenting clinical cases in virtual environments, suggesting strong potential for long-term integration. Based on these preliminary findings, BPEI has set its course to adapt the current VR ophthalmic curricula to comply with the Association of University Professors of Ophthalmology requirements, as well as open lines of research into the causes of cyber motion sickness and VR usability issues.

6.4 Expanding the educational impact

Beyond training, XR technologies are being used to enhance patient education and engagement. Interactive modules help patients understand their diagnoses, manage vision-related challenges, and participate more actively in their care. XR also supports early detection and preventive strategies by integrating AI-assisted remote patient monitoring and VR-based diagnostics into clinical workflows.

To ensure compliance with federal and state telemedicine regulations, BPEI maintains strict adherence to licensing requirements and employs secure communication

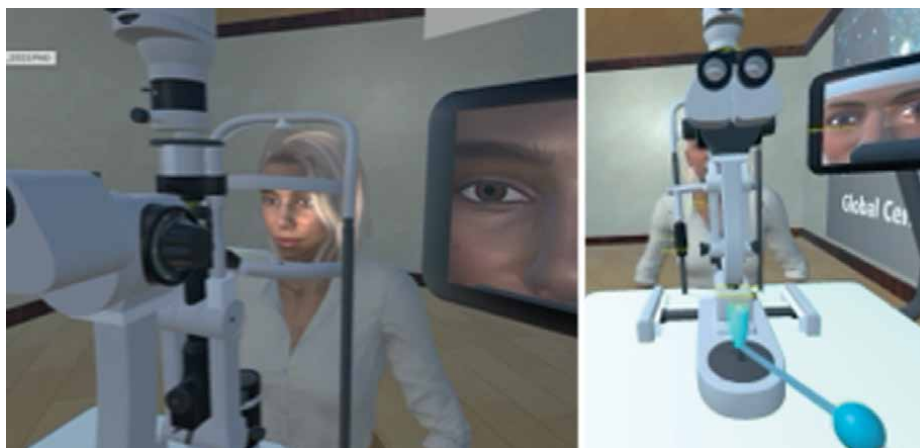


Figure 5.
Virtual reality slit lamp simulator, featuring a practice avatar and labeled components for educational guidance. Stand-alone App developed with Unity 2022 v2.3f1 (San Francisco, CA), and Blender 4.0 (Amsterdam, Netherlands). Image visualized on a Meta Quest Pro (Meta, Menlo Park, CA).



Figure 6.
University of Miami's Miller School of Medicine students engaging with virtual reality to participate in the Bascom Palmer Verse.

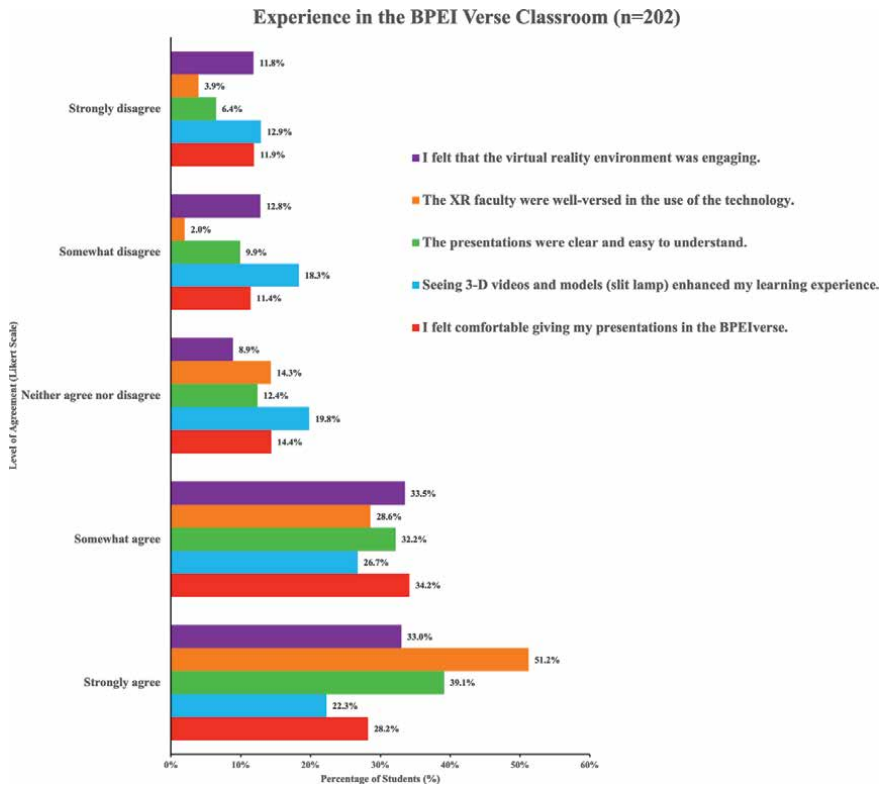


Figure 7.
Student experiences in the BPEIverse, measured on a 5-point Likert scale ranging from “strongly disagree” to “strongly agree” (Qualtrics XM).

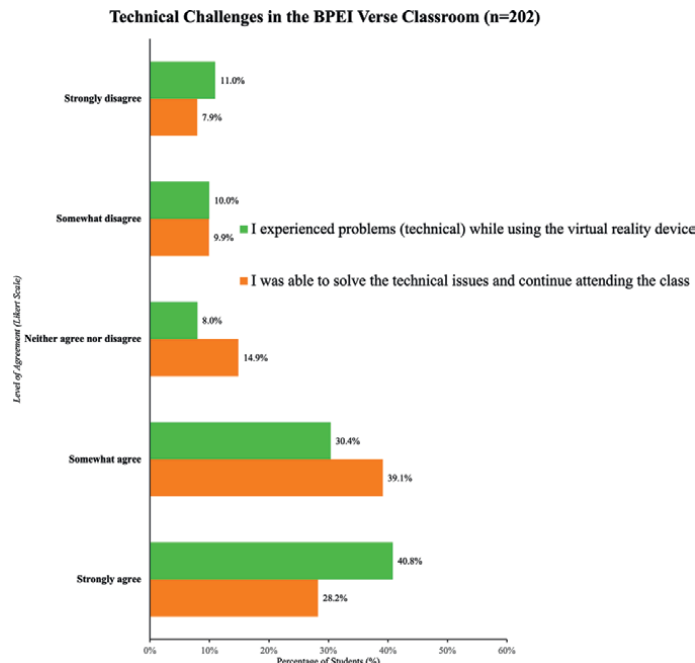


Figure 8.
Student-reported technical challenges in the BPEIverse class, measured on a 5-point Likert scale from “strongly disagree” to “strongly agree” (Qualtrics XM).

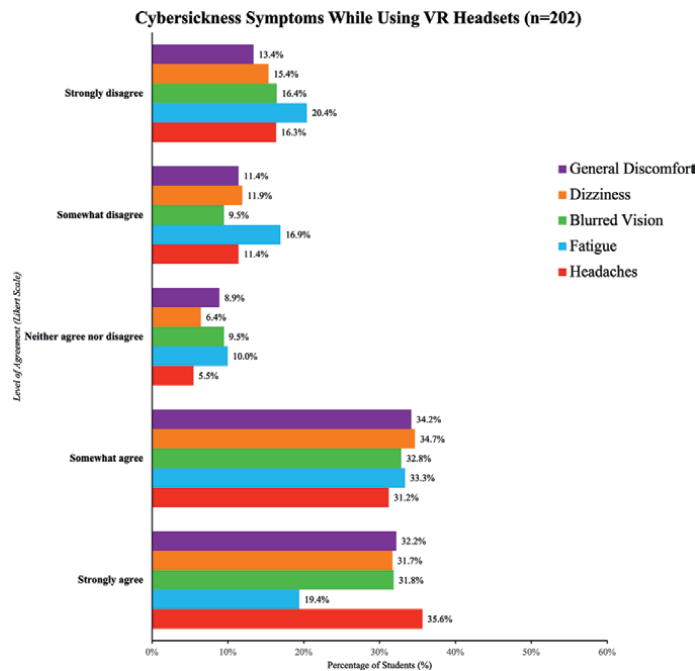


Figure 9.
Student-reported symptoms of cybersickness during the BPEIverse class, measured on a 5-point Likert scale from “strongly disagree” to “strongly agree” (Qualtrics XM).

protocols. Mobile device management policies and robust encryption safeguard patient data, enabling clinicians and trainees to confidently incorporate digital tools into practice.

By integrating MXR, AI-enhanced diagnostics, and telehealth into ophthalmic education and care, BPEI continues to set a precedent for innovation in academic medicine. These technologies are redefining the standards of excellence in ophthalmology, offering scalable, immersive training environments and enhancing diagnostic precision. As XR continues to evolve, its role in shaping the future of ophthalmic learning and patient empowerment will be transformative.

7. The near future

Virtual eye care is poised to remain a strategic pillar in the evolution of ophthalmic services, offering a powerful means to enhance patient access, streamline clinical workflows, and elevate both the patient and provider experience. By thoughtfully mapping the care journey and integrating relevant technologies at each touchpoint, institutions can deliver more personalized, efficient, and equitable care.

Since 2020, the acceleration of teleophthalmology at the UM Health System, particularly through the BPEI, demonstrated the transformative potential of digital health when aligned with clinical excellence and innovation. As technologies become increasingly portable and AI is embedded into the core of virtual platforms, the scalability and precision of these solutions will continue to improve. With ongoing validation and regulatory support, telehealth is well-positioned to become a gold standard for managing specific conditions and serving diverse patient populations.

Looking ahead, the challenge is not merely to adopt new technologies, but to ensure they are implemented thoughtfully, equitably, and sustainably. We call upon healthcare leaders, educators, technologists, and policymakers to collaborate in shaping a future where digital health and extended reality are not just adjuncts to care—but integral components of a more connected, compassionate, and visionary healthcare system.

8. Conclusion

The integration of digital health innovations and medical extended reality at BPEI represents a transformative shift in ophthalmic care and education. By leveraging teleophthalmology, AI diagnostics, and immersive XR training, BPEI has expanded access, improved clinical precision, and enriched educational experiences.

The VEC program's success emphasizes the value of patient-centered, technology-enabled models that blend virtual and in-person services to optimize outcomes. Meanwhile, MXR platforms offer scalable, engaging learning environments critical for preparing clinicians to meet evolving healthcare demands. As these technologies mature, their thoughtful implementation will be pivotal in addressing barriers to care and fostering equitable, high-quality eye health services.

BPEI's multidisciplinary, iterative approach provides a replicable framework for institutions seeking to harness digital innovation responsibly and sustainably. Ultimately, embracing these tools is essential not only for advancing ophthalmology but also for fostering a more connected, compassionate, and accessible healthcare future.

Acknowledgements

The authors acknowledge the use of UM's licensed Microsoft Copilot to check spelling and grammar.

No funding sources need to be acknowledged.

Conflict of interest

The authors declare no conflict of interest.

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Telehealth in Hospital Medicine beyond the COVID-19 Pandemic: Expanding Access, Enhancing Efficiency, and Transforming Care

Gabriel Bianchi and Jeydith Gutierrez

Abstract

Before the onset of the COVID-19 pandemic, inpatient telehealth adoption was minimal. It was confined mainly to tele-critical care and the provision of specialty consultations to support rural hospitals. The pandemic accelerated a rapid telehealth expansion and adoption within the United States and worldwide, offering a chance to reshape healthcare delivery. This chapter explores the transformative role of telehealth in hospital medicine, particularly how this role was shaped by the extreme public health emergency of the COVID-19 pandemic. It provides an overview of the literature regarding telehealth applications across the continuum of care and within the scope of hospital medicine, including pre-hospital triage and consultation, telehospital medicine programs, hospital at-home, and post-acute care applications. Although the data is sparse and clinical trials are still needed, telehealth has shown promising results, including improved clinical outcomes, care efficiency, and reduced costs in many settings within the scope of hospital medicine. Most importantly, telehealth represents a unique opportunity to address the increasing challenges of hospital medicine, such as staffing shortages, multi-site healthcare systems, and the need for continuing education and mentoring for providers practicing in rural areas. Lastly, we assess challenges, opportunities, and future directions for hospital medicine telehealth applications in the post-pandemic era.

Keywords: telehealth, telemedicine, hospital medicine, telehospitalist, virtual hospitalist, rural health

1. Introduction

Medicine is shaped by tradition, yet history shows us that progress comes from challenging the status quo and embracing innovation. As new technologies emerge, telehealth can transform healthcare and, more specifically, the way in which acute and inpatient care is delivered. Telemedicine has traditionally been defined as the ability to provide medical care from a distance, while telehealth is a broader term encompassing all remote healthcare services, including clinical care, education, patient monitoring, and health administration [1].

Telehealth and telemedicine are not new, with records dating as far back as the Middle Ages, when physicians offered prescriptions to patient's based on letters describing their symptoms [2]. The first documented inpatient application of telemedicine might have been in 1906, when Einthoven, the inventor of the electrocardiogram, used the "telecardiogram" to obtain electrocardiograms for patients admitted to the hospital when his non-portable machine was in his laboratory [3, 4].

Modern telehealth modalities, including real-time video consultations, have been evolving since the late 1990s. Despite gradual increase in utilization, widespread adoption had been hindered by barriers including interstate licensing restrictions, reimbursement issues, limitations on care modalities, and restricted diagnoses and specialties that could utilize telehealth [5]. Most of early successes with telehealth were seen in rural areas, particularly in mental health [6], and subspecialty consultations [7]. Hospital medicine, which involves multidisciplinary teams specialized in the care of the acute ill, inpatient, saw very few telehealth applications prior to the pandemic. The COVID-19 pandemic accelerated telehealth expansion, inspiring innovative, patient-centered acute care delivery models aimed at improving quality, efficiency, and reducing costs.

2. The pre-pandemic landscape of telehealth in hospital and inpatient medicine

Prior to the COVID-19 pandemic, telehealth applications in hospital settings were often limited to emergency department (ED) (tele-ED) and intensive care unit (ICU) (tele-ICU) settings, with very few hospital medicine applications. We briefly describe how tele-ICU and tele-ED utilization provided a framework for inpatient telehealth [8, 9], and review the early telehospitalist programs.

2.1 Tele-ICU

The tele-ICU model began to gain traction in the early 2000s. By the late 2010s, many rural hospitals and hospital systems had turned to tele-ICU to address challenges such as geographic disparities in access to intensivists and the need to improve patient outcomes. Furthermore, maintaining high-acuity patients locally was crucial for rural and critical access hospitals, which were facing financial struggles that resulted in the closure of more than 100 critical access hospitals between 2013 and 2020 [10].

The tele-ICU model generally consists of a centralized hub staffed by intensivists and critical care nurses who can remotely monitor patients in multiple units simultaneously, providing real-time support and guidance to bedside clinicians and staff. Some practices have extended tele-ICU model to progressive care or intermediate care units [11]. Initial goals of the tele-ICU programs were to improve patient outcomes, reduce mortality, and increase adherence to best practices in critical care. As Goran reported the purpose was "to provide improved safety through redundancy and enhance outcomes through standardization" [12]. Results of large tele-ICU studies have shown positive outcomes, including lower ICU mortality rates, reduced lengths of stay (LOS) [13], fewer complications and readmissions, and allowing patients to receive local care that is on par with academic centers.

Despite the promising outcomes in the tele-ICU, initial up-front investment, estimated to be between \$2 and \$5 million, challenges with reimbursement and logistics have limited its widespread adoption. Some studies suggest positive return on

investment due to decreased care cost per case, lower ICU LOS and improved outcomes [8]. The United States (U.S.) Veterans Health Administration (VHA) has widely adopted the tele-ICU model as the standard of care, which now supports a significant proportion of ICU beds and patients especially in rural hospitals. Evaluations of these programs have shown reduced interhospital ICU transfer rates, increased palliative care consultations and improved outcomes for high-acuity patients [14–16].

2.2 Tele-ED

The use of telehealth in emergency departments emerged in the late 2000s, similarly in response to access issues, geographic challenges to access specialists, increased cost of care, and the rise in advanced practice providers (e.g. nurse practitioners and physician assistants) staffing emergency rooms in rural areas without adequate physician support.

Many tele-ED applications were described prior to the COVID-19 pandemic. Their goals included providing support to rural areas, facilitating triages and transfers [17], reducing ED overcrowding [18], supporting pre-hospital care through consultations with emergency medical services (EMS) [19, 20], and facilitating access to mental health and other subspecialty consultations for patients in rural hospitals.

Programs such as Avera eCARE [21] helped demonstrate the model's feasibility. Despite growing evidence regarding benefits of tele-ED, including cost-reduction [22, 23], improved response time [24, 25], decreased transfer and mortality rates, and improved quality of care [26, 27], widespread adoption has not been attained. Studies cite barriers including technological and infrastructure challenges, implementation issues, cost and long-term feasibility that require further investigation [9, 23, 28, 29].

2.3 Telehospitalist pre-COVID-19 pandemic applications

The term “hospitalist” was first coined by Drs. Robert Watcher and Lee Goldman in 1996 [30] and by the 2000s, hospital medicine became the fastest growing specialty in the U.S. This approach brought improvements in both efficiency and outcomes [31, 32]. However, for rural hospitals operating with tight budgets and a limited workforce, keeping hospitalist around the clock 24/7 became a significant challenge.

Initial reports of telehealth applications in hospital medicine were aimed at demonstrating feasibility and addressing the staffing challenges of rural hospitals. The “remote hospitalist study” was used to admit patients at a distant emergency room (ER) location early as 2008 [33, 34], while other studies demonstrated the value of these models to support remote providers [35, 36]. Similarly, Sanders concluded in 2014 that the hospital medicine market was primed for a nighttime telehospitalist model to support staffing needs of rural and critical access hospitals with low overnight patient volume [37]. By 2017, Eagle Telemedicine had already popularized their telehealth night coverage solution, offering a range of services from after-hours admissions to cross-coverage and physician support for advanced practice providers [38]. One study reported the experiences of patients and care team members from three critical access hospitals with overnight telehospitalist support at a large metropolitan tertiary center. It showed that patients and care-teams alike thought that overnight telehospitalist model was better than the current system, and they would overwhelmingly recommend the program [39].

In the later 2010s, daytime care models also emerged, with hospitalist physicians from tertiary or academic centers providing support to critical access and rural

hospitals [40, 41]. The “Virtual Hospitalist” model described by Kuperman et al. resulted in decreased transfers from critical access hospital to tertiary centers, allowing the critical access hospital to care for more complex patients while creating bed capacity in the tertiary centers by preventing unnecessary transfers [40]. Boltz et al. reported up to 58% cost-savings using a nurse practitioner/telehospitalist physician dyad, compared with traditional hospitalist staffing, while maintaining quality and increasing access to care [41].

Within the VHA, a pioneer healthcare system in telemedicine applications in the U.S., our research group identified the need for a telehospitalist model to support rural hospitals within the system [42]. Rural hospital administrators identified possible applications, including primary staffing and direct care delivery via telemedicine, support for local providers, and as-needed coverage [43]. Our pilot Telehospital program to support rural VHA hospitals showed that the model was feasible and had resulted in lower length of stay, no changes in patient satisfaction, and high acceptance from the care team [44]. These models not only provided access to hospital medicine expertise, but also decreased unnecessary transfers to tertiary centers, facilitated dissemination of best practices, and decreased costs of care.

2.4 Hospital-at-home

Hospital-at-Home (HaH) was developed as a healthcare model that offers hospital-level treatment to eligible patients in their own homes instead of treating them in a traditional brick and mortar hospital. The concept of delivering hospital-level care at home has been described since the 1970s in the United Kingdom [45] but it was first introduced in the U.S. when Johns Hopkins University reported on a safety and feasibility pilot of a hospital-at-home program in the late 1990s [46, 47]. The goal is to provide hospital-level care in the comfort of a patient’s home, particularly for vulnerable populations, including those with dementia and increased risk of hospital-acquired conditions, allowing them to receive treatment in a familiar environment.

Patients can be enrolled in a HaH program through one of two different mechanisms. The most common is called admission-avoidance HaH or direct admission pathway, in which an initial medical evaluation of the patient is done in the ED, after which the patient is enrolled in the HaH service, bypassing a conventional hospital ward [48]. The other mechanism is an indirect admission pathway often referred to as early supported discharge, in which patients are initially hospitalized in a traditional brick-and-mortar hospital for 24 to 48 hours, after which they transition to the HaH program to continue receiving acute medical care at home [49]. Following the success of the Johns Hopkins program, other institutions began implementing similar HaH programs to treat specific conditions such as community-acquired pneumonia, heart failure exacerbations, and chronic obstructive pulmonary disease (COPD) [46, 50, 51]. These early models focused on using HaH proving the model’s feasibility and cost effectiveness [50, 52].

Over time, HaH use has expanded to treat many conditions, leveraging emerging technologies for remote patient monitoring to deliver comprehensive care at home. Large studies about HaH programs have shown clinical outcomes that are comparable or even superior to traditional inpatient care, in addition to reducing cost, hospital acquired conditions, and readmissions. A meta-analysis involving over 6000 patients from 61 different studies treated in HaH, showed a reduction in mortality, readmission rates and cost compared with traditional in-hospital care [53]. Similarly, a systematic review concluded that for suitable patients, HaH generally results in similar or improved clinical outcomes compared with inpatient treatment [49].

Yet, despite promising results, HaH models had limited adoption, due to lack of reimbursement, logistical difficulties and limitations in telehealth use. Only two reports of HaH use pre-pandemic report in the use of telehealth in this care model [54, 55].

3. COVID-19 pandemic as a catalyst for hospital medicine telehealth expansion

The COVID-19 pandemic reshaped healthcare in ways few could have predicted. As cases surged worldwide, providers had to rethink how to safely care for their patients while limiting the spread of COVID-19. Especially early in the pandemic when lockdowns were in effect, the need for alternative care models became urgent.

Financial, regulatory, and technical barriers to telehealth implementation were rapidly eliminated through public health emergency waivers. The U.S. Department of Health and Human Services (HHS) allowed providers and health systems to utilize common video-conferencing technologies (e.g., FaceTime and Zoom) for healthcare delivery, provided parity reimbursement for telehealth visits and relaxed licensing regulations, like interstate licensing restrictions [56]. These changes resulted in rapid and massive adoption of telehealth, with up 3000% increase in telehealth visits by October 2020, keeping millions of people connected to care.

In acute care settings, COVID-19 infections imposed many challenges on traditional hospital care, including high infectivity rates, potential for rapid progression, and high mortality rates in patients with underlying conditions. Rural telehospitalist models were no longer a remote concept, but a necessity. Many hospitals turned to telehealth to decrease infection risks and address workforce shortages. Furthermore, telehealth extended the care of acutely ill patients beyond traditional hospital walls, providing mechanisms for care interactions, before, during, and after the hospital encounter. The review below is by no mean exhaustive of all studies reporting on telehealth utilization but aims to provide a broad perspective of the heterogeneous applications within hospital medicine scope. **Figure 1** provides a graphic representation of these telehealth applications that are pertinent to hospital medicine, across the continuum of care.

3.1 Expansion of applications of telehealth pre- hospitalization

Telehealth was rapidly embraced as a critical tool in the pre-hospital care of COVID-19 patients, facilitating identification of symptoms and need for testing, while decreasing infection risks. Several studies described the implementation of pre-hospitalization telehealth applications including tele-triage, tele-consultations, and remote patient monitoring during the pandemic [57–61]. **Table 1** summarizes these applications and potential benefits.

Home monitoring was rapidly implemented by many groups to improve outcomes, manage hospital bed-capacity and quickly identify patients with clinical decompensation [62–66]. These programs allowed patients with diagnosed COVID-19 to be followed at home, by monitoring vital signs, stratifying patients based on risk factors, and expediting the detection of clinical decompensation. Patients could then be directed to a higher level of care if needed, often bypassing the ED.

Tele-triage was used to screen patients prior to in-person visits. Patients describe their symptoms via patient portal, or triage line, and cases were referred to physicians

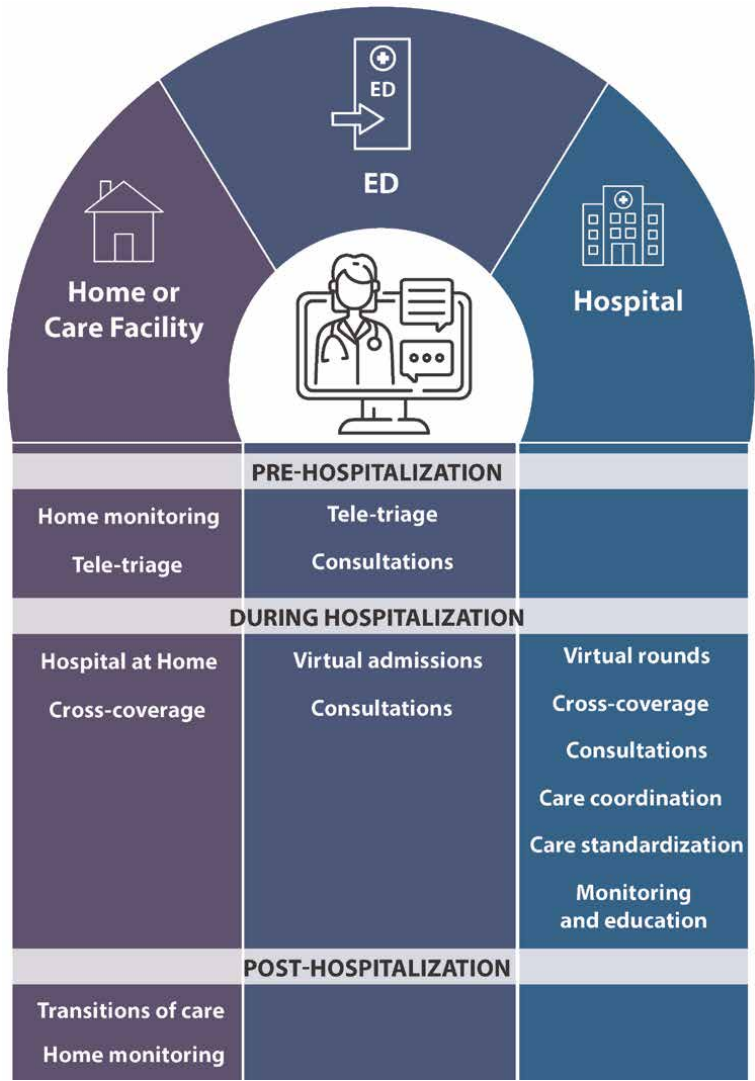


Figure 1.
Telehealth applications in hospital medicine across the continuum of care.

or advance practice providers for a final triage decision. Programs often included deciding need for testing, communication of test results and follow-up care [59, 67, 68]. Triage was also utilized to assess patients at distant hospitals as part of a Command Centre. Command centers has shown the potential to improve quality of care and efficiency, by supporting real-time management of patients at risk of clinical deterioration and optimizing patient disposition [69].

Consultations with EMS, increased in use during the COVID-19 pandemic, although only a handful of studies have reported on real-world applications, and outcomes on this intervention [70]. This strategy allowed hospital physicians to assess patients remotely during an EMS visit, discuss the risks and benefits of transport to hospitals and was intended to lessen ED surge volumes [71, 72].

Patient location	Telehealth application (example references)	Description	Benefits	Challenges
Pre-hospital care	Home	Home monitoring [62–66]	Proactive assessment of patients with high-risk for hospitalization	Decreased ED visits, hospitalizations, and infection risk; improved patient outcomes; PPE conservation
	Home, clinic, care center	Tele-triage [59, 67–69]	Telehealth patient evaluation/screening prior to hospital/ED presentation; can be used for patients at home or other care centers (nursing homes, rehab facility, etc.)	Decreased ED visits, hospitalizations, and infection risk; improved patient outcomes; PPE conservation
	ED	Consultations [70–72]	Telehealth consultation for patients in the same ED or referral hospital; assist with decision to admit and appropriate level of care; can be stand-alone consults or part of hospital command center	Reduced unnecessary transfers; allows patients to receive care locally; optimized resource allocation across multi-site health systems; decreased infection risk
During hospitalization	ED or hospital ward	Virtual admissions [33, 34, 73]	Completion of admission via telehealth for patient located in same hospital or distant ED; could provide supervision for remote trainee or APP.	EHR integration; licensing and credentialing restrictions; on-site provider for care escalation needed; workflow
	Hospital	Virtual rounds [40, 41, 44, 74–78]	Completing daily rounds at distant or same site using telehealth technologies; can provide support for on-site staff or supervision for remote trainee or APP	EHR integration; licensing and credentialing restrictions; on-site provider for care escalation needed; workflow
		Cross-coverage [38, 39]	After-hours coverage of patients admitted to hospital units for acute events; facilitates care escalations during acute/emergent situations	EHR integration; licensing and credentialing restrictions; on-site provider for care escalation needed
		Consultations [76]	Provides medical consultations to patients admitted to other services at the same or distant location; obtain subspecialty consultation for hospital medicine patients	EHR integration; licensing and credentialing restrictions; technology limitations; might only apply to certain specialties/pathologies

Patient location	Telehealth application (example references)	Description	Benefits	Challenges
	Patient monitoring [76, 79]	Remote monitoring of vital signs, test results, or patient behavior (e.g., video monitoring units)	Decreased infection risk; PPE conservation; increased efficiency	Equipment cost; may lead to less frequent in-person visits; alert fatigue
	Care coordination [74, 76]	Virtual interdisciplinary team meetings; discharge planning; goals of care discussions; virtual family visits	Improved communication and efficiency; enhanced patient-family communication; decreased infection risk; PPE conservation	Decreased in-person interaction could negatively impact team-dynamics
	Care standardization [74, 76]	Central telehospitalist to facilitate adoption and standardization of clinical practices; prevent hospital acquired conditions; improve quality metrics	Increased access to hospital medicine expertise; increased quality of care; disseminate best practices; support for on-site providers	Needs centralized process; could undermine practice autonomy from clinicians
	Mentoring and education [74, 80]	Participation of learners in patient care through virtual interactions; could be remote precepting of on-site trainees; redeployed clinician or student by hospitalist staff; learner may join rounds remotely	Decreased infection risk; PPE conservation; increased learning opportunities; support for on-site providers	Challenges with access and availability across settings and sites; cost might be higher initially
Home	Hospital at Home [46, 47, 81, 82]	Acute care level provided at home; telehealth, remote patient monitoring used in conjunction with care delivery services	Increased bed capacity; decreased cost; patient-centered care; decreased infection risk	Challenging logistics; EHR system integration; high up-front costs
Post-acute care	Home or care facility	Transitions care clinic [83, 84] or Home monitoring [85–88]	Virtual assessment of patients after discharge; might include remote patient monitoring	Access to/availability of the technology

**Representative examples of each application are listed. Not meant to be an exhaustive reference list.*

Table 1.
Telehealth applications, benefits, and challenges across the continuum of care.

3.2 Expansion of in-hospital applications of telehealth

Within the hospital setting, telehealth played a pivotal role in minimizing transmission of the COVID-19, optimizing resource allocation, facilitating the deployment of physicians from other specialties to the care of COVID-19 patients, and even allowing providers quarantined due to viral exposure to participate in clinical care. Remote patient monitoring systems enabled continuous assessment of physiological parameters, while helping with PPE conservation and decreasing infection risk. We identified several domains in which telehealth was applied within the context and scope of hospital medicine. **Table 1** summarizes these applications and potential benefits.

Telepresence is defined as the use of technology to create a sense of physical presence in the room with the patient. In this context, we refer to telepresence to describe telehealth activities that allow providers to perform the same duties as they would in-person, including *virtual admissions, virtual rounding, consultations, and cross-coverage*. Pandemic-era flexibilities facilitated rapid adoption across multiple hospital systems.

Multiple groups reported on the adoption of “virtual hospitalist” or telehospitalist models during the pandemic. Their functions ranged from admitting patients in the ED, conducting virtual rounds, supporting on-site advance practice providers (APPs), to providing medical consultations to patients admitted in other clinical areas (i.e.: psychiatry, surgery). Studies found that value added included facilitation of communication and collaboration across teams, increase census capacity, and the ability of the programs to adapt to the rapidly changing needs during the pandemic [74–77].

One study showed that the deployment of over 1800 telehealth devices for inpatient use across seven hospitals resulted in the preservation of over 600,000 personal protective equipment (PPE) items [75]. While another one describing how three affiliated institutions, including one academic medical center, a pediatric teaching hospital, and a safety net county health system, rapidly and successfully deployed inpatient telemedicine across the organizations with the goals to reduce pathogen exposure, conserve PPE and facilitate healthcare work participation, demonstrating the value of inpatient telemedicine as a tool to response to infectious disease outbreaks and conserve PPE [78]. Yet, when PPE was sufficiently available, there was a low adoption of inpatient telemedicine by providers and patients at two academic centers [89]. These findings highlight the importance of involving front-line staff and end-users in the needs assessment, in order to deploy technologies that are perceived to be useful and facilitate adoption.

Care coordination includes discharge planning, goals-of-care discussions, communication with other team members, ancillary staff, and with patient’s families. Telehealth applications allowed for increased time communicating with the families without added burden to the on-site staff [74, 76], provided an avenue for family communication and goals of care discussions, among others. Remote interdisciplinary care meetings also provided additional flexibilities for inpatient staff (i.e. pharmacists, social workers, care managers) to work remotely, which not only decreased exposure risk but also reduced burnout and improves provider well-being.

Patient monitoring, deployed either synchronously, using real-time data, or asynchronously, via stored data, facilitated the detection of patient deterioration and helped manage stable patients remotely. Many hospitals used inpatient telemonitoring during the pandemic to reduce the risks of staff exposure to COVID-19 virus while maintaining consistent patient care [76, 79].

Limitations to broad adoption of inpatient video monitoring included cost of the equipment, concerns about privacy and consent, and the need for input from front-line staff and patients to facilitate implementation and adoption of such systems.

Care standardization. Several studies have documented how the use of telehospitalist models facilitated the adoption and standardization of clinical practices across multiple sites and units within hospital systems. Particularly early in the pandemic when providers struggled to keep up with the rapidly changing clinical guidelines and providers were redeployed from different areas of the hospital to cover surges in cases. One study mentioned how the telehospitalist providers were responsible for staying up-to-date with the national guidelines of care, while their on-site counterparts could focus on their bedside rounding [74]. Some programs extended duties beyond COVID-19 management, to include verification of isolation status, venous thromboembolism prophylaxis, and utilization of telemetry, among other quality metrics [76].

Mentoring and education. Telemedicine can facilitate provider education and mentorship. First, it allowed medical students early in the pandemic to have ongoing participation in clinical care teams and rounding without exposing them to COVID-19 patients [80]. Second, Bloom-Feshbach [74] points out how virtual hospitalists, paired with redeployed physicians temporarily working in hospital medicine, could provide the needed medicine expertise and assistance needed for the non-medicine provider to care for these acutely ill medical patients. Third, remote hospitalists can help provide support, education, and mentorship for advanced practitioners in hospital medicine. Despite increased states liberalizing the independent practice of nurse practitioners and physicians' assistants; many institutional bylaws still require physician oversight in the inpatient settings, which presents a unique opportunity for telehospitalist programs to provide.

3.3 Expansion of hospital at home models during the COVID-19 pandemic

In response to the crisis, the Centers for Medicare and Medicaid Services (CMS) issued an Emergency Use Authorization waiver of certain hospital regulations, therefore initiating the Acute Hospital Care at Home initiative in November 2020. These measures waived the need for 24/7 nursing services on-premises, the immediate availability of a registered nurse for the care of an acute patient, among others. Furthermore, telehealth flexibilities allowed hospitals to deliver provider services to patients' homes via telehealth, a pivotal moment for Hospital-at-home (HaH). This milestone not only helped relieve the pressure on overcrowded hospitals, but it also revealed new possibilities for delivering care that is more flexible, personal, and cost-effective. What began as temporary solutions have sparked long-term changes in how we think about hospital care.

We witnessed a rapid HaH expansion, from 12 standalone programs prior to the pandemic to 398 hospitals across 142 health systems and 39 states who are approved for the CMS waiver as of April 1, 2025 [90]. Available results of the HaH expansions during the pandemic are encouraging with both U.S. and international studies showing that HaH models have resulted in reduced hospital length of stay, readmissions, emergency service use, and cost compare with in person care [81, 82]. A qualitative study of Singapore's Mobile Inpatient Care at Home (MIC@Home) identified key strategies for successful scalability of HaH program. They encompass redesigning policies to optimize manpower and financing, operational improvements via standardized protocols and IT integration, and strengthened leadership through clear governance and accreditation pathways [91].

HaH has the promise to be an innovative, effective and sustainable alternative to conventional hospital care, particularly in aging populations. The pandemic-associated expansion of the model was a catalyzer to increase acceptance and uptake. Nevertheless, the current regulatory flexibilities which promoted this expansion have been only temporally extended after the culmination of the public health emergency. This regulatory instability represents a significant risk for the long-term sustainability of the hospital at home model.

3.4 Expansion of telehealth applications in post-hospitalization care

Post-hospitalization, telehealth also provides a mechanism to facilitate early discharges from the hospital and improve continuity of care, allowing patients to transition to home or post-acute care settings in a safer way. Some studies have shown that telehealth transitions of care clinics can improve patient engagement and adherence to medications and decrease readmissions [84, 92].

Home monitoring models like those used in the pre-hospital setting for COVID-19 were used to follow up patients' post-hospital discharge. Data regarding impact and outcome is conflicting, with some studies finding that such programs promoted early discharges from the hospital, reduced hospital readmissions, and facilitated the detection of clinical deterioration during the convalescent period; [85] while others found no evidence that post-discharge virtual wards resulted in early discharges or readmissions [86]. Home monitoring for post-hospital care has been used for decades for other common hospital conditions including heart failure [87] and COPD [88] with promising results.

4. Telehealth applications in hospital medicine, summary of impact and opportunities

The COVID-19 pandemic presented an unprecedented challenge for already strained healthcare systems across the world. As necessity is the mother of invention, many telehealth applications around the world were rapidly adopted to mitigate access issues, infection risk, and overcrowded hospitals. These innovations prove to be effective in maintaining access and decreasing infection risk in a time of critical need, regardless of the specific application, modality, or point in the continuum of care.

However, many of these innovations have been discontinued with the removal of the telehealth flexibilities enacted during the COVID-19 public health emergency. Yet, the need for access to acute care and hospital medicine will only continue to increase, demanding innovative and alternative healthcare delivery models. Higher life expectancy, an aging population, a growing number of people living with multiple chronic conditions, and the development of more advanced medical treatments -coupled with shortage of providers-, suggest that access to hospital care will remain challenging. The pandemic might have just provided us with a glimpse of a future of overcrowded hospitals, a future that we can avoid if we embrace the technologies and implement many of the innovations sparked by the pandemic. Let us review the opportunities to impact access, efficiency and cost of care.

4.1 Impact on access

Telehealth applications across the continuum of care, from pre-hospital triage to post-acute care has expanded access to hospital medicine specialists at many levels

within health system. Highlighting the value that hospitalists add to the care of patients across the continuum of care, within and beyond the hospital walls. Telehospitalist models can increase access to hospital care by:

- decreasing unnecessary ED visits and decreasing admissions [66]
- increasing bed capacity by allowing patients to be treated locally at rural centers or at home [40, 82]
- facilitating appropriate level of care determination at the time of admission and appropriate resource allocation across a multi-site health system [68]
- supporting on-site providers with flexible scheduling, surge capacity and mentorship, which improves recruitment and retention of providers [93]
- training the next generation of hospital medicine providers and providing remote staffing for trainees and APPs.

4.2 Impact on efficiency and cost of care

- Telehospitalist models can efficiently provide support to multiple facilities and units with a reduced number of providers, particularly when combining multiple rural/critical access hospitals (<20 acute care beds), allowing the economy of scales to take place and reduce staffing costs [41, 93].
- Telehealth applications across the continuum of care can improve the efficiency of the system. Telehospitalists involved in triage processes can direct patients to the most appropriate level of care, or hospital at home option if available.
- Post-discharge home monitoring or transitions of care facilitate early discharges, increases adherence to treatment and can prevent avoidable readmissions.
- Enhanced efficiency can also be achieved through task redistribution and centralized expertise. Allowing on-site hospitalists to care for the most acutely ill-patients while tele hospitalists can provide additional support with cross-coverage duties, low- acuity patients and surge capacity.
- Improved quality can be achieved through hospitalist directed mentored quality improvement projects, monitoring of best practices and strategies to reduce hospital-acquired conditions.

Despite increasing and promising evidence of these telehospitalist applications, long-term data and randomized controlled trials are needed to strengthen the evidence on clinical and financial outcomes.

Lastly, telemedicine cannot fully replace in-person care particularly in the acute care setting. A provider available at bedside to perform procedures, complex physical exam maneuvers, is indispensable. Nevertheless, telehealth can help optimize efficiency by delegating tasks to remote providers, facilitating access to expertise, and disseminating best practices. Ultimately, the viability of these innovations in the long-term depends on reimbursement, regulatory policies, and the way the programs are

implemented. These factors are critical to prevent unintended consequences including increased disparities.

5. Policy and regulatory considerations

During the pandemic, several flexibilities enacted in response to the public health emergency facilitated the rapid adoption and reimbursement for telehealth. Those flexibilities included the temporary removal of geographic and originating site restrictions for patient and provider location. Expanded reimbursement of parity for telehealth services (including audio-only visits), and relaxed licensure requirements for cross-state practice [94, 95]. In addition, the CMS Acute Care Hospital at Home program catalyzed the rapid expansion of hospital-at-home models across the country.

These changes allowed Medicare and other federal payers to reimburse telehealth services delivered to patients in their homes or other facilities, regardless of urban or rural location. Private payors followed suit and reimbursed services in a similar manner. It also permitted new patient visits, and telephone-only encounters to be conducted via telehealth and billed at rates equivalent to in-person care.

Within the VHA, the federal nature in addition to new flexibilities created fertile ground for a dramatic expansion of telehealth services across all care settings [96, 97]. For example, VHA reported an 11-fold increase in encounters in video and 5-fold increase in audio-only visits for mental health by June 2020, compared to pre-pandemic levels [98]. Nevertheless, concerns about the impact of digital literacy, broadband access, and other socioeconomic characteristics might present barriers to telehealth access. These considerations are very important as we discuss the future of telehealth policies, given that without guardrails telehealth has the potential to exacerbate health disparities [99].

Many of the regulatory flexibilities have been extended beyond the public health emergency but are set to sunset in 2025. For example, the temporary waiver that allowed Medicare services to reimburse for audio-only visits, as well as many of the waivers that allowed for hospital at home expansion, are set to expire on September 30, 2025. No definitive mechanisms have been established to ensure that the telehealth care delivery models adopted during the pandemic can continue indefinitely.

6. Conclusions

The heterogeneity of telehealth applications in hospital medicine before, during and after the pandemic reflects the diverse practice models and needs of hospital medicine across institutions and health systems. It also presents tremendous opportunities for hospital medicine to capitalize on and be at the forefront of the much-needed U.S. healthcare system transformation.

As experts not only in the management of acute illnesses, but also in patient triaging and throughput, transitions of care, and post-discharge needs, the hospitalist is uniquely positioned to guide and facilitate the patient's journey through the system during an acute illness event. The hospital medicine team can navigate the use of different telehealth care modalities and tools to deliver patient-centered, timely care, while optimizing access and improving efficiency in the system.

Acknowledgements

The authors thank Kristina Greiner, medical editor, for her valuable input on editing and reviewing the manuscript, and Ann Armstrong, for her support with figure design.

Conflict of interest

The authors declare no conflict of interest.

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Perspective Chapter: A Tele-Ultrasound Service Model for Early Detection of Fetal Stunting in Remote Areas of Indonesia

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Abstract

Stunting remains a serious public health challenge in Indonesia, often starting as early as the prenatal stage due to factors such as maternal undernutrition, limited antenatal care, and inadequate fetal monitoring. Detecting fetal growth restriction early through quality prenatal ultrasound screening is essential, but it can be quite challenging in remote areas where specialists, infrastructure, and geographic barriers are lacking. To address this issue, an innovative tele-ultrasound service model has been introduced to identify the risk of fetal stunting in underserved regions. This model empowers local certified general practitioners and frontline health workers to conduct basic ultrasound scans and send images to remote ob-gyn experts for real-time analysis. It consists of few key components: an ultrasound device, a secure telemedicine platform, a standardized imaging, and referral protocol. This setup ensures timely fetal health assessments, even in resource-limited areas. The chapter details the workflow, technical requirements, human resources, and coordination between community clinics and referral hospitals, taking advantage of Indonesia's expanding digital health and mobile networks. It adapts to the area with limited internet connectivity by using work offline and asynchronous methods. A pilot in a rural district showed impressive diagnostic accuracy, quick feedback hour, and high satisfaction rates among both patients and healthcare workers. The model also improved coordination between primary and referral care. Some challenges, like intermittent connectivity and equipment maintenance, were identified, along with potential solutions. This approach offers a practical and sustainable way to improve healthcare for mothers and children, helping to close health disparities in Indonesia.

Keywords: tele-ultrasound, fetal stunting detections, fetal growth restriction, remote healthcare, digital health innovations, telemedicine

1. Introduction

Indonesia faces significant challenges in ensuring maternal and fetal health, particularly in its remote and underserved regions. Even though there have been strides in healthcare access, the country still faces a maternal mortality ratio of 189 per 100,000 live births and an infant mortality rate of 17 per 1000 live births [1, 2]. These numbers are quite high in comparison with other countries in the region. A major concern is maternal malnutrition, with around 50% of pregnant women suffering from anemia and 16% being underweight [3]. These nutritional issues can lead to negative pregnancy outcomes, such as low birth weight and a higher risk of fetal stunting [4]. Moreover, maternal depression during pregnancy has been linked to increased rates of stunting in children [5].

Fetal stunting, which refers to impaired growth and development in the womb, affects over 21% of Indonesian children under five [5]. This condition can have lasting effects, including cognitive deficits and chronic health problems. The prevalence of stunting is worsened by factors such as insufficient antenatal care, poor maternal nutrition, and limited access to quality healthcare services, particularly in rural regions [6]. Geographical barriers and the uneven distribution of healthcare resources make it difficult to diagnose and address maternal and fetal health issues in a timely manner.

Early detection during pregnancy is incredibly important for the health and development of both the mother and her unborn baby [7]. This process includes detecting possible complications such as high blood pressure, gestational diabetes, infections, or problems with fetal growth through regular check-ups, lab tests, and ultrasounds. When these problems are identified early, healthcare providers can take action sooner, which helps reduce the risks of serious conditions such as preeclampsia or intrauterine growth restriction (IUGR), leading to better fetal growth and overall development. It also aids in preventing birth defects and developmental delays by facilitating timely referrals to specialists [8].

There are some serious challenges when it comes for providing fair maternal and fetal healthcare, especially in its more remote and rural areas. The geographical hurdles make it tough for people to get to healthcare facilities in a timely manner. In some underdeveloped regions, pregnant women often have to embark on exhausting journeys that involve various modes of transport just to reach the nearest health center, which can delay their access to crucial antenatal care [9]. The lack of proper infrastructure only intensifies the already difficult conditions. Many rural regions struggle with poorly maintained roads, inconsistent electricity, and poor internet connectivity, all of which are vital for both traditional healthcare and telemedicine [10]. The shortage of healthcare professionals, such as obstetricians and trained midwives, means there are not enough skilled birth attendants available, which raises the risk of complications during pregnancy and childbirth [11]. Access to healthcare is also affected by socioeconomic issues. Even though national health insurance programs like Jaminan Kesehatan Nasional (JKN) aim to offer universal coverage, many families in remote areas still face hefty out-of-pocket expenses for transportation and other non-medical costs. Additionally, cultural beliefs and low health literacy can lead to underutilization of available maternal health services, as some communities might prefer traditional birth attendants over formal healthcare providers [12].

To address these issues, innovative solutions such as telemedicine and mobile health services are being considered to enhance access to prenatal care and early detection of fetal growth problems. Implementing tele-ultrasound services in remote areas could enable timely interventions, potentially reducing the rates of fetal stunting and improving overall maternal and child health outcomes [13].

The objective of this chapter is to provide a tele-ultrasound service model intended to help with the early identification of fetal stunting in remote and underdeveloped regions of Indonesia. The main goal is to investigate how telemedicine platforms combined with portable ultrasound technology can help address current obstacles in the delivery of healthcare for mothers and fetuses, especially the restricted availability of diagnostic services and expert consultation in rural areas. The suggested model aims to facilitate prompt interventions that can greatly enhance birth outcomes and lower long-term developmental risks in children by emphasizing the early detection of IUGR, a crucial sign of fetal stunting.

The chapter also aims to explore on the technical aspects of a tele-ultrasound system, covering everything from equipment needs and communication infrastructure to workflow design, data management protocols, and user roles. It discusses how this model can be adapted to fit Indonesia's varied geographical and infrastructural landscapes, particularly in resource-limited settings.

2. The concept of tele-ultrasound

Tele-ultrasound plays a crucial role in telemedicine that allows ultrasound exams to be conducted and interpreted from a distance, thanks to modern information and communication technologies. This innovative approach empowers healthcare professionals to deliver diagnostic imaging services in remote or underserved regions where finding skilled sonographers can be a challenge [14]. By merging traditional ultrasound techniques with real-time data sharing, it enables remote consultations and expert evaluations without needing a specialist to be physically present [15].

At its core, tele-ultrasound operates on three essential components: the ultrasound imaging system, the communication network, and the remote referral center. Initially, a trained general practitioner performs the ultrasound scan using a portable or handheld device. The imaging data is captured in real time and securely transmitted over a network to a specialist located elsewhere, often in a hospital or diagnostic facility. This data transfer can happen in real time (live interaction) or asynchronously (store-and-forward), depending on the technical setup and the specific clinical requirements [16].

In a synchronous system, a remote expert can guide the on-site operator during the scanning process, making sure that the right anatomical views are captured and enhancing diagnostic accuracy. On the other hand, asynchronous systems allow ultrasound images and videos to be stored and sent to the remote expert for review and diagnosis later on. Both approaches offer flexibility and can be tailored to fit various healthcare environments [17].

The advantages of tele-ultrasound are substantial, particularly for maternal and fetal health, emergency care, and healthcare delivery in rural areas. It broadens access to diagnostic imaging services, speeds up the time to diagnosis, and allows for early detection of medical issues without the need for patients to travel long distances. Additionally, it supports task-shifting strategies by enabling non-specialist healthcare workers to conduct ultrasound scans under remote supervision [17].

Tele-ultrasound is highly suitable for Indonesia's geographically diverse and archipelagic landscape, where access to specialized healthcare services remains limited, particularly in remote, rural, and island communities. Many of these areas lack qualified sonographers or obstetricians, making it difficult to provide consistent and high-quality prenatal care. Tele-ultrasound offers a practical and scalable solution to bridge this gap by enabling midwives or general practitioners in community clinics to perform ultrasound examinations, which can then be interpreted by specialists in regional or national referral hospitals [18].

The infrastructure challenges in Indonesia, such as poor road access, limited transportation options, and uneven distribution of healthcare professionals, make telemedicine technologies particularly relevant. Studies have shown that task-sharing combined with telemedicine can increase diagnostic capacity and reduce delays in clinical decision-making. In the context of maternal health, this means earlier detection of fetal anomalies, better management of high-risk pregnancies, and reduced maternal and neonatal mortality rates [19].

Pilot studies and implementation trials have demonstrated that telemedicine is feasible even in areas with low internet bandwidth by using store-and-forward methods, and smartphone-based transmission platforms [19, 20]. Indonesia's growing digital infrastructure, supported by national telemedicine initiatives such as SATUSEHAT platform and Telemedicine Indonesia (TEMENIN), provides a foundation for scaling up such services across the archipelago [21, 22].

Furthermore, the cultural acceptability of midwives and primary healthcare workers as trusted providers in rural communities makes them ideal candidates for conducting ultrasound scans under remote guidance. Training programs for mid-level providers, supported by teleconsultation with urban-based obstetricians, have already proven successful in similar low-resource settings. These approaches align well with Indonesia's existing healthcare delivery model, which relies heavily on community health centers (Puskesmas) and village-level services (Posyandu).

3. System design and architecture

The configuration of the tele-ultrasound system to support remote prenatal diagnostics is shown in **Figure 1**. This infrastructure consists of three primary components: the data acquisition system, the viewer, and the cloud server.

The data acquisition system plays a crucial role in capturing ultrasound images and gathering vital sign data, including maternal heart rate, blood pressure, and oxygen saturation. This system is typically found right where care is needed, like in a community clinic or a public health center (puskesmas), and is operated by trained general practitioners. This system acts as a hub for medical devices. The setup includes a notebook equipped with a video camera and microphone, along with several key diagnostic tools like an ultrasound machine and a vital signs monitor, all aimed at collecting detailed physiological data from the pregnant woman. The ultrasound images are standardized and saved in the Digital Imaging and Communications in Medicine (DICOM) format, which ensures they work seamlessly across different imaging platforms. During consultations, local healthcare providers, such as general practitioners, enter the patient's reported symptoms and clinical history into the system to enhance the diagnostic information. The system is designed to be user-friendly and modular, making it well suited for rural or resource-limited healthcare settings.

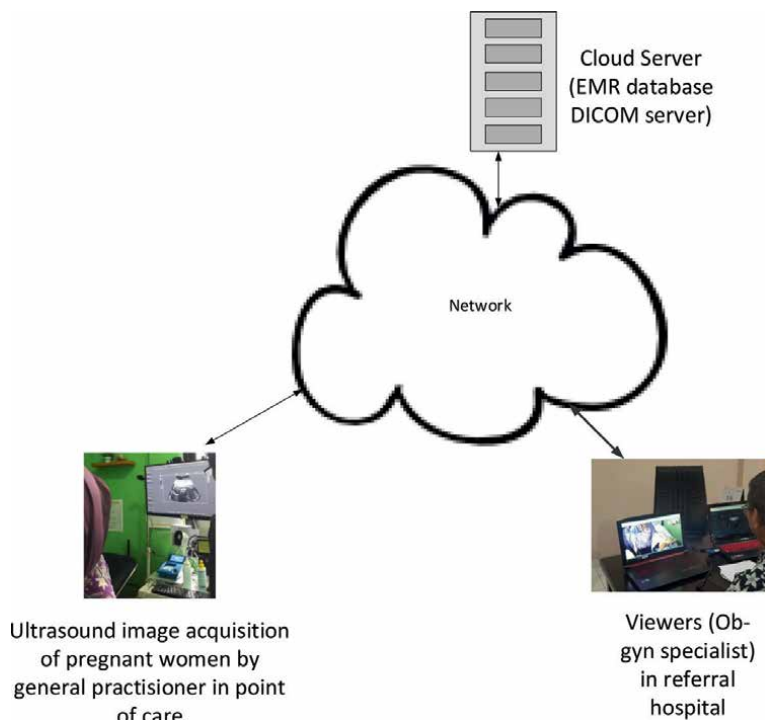


Figure 1.
 Configuration of Telemedicine System with tele-ultrasound service.

The cloud server serves as a central storage for electronic medical records, vital sign data, and ultrasound images. It keeps ultrasound images in the standardized DICOM format, which guarantees compatibility across different platforms and allows for precise remote interpretation. Powered by Orthanc, an open-source DICOM management system, this cloud server efficiently handles the storage, indexing, and retrieval of ultrasound images [23]. It also houses the patient's electronic medical records (EMR) and features image analysis tools tailored for ultrasound evaluations, boosting diagnostic capabilities. OB/GYN specialists can access the server through the Image viewer on their smartphones or laptops, connecting to the cloud to pull up ultrasound images, clinical notes, and patient complaints. This setup facilitates both synchronous and asynchronous consultations, making remote diagnosis possible even when real-time communication is not an option. The seamless interoperability between the acquisition system, cloud server, and viewer ensures a smooth flow of clinical information throughout the tele-ultrasound framework [24]. This model aligns with WHO's recommendations on antenatal care in low-resource settings and is further supported by global and national strategies for stunting prevention.

3.1 Integration of image transmission and teleconsultation platforms

Combining image transmission systems with teleconsultation platforms can greatly enhance healthcare access in remote areas. These systems enable the local capture of ultrasound and other medical images, which can then be securely sent in real time to specialists for expert review, ensuring that both image quality and patient privacy are maintained. Teleconsultation tools facilitate direct communication, whether

through video, voice, or chat, between local providers and remote experts, improving diagnosis, treatment, and follow-up, particularly in regions where specialist access is scarce. This model fosters comprehensive, ongoing care by allowing shared access to medical histories and real-time data. In maternal care, this integration supports remote fetal monitoring and the early detection of complications like growth restrictions [25]. A stable internet connection is essential for this system, which can adapt to bandwidth fluctuations by using platforms like Jitsi Meet or Zoom. This flexible and secure setup ensures reliable, expert-driven care delivery, even in areas with limited digital infrastructure.

3.2 Network and data security integration

The tele-ultrasound system is built to work seamlessly over different types of internet connections, making it well suited for remote locations. Having a stable connection is a key for sending high-resolution ultrasound images securely and reliably to specialists or cloud servers, which is vital for accurate and timely diagnoses [26]. The system utilizes standardized formats like DICOM and works well with secure EMRs. It boasts robust security features, including end-to-end encryption, Virtual Private Networks (VPNs), multi-factor authentication, and access control, all designed to safeguard sensitive patient information and adhere to privacy regulations [27]. Regular updates and security audits are conducted to fend off cyber threats [28]. In areas where connectivity is spotty, offline storage and mobile backups ensure that operations can proceed smoothly. Educating healthcare workers and patients about data security is also crucial in preventing breaches. Dependable network access and strong data protection measures are essential for delivering safe, effective, and accessible healthcare through telemedicine and tele-ultrasound systems in underserved regions [29].

3.3 Telemedicine workflow model

To enhance patient outcomes, the workflow model for utilizing tele-ultrasound technology in remote healthcare settings follows a well-organized procedure that ensures effective data collection and professional interpretation. Certified midwives or general practitioners serve as the first point of contact for patients in underserved areas, initiating the process. These frontline workers are trained to use portable ultrasound devices and other diagnostic tools, allowing them to conduct initial screenings for pregnant women and other patients either in the field or at local health posts. Once they gather the necessary images or information, such as fetal development ultrasound scans, they securely upload this data to a telemedicine platform. The platform is designed to protect sensitive information, ensuring that medical data is handled safely and in compliance with patient confidentiality laws. Once the ultrasound data is uploaded, it is rapidly transmitted through secure digital networks to a team of OB/GYN specialists, most of whom are located in urban hospitals or advanced medical centers, ensuring prompt review and expert interpretation by obstetricians and other relevant medical professionals.

The teleconsultation platform allows these specialists to access high-resolution scans, patient histories, and other important health information alongside the images or data. They provide professional interpretations, including diagnoses, recommended treatments, and advice on necessary follow-up care. Additionally, specialists can communicate directly with rural healthcare providers through video calls or messaging apps on the platform to clarify information or answer questions.

This interaction fosters a collaborative approach to patient care by equipping local healthcare professionals with the insights they need to make informed decisions.

Furthermore, the interpretation of the specialist aids in directing the subsequent phases of the patient's care, including treatment modifications, referral to higher-level facilities, or ongoing monitoring. Following the consultation, the data is safely saved in the cloud-based system for convenient access at follow-ups or subsequent visits. This workflow model bridges the gap between remote communities and specialized healthcare expertise by improving diagnostic accuracy, facilitating continuity of care, and improving healthcare access for patients in rural or remote areas.

3.4 Stakeholder mapping

The active participation of important stakeholders at various levels of the healthcare ecosystem is crucial to the success of the tele-ultrasound service model for the early detection of fetal stunting. To determine the roles, duties, and potential contributions of every group involved in the system's design, implementation, and sustainability, a thorough stakeholder mapping process was carried out.

Healthcare professionals, especially trained general practitioners at community health centers (Puskesmas) in outlying areas, are at the forefront of service delivery. These providers are in charge of performing fetal scans, documenting patient information, and enabling teleconsultations with distant specialists. They also act as the main operators of ultrasound equipment. For the tele-ultrasound model to be implemented practically, their technical training, workflow adaptation, and acceptance are essential.

As remote specialists, obstetricians at referral hospitals evaluate ultrasound pictures as well as biometric fetal data and contribute to diagnosis. Their clinical background guarantees timely recommendations for intervention or follow-up, accurate interpretation, and quality control.

Since they are the main users of the tele-ultrasound service, expectant mothers in the target communities are important stakeholders. Their willingness to attend prenatal visits where the technology is used, their comprehension of the advantages of early fetal screening, and their level of trust in local healthcare professionals are all necessary for their participation. Their involvement is influenced by sociocultural elements like transportation accessibility, awareness levels, and decision-making autonomy. To promote involvement, the project design incorporates culturally relevant communication techniques, education campaigns, and community outreach.

Regional health offices are strategic partners at the administrative and policy level. In addition to allocating local resources and facilitating regulatory approvals, they also incorporate the tele-ultrasound service into the current maternal and child health programs. Long-term sustainability depends on their assistance, particularly when it comes to managing referrals, keeping an eye on program effectiveness, and expanding the model to other districts.

Village chiefs, community health volunteers, telecom companies, and maternal health-focused non-governmental organizations are additional supporting stakeholders. These organizations support public advocacy, infrastructure development, and community mobilization.

The tele-ultrasound service is guaranteed to be socially and locally acceptable in addition to being clinically effective. In addition to being clinically effective, this multi-level stakeholder engagement model guarantees that the tele-ultrasound service is socially acceptable, locally owned, and in line with Indonesia's larger healthcare priorities.

3.5 Service flow diagram and key activities

The tele-ultrasound service model is designed to provide accessible and timely fetal growth monitoring in remote areas, where access to specialist care is limited. The service flow is structured to integrate seamlessly into existing antenatal care (ANC) visits at local community health centers (Puskesmas), ensuring minimal disruption to routine healthcare delivery. The workflow emphasizes efficiency, clinical accuracy, and collaboration between frontline providers and remote specialists.

The service flow as shown in **Figure 2** begins when a pregnant woman visits a Puskesmas for a scheduled ANC appointment. Upon arrival, her medical history, gestational age, and previous ultrasound data are recorded by the attending midwife or general practitioner, who has been trained in basic obstetric ultrasonography.

The key activity at this stage is the performance of a standardized fetal ultrasound scan using a portable device. The scan focuses on critical fetal biometric parameters such as biparietal diameter (BPD), head circumference (HC), abdominal

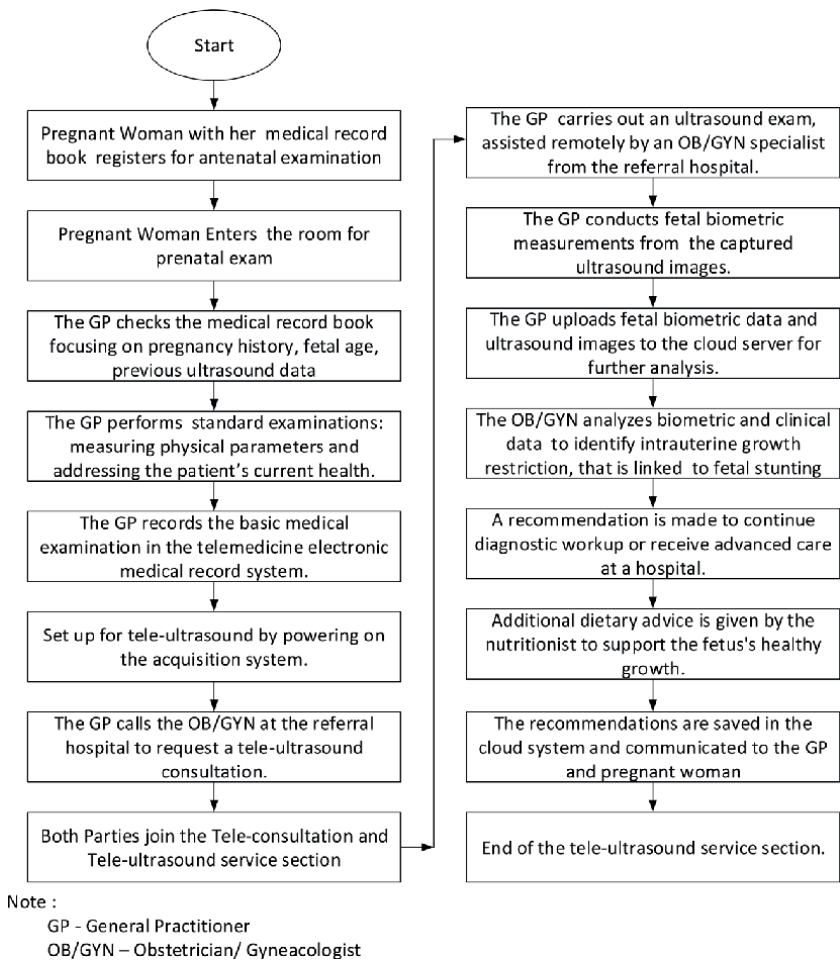


Figure 2.
Service flow diagram.

circumference (AC), and femur length (FL), which are used to estimate fetal growth and detect early signs of stunting [30].

Captured ultrasound images and relevant clinical data are then digitally uploaded to a secure telemedicine platform. Depending on the internet connectivity of the site, this can be done in real time (live video consultation) or through a store-and-forward mechanism (images and data sent asynchronously).

At the referral hospital or telemedicine center, a remote obstetrician accesses the uploaded information, reviews the ultrasound images, and provides a diagnostic assessment. If signs of IUGR or fetal stunting are detected, a referral recommendation is issued for further diagnostic workup or hospital-based care.

4. Implementation strategy in remote area

4.1 Site selection and characteristics

East Sepatan is one of the districts in Tangerang Regency, Banten Province, Indonesia. Established in 2006 from the split of Sepatan district, East Sepatan has an area of 23.05 km². Administratively, it has eight villages: Sangiang, Tanah Merah, Lebak Wangi, Jatimulya, Kedaung Barat, Gempolsari, Kampung Kelor, and Pondok Kelor. As of the latest data, the population of East Sepatan is over 80,000 people with a high population density due to its proximity to the city. Many people with low economic status live in rural areas, and most of them are laborers and farmers. A large portion of East Sepatan maintains its semi-rural character despite its urbanizing



Figure 3.
Pregnant woman scanned by certified general practitioner at posyandu.

surroundings, with residential clusters dotted with agricultural plots and rice fields. Ultrasound images were captured at four integrated health posts (posyandu), while the referral hospital, RSUD Pakuhaji, is situated in a separate district. **Figure 3** shows the pregnant woman scanned by general practitioner at posyandu, while performing consultation as shown in **Figure 4**.

4.2 Selection criteria of pregnant women

To guarantee that the service targets the appropriate population and produces clinically meaningful results, the selection criteria for pregnant women eligible for tele-ultrasound examinations aimed at detecting fetal growth disorders are crucial. In order to rank the cases that might gain the most from early screening and remote diagnostic assistance, these criteria were created taking into account medical, gestational, and logistical factors [31]. Pregnant women with risk factors for IUGR or other fetal developmental abnormalities are given priority in the medical field. These could include abnormal fundal height measurements taken during prenatal visits, a history of prior pregnancies with growth-restricted fetuses, and chronic maternal conditions such as diabetes, hypertension, malnutrition, anemia, or infectious diseases.

Another important factor is gestational age; the tele-ultrasound is usually performed between weeks 20 and 32 of pregnancy, which is a crucial time frame for assessing fetal biometric parameters and determining fetal weight. Furthermore, logistical considerations are crucial, especially in isolated or underdeveloped regions. To close the healthcare accessibility gap, priority is given to pregnant women who live in remote areas, have little to no access to specialized obstetric care, or rely mostly on primary healthcare centers (Puskesmas) for prenatal care. Selection is also influenced by socioeconomic factors, such as the lack of dependable transportation or the inability to pay for a referral to an urban hospital. Women must also give their

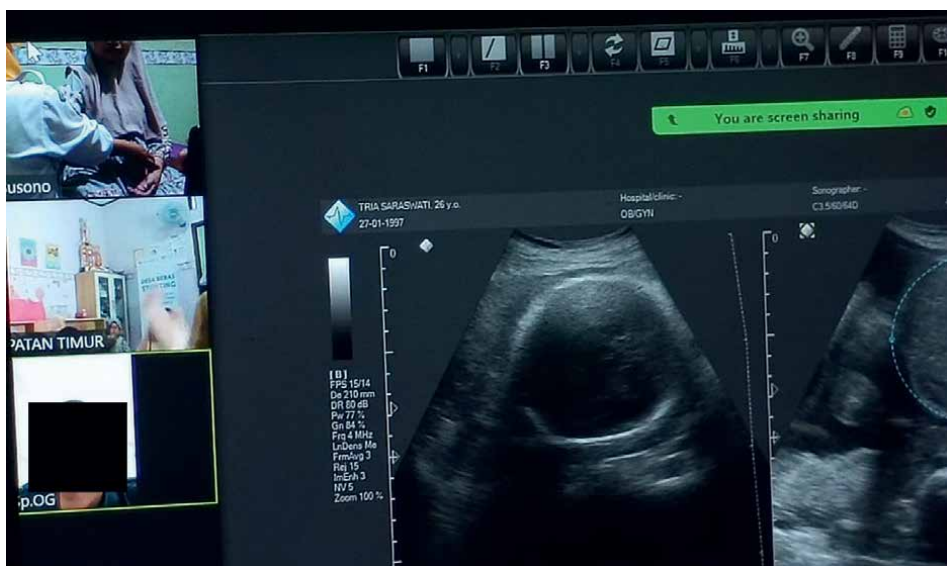


Figure 4.
Consultation with OB-GYN specialist and while performing ultrasound scanning.

informed consent and agree to use the telemedicine-based service, which includes being accessible for follow-up and scheduled remote scanning sessions.

4.3 Number of scans performed, successful transmissions, and consultations

During the pilot implementation, 42 pregnant women were scanned. The scans were conducted in four integrated health services posts (posyandu) in between March until May 2024. The scans from 41 pregnant women (97.61%) were successfully transmitted to the referral hospital. The 39 cases (92.86%) received full consultations and diagnostic feedback from obstetricians. The transmission failure was about 2% attributed by unstable internet connectivity. From the total 42 scanned pregnant women, 9 cases (21.4%) were flagged as having suspected IUGR, based on fetal biometric parameters falling below the 10th percentile for gestational age. The biometric parameters measured were BPD, FL, AC, HC, and EFW. Such fetal biometric parameters were measured and plotted against standard growth charts.



Figure 5.
The scanned image and its corresponding examination report.

If two or more parameters were below the gestational age 10th percentile, the case was marked as suspected IUGR. The values of detection rate highlight the importance of early screening tools made possible by tele-ultrasound and illustrate the vulnerability of maternal-fetal health in underserved areas. **Figure 5** shows the scanned image and the corresponding examination report.

5. Evaluation

5.1 Parameters for evaluation

To ensure that the tele-ultrasound service model really makes a difference in maternal and fetal health in remote areas, a comprehensive evaluation is needed. A set of key performance indicators has been identified in order to thoroughly evaluate the efficacy of the tele-ultrasound service model was accuracy, timeliness, acceptance, and usability [32].

5.1.1 Accuracy

In this study, 40 fetal images were examined, focusing primarily on abdominal circumference measurements. Results showed a 92% agreement rate between local and remote interpretations. The Cohen's kappa coefficient was 0.87, indicating a very high level of agreement beyond chance. Most discrepancies occurred in cases where image quality was poor, often due to insufficient training of the operator capturing the ultrasound images.

5.1.2 Timeliness

Timeliness was assessed by measuring the average time between image acquisition and the receipt of the interpretation results by the local operator. Results showed that the average turnaround time was 43 minutes, with 83% of cases receiving interpretation results within less than 1 hour. This represents a significant improvement compared to the conventional system, where interpretation could take 2 to 3 days, depending on the availability and schedule of specialist visits. This substantial reduction in waiting time highlights the efficiency of the tele-ultrasound system in accelerating diagnostic feedback, thereby supporting faster clinical decision-making in remote settings.

5.1.3 Acceptance

System acceptance by healthcare workers and patients was evaluated through surveys and structured interviews. The results indicate that 87% of healthcare workers expressed willingness to use the system routinely in their daily practice. The 93% of pregnant women were reported feeling more at ease, knowing that their ultrasound results were being reviewed by a specialist, even though they live in remote areas. The main concern raised by healthcare workers was the stability of internet connectivity in certain regions, which could potentially affect the reliability and consistency of system use.

5.1.4 Usability

The usability score was obtained using the System Usability Scale (SUS), which was calculated based on responses to a questionnaire distributed to 12 participants.

These participants consisted of general practitioners, midwives, and nurses who had used the system for a two-week trial period.

The average SUS score was 84.65, which falls into the “Excellent” category, indicating a high level of user satisfaction and ease of use.

User feedbacks noted that the system interface was intuitive, image acquisition and transmission were easy to perform, and the user manual provided sufficient guidance for operation.

5.2 Cost-effectiveness

Cost-effectiveness stands out as a major benefit of introducing the tele-ultrasound service in remote areas. Unlike the usual obstetric care model that requires pregnant women to travel to district hospitals, resulting in extra transportation costs and time away from work or family, this approach enables ultrasound exams to be performed right in local puskesmas or posyandu, with specialists offering remote support. This significantly reduces the indirect costs for patients and reduces infrastructure and staffing expenses by using portable ultrasound devices and cloud-based platforms. Additionally, obstetricians can avoid frequent travel to remote facilities; they can now offer expert consultations and second opinions by reviewing transmitted ultrasound images and clinical data. This system boosts efficiency, guarantees ongoing access to specialist care, and makes maternal health services more scalable and sustainable in underserved areas [33].

From a health economics standpoint, catching fetal stunting early through this telemedicine model can lead to significant long-term savings. By spotting growth issues during pregnancy, healthcare providers can step in with timely nutritional and medical interventions, potentially averting more serious health problems down the line, like low birth weight, chronic malnutrition, or developmental delays. These early actions can lessen the need for expensive treatments after birth and ease the societal burden of childhood stunting, which is often tied to lower educational achievement and economic productivity. Moreover, this model encourages a smarter use of medical personnel by allowing general practitioners or midwives in rural areas to consult directly with obstetric specialists, ensuring that resources are allocated effectively [34].

5.3 Comparison with conventional services

The comparison between tele-ultrasound and traditional ultrasound services reveals some significant benefits of the tele-ultrasound approach, especially when it comes to tackling healthcare disparities in remote regions of Indonesia. Typically, conventional services require pregnant women to travel to urban hospitals or clinics for prenatal imaging, which can be time-consuming, expensive, and logistically tricky, particularly in areas where transportation options are limited. On the other hand, tele-ultrasound brings the diagnostic process right into the community. Local healthcare workers, like midwives or general practitioners, can perform ultrasound scans with real-time support from specialists who are miles away. This not only breaks down access barriers but also ensures that pregnant women in underserved areas can get timely assessments of fetal growth and development without having to leave their villages.

When it comes to clinical outcomes, the tele-ultrasound model has proven to be just as accurate as conventional services, provided that the right protocols and training are in place. Remote specialists can interpret images either in real time or later,

giving diagnostic support and treatment recommendations. The addition of teleconsultation fosters better collaboration between local and specialized providers, leading to a more responsive and efficient healthcare system. While traditional services have the advantage of established infrastructure and direct access to specialists, they often are not practical for regular use in rural areas. Tele-ultrasound, however, offers a flexible, scalable, and cost-effective solution that can be customized to meet the needs of low-resource settings. This makes it a promising option for early detection of fetal stunting and broader maternal health monitoring in Indonesia's remote communities.

6. Challenges and lessons learned

There are some challenges to setup the tele-ultrasound service in remote regions in Indonesia namely: technical, logistical, and human resource challenges. These challenges should be handled carefully in order to make the program running effective and sustainable. On the technical side, using portable ultrasound devices in areas with the limited resources requires equipment that is not just affordable and sturdy, but also easy to use for non-specialist operators such as nurses or midwives. Unfortunately, many remote health facilities do not have the necessary infrastructure to support the ongoing use of digital equipment, such as a reliable electricity supply, sufficient lighting, and proper storage for the equipment. Reliable internet connectivity poses a significant challenge, as tele-ultrasound relies on sending high-quality image data to specialists at referral centers. In many rural and island areas, limited bandwidth and network disruptions can slow down diagnoses or even affect the accuracy of remote assessments. Additionally, it is crucial to protect cybersecurity and patient data privacy, especially when sharing sensitive medical information over public or unreliable networks.

Transporting and maintaining medical equipment in remote areas, like mountainous villages or small islands, can be quite a challenge. Keeping a steady supply of consumables, carrying out regular maintenance, and offering timely technical support are all essential yet tough tasks in these settings. From a human resources standpoint, the shortage of trained healthcare workers poses a major challenge. In remote areas, many midwives and general practitioners lack experience with ultrasound imaging and need thorough training, not just in capturing images, but also in navigating tele-ultrasound platforms and understanding referral processes.

6.1 Legal and regulatory issues

As telemedicine evolves, it is essential to ensure that these services follow national healthcare regulations, particularly those that deal with medical devices, patient data protection, and professional licensing. In Indonesia, telemedicine practices must align with the guidelines set by the Ministry of Health and the Medical Council, which require that all remote consultations be conducted by licensed professionals. Moreover, obtaining patient consent and maintaining data confidentiality are critical. It is also crucial to ensure that the ultrasound devices used in this initiative are certified and meet the safety standards to minimize legal risks and ensure patient safety.

One important regulatory challenge is the need for collaboration between local healthcare centers and remote specialists. It is crucial that legal frameworks clearly outline the roles and responsibilities of everyone involved, especially when it comes to accountability in making diagnostic decisions and providing follow-up care.

Moreover, since this service relies on the digital transmission and storage of sensitive medical images and health information, adhering to data privacy laws, like Indonesia's Personal Data Protection Act, is vital. This means implementing secure data encryption, controlling access to patient records, and establishing clear policies for data retention and sharing.

6.2 Cultural and social barrier

In many rural communities, traditional beliefs and low health literacy can heavily influence how pregnancy, medical technology, and maternal care are viewed. Some expectant mothers may be hesitant to undergo ultrasound examinations due to fears, misconceptions, or simply not understanding the purpose and safety of the procedure.

Gender dynamics play a crucial role in how decisions are made regarding maternal healthcare. In various regions, it is typically the husbands or extended family members who wield the most influence over health-related choices for pregnant women. This can sometimes lead to delays or even limit access to antenatal services, such as tele-ultrasound. Additionally, there can be resistance to adopting new technologies, especially those that involve remote consultations with specialists who may not be well-known to the family, often due to worries about privacy, trust, or cultural relevance. Language barriers and a lack of digital literacy among healthcare workers and patients can also create obstacles to effective communication during tele-ultrasound consultations. As a result, training programs should not only focus on technical skills but also embrace culturally sensitive strategies that promote trust and understanding within the community. Engaging local leaders, religious figures, and community health volunteers can help bridge the gap between contemporary healthcare practices and traditional beliefs.

7. Future direction

This research highlights the crucial role of artificial intelligence (AI)-assisted ultrasound interpretation in enhancing the diagnostic capabilities of a proposed tele-ultrasound service model. The model is specifically designed to meet the urgent need for early detection of fetal stunting in Indonesia's remote and underserved regions, where experienced sonographers and obstetricians are often hard to come by. To help fill this skills gap, a machine learning-based image analysis module will be installed to aid the frontline health workers, such general practitioner who might not have extensive ultrasound training.

This AI component is trained on a comprehensive dataset of obstetric ultrasound images to accurately identify key biometric parameters such as BPD, HC, AC, and FL. These measurements are crucial for estimating gestational age and detecting any signs of IUGR, which is a key early indicator of fetal stunting. Once a portable ultrasound device performs a scan, the images it captures are automatically analyzed by an AI system that offers a preliminary interpretation. This includes estimating fetal measurements, comparing them to standard growth charts, and flagging any signs of potential stunting or abnormal growth patterns. The results are then sent through a telemedicine platform to a remote obstetrician, who reviews the AI's findings and provides a final recommendation to the local health facility.

A key factor that makes the proposed tele-ultrasound service model work is its ability to connect with Indonesia's national health information systems, especially

the SATUSEHAT platform launched by the Ministry of Health. SATUSEHAT aims to bring together and standardize electronic health records (EHR) across different healthcare facilities in Indonesia. This ensures smooth data sharing, continuity of care, and better decision-making for both clinical practices and policy-making. To fit into this national digital health framework, the tele-ultrasound system is built to meet health data standards like HL7 Fast Healthcare Interoperability Resources (FHIR). This allows it to seamlessly integrate ultrasound results, patient demographics, and referral details right into the SATUSEHAT ecosystem. As a result, fetal growth data and potential stunting indicators collected during remote consultations are securely stored and can be accessed by authorized healthcare providers throughout the care continuum, from village midwives and Puskesmas to district hospitals and specialist centers.

The ability to share information seamlessly really boosts the ongoing tracking of both maternal and fetal health. It ensures timely follow-ups and enables population-level analysis for monitoring public health. When it is integrated with national systems, data silos can be avoided, duplicated efforts can be reduced, and reporting to health authorities can be streamlined. This all leads to more effective maternal and child health surveillance programs. In real-world terms, this interoperability makes the referral process smoother. For instance, data from a tele-ultrasound session can easily connect to a digital referral system, allowing for quick coordination between primary and secondary care facilities. This is crucial, especially in urgent situations such as suspected fetal growth restrictions or congenital anomalies that need specialist care. By ensuring that the tele-ultrasound service model is well integrated with SATUSEHAT and other national health databases, clinical effectiveness at the local level is enhanced, and the larger goals of digital transformation and data-driven healthcare governance in Indonesia are supported.

8. Conclusions

This study successfully showed the possibility and good performance of the tele-ultrasound model for early detection of fetal stunting in remote and underserved areas in Indonesia. Incorporating a portable ultrasound machine, a wireless data transmission system, and remote expert reporting, this model made it feasible for general practitioners in community medical service centers to conduct basic ultrasound procedures with real-time assistance from specialist doctors from hospitals. Primary outcomes of this study show that this model of service has a positive impact on improving access to diagnostic pregnancy imaging for regions without specialist obstetricians.

The major findings of this study show that this service paradigm makes it easier for people to get diagnostic prenatal imaging in places where there are not many specialized obstetricians. With a standardized fetal biometric technique and real-time teleconsultation, it was possible to find fetal growth problems that could be signs of stunting. The field trial showed that it was easier to find cases of IUGR, which led to faster medical care and better health for both the mother and the baby.

In addition to medical outcomes, the study also emphasized the operational and social effects of the implementation of the tele-ultrasound service. Health workers reported increased confidence and ability in using tele-ultrasound, while local communities reported increased levels of trust and satisfaction with maternal health services. From an economic perspective, the model proved efficient as it reduced the

need for patient referrals and transportation burdens that have been major constraints in remote areas.

According to the results, a scalable tele-ultrasound system can significantly reduce healthcare disparities for mothers, especially in remote or rural areas. This innovation immediately supports national efforts to improve perinatal care, reduce childhood stunting, and meet maternal and child health targets for the Sustainable Development Goals by promoting early and accurate fetal growth monitoring.

The introduction of a tele-ultrasound service model has the potential to greatly enhance maternal and child health equity in Indonesia, especially in areas that are underserved and geographically isolated. This model addresses significant gaps in antenatal care that arise from limited infrastructure, workforce shortages, and geographic challenges. With the help of remote expert support and portable diagnostic tools, tele-ultrasound enables local healthcare workers to conduct vital screenings, ensuring that pregnant women can access necessary interventions without having to travel long distances. This approach aligns with national objectives aimed at reducing maternal and infant mortality, tackling malnutrition, and fostering early childhood development. It promotes fair access to quality health services for marginalized communities, enhancing inclusivity within Indonesia's healthcare framework.

Innovation is a key to broadening access to healthcare services for underserved communities, especially in a diverse country like Indonesia. The tele-ultrasound service model is a perfect example of how tech-driven solutions can tackle systemic challenges, like inadequate infrastructure, a lack of skilled healthcare workers, and geographic isolation, to provide vital maternal and fetal health services. By combining portable ultrasound devices with remote expert consultations, this model not only boosts local diagnostic capabilities but also delivers high-quality prenatal care to areas that would otherwise be left behind. This innovation champions inclusive healthcare by facilitating early detection and timely intervention, both of which are essential for preventing fetal stunting and enhancing maternal health outcomes. Moreover, it showcases how transforming health systems with digital tools can close equity gaps, empower frontline health workers, and strengthen community resilience.

Acknowledgements

The first phase of the design and development of the telemedicine system, covering everything from design and prototyping to limited testing and initial deployment, received funding from the Agency for the Assessment and Application of Technology (BPPT) for fiscal year of 2019-2021. The phase of improvement, validation, and deployment were supported by the Indonesian Endowment Fund for Education (LPDP) – Ministry of the Finance Republic of Indonesia through the funding program named the Research and Innovation for Advanced Indonesia (RIIM), Batch 2, Year 1 and 2 (2023-2024) - National Research and Innovation Agency (BRIN). This project is a collaborative effort between BRIN and the Regional Government of Tangerang Regency, both dedicated to supporting stunting prevention initiatives in the Sepatan Timur District.

Conflict of interest

The authors declare no conflict of interest.

Notes/thanks/other declarations

We would like to express our heartfelt gratitude for the successful collaboration and support received throughout the implementation of this initiative to:

- **dr. H. Achmad Muchlis**, Head of the Tangerang Regency Health Office, for facilitating the integration of this program within the public healthcare system.
- **dr. Umi Kulsum**, Director of RSUD Pakuhaji – Tangerang Regency, for the hospital's role as the referral center for the telemedicine program.
- **Mr. Miftah Shuritho, S.STP, MM**, Subdistrict Head (Camat) of Sepatan Timur, for his valuable coordination and encouragement at the regional level.
- **Ms. Masitoh, S.Ag., SIP, M.Si**, Secretary of Sepatan Timur Subdistrict, who first introduced the idea of using telemedicine to address stunting in Sepatan Timur and has generously dedicated her time to support and oversee the initiative from beginning to end.
- **dr. Lidya Arita**, Head of Kedaung Barat Community Health Center (Puskesmas), for her leadership and active involvement in implementing maternal healthcare services.
- The **Telemedicine Development Team from BPPT and BRIN**, for their technical expertise, innovation, and dedication in designing and deploying the system.
- **dr. Johan, SpOG**, Obstetrics and Gynecology Specialist, along with the **Nutrition Team of RSUD Pakuhaji**, for their professional medical contributions to the program.
- **dr. Devita**, along with the nurses and midwives at Puskesmas Kedaung Barat, for their commitment and dedication in delivering on-the-ground health services.
- The **Village Heads and their teams** in Sepatan Timur Subdistrict, for providing local facilities such as posyandu (integrated health service posts) to support antenatal check-ups.
- The **PKK and village volunteers (kaders)** across Sepatan Timur, for their active participation, community mobilization, and support of the field activities.

This collaborative effort would not have been possible without the contributions and commitment of each stakeholder mentioned above.

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Perspective Chapter: Telemedicine in Public Health – Trends, Impacts, Challenges, and Prospects – Insights from Ghana and Nigeria

Martin Zang Pam and Michael Abugah

Abstract

The delivery of healthcare around the world is evolving. This transformation is driven by the growing use of digital technologies and the urgent need to strengthen public health systems. One of the most notable developments is the integration of telemedicine. It allows health services to be delivered remotely using communication technologies. In high-income countries, telemedicine is now part of routine care. In contrast, uptake in Sub-Saharan African countries has been slower. This is due to socio-economic and infrastructural challenges, data privacy concerns, and weak policy support. The COVID-19 pandemic marked a turning point. It accelerated the use of telemedicine and showed how it can support health services during public health emergencies. Sub-Saharan African countries like Ghana and Nigeria have taken steps by developing national strategies and piloting telemedicine programs. In this chapter, we discussed the trends, impact, challenges, and prospects of telemedicine in public health, drawing insights from Ghana and Nigeria. Both countries' efforts in telemedicine have shown promising results. However, to realize full potential, telemedicine should not become a solution in search of a problem. Instead, it must respond to barriers that people already face such as distance, cost, long waiting times, and shortage of providers. If these real challenges remain central to policymaking, then telemedicine can move from promise to impact. It can help build stronger, fairer, and more responsive health systems in Sub-Saharan African countries.

Keywords: telemedicine, digital health, health systems, Sub-Saharan Africa, Ghana and Nigeria

1. Introduction

Healthcare delivery is changing across the world. This change is being driven by the growing use of digital technologies and the urgent need to improve public health systems. One of the most important developments is telemedicine. The World Health

Organization defines telemedicine as the use of information and communication technologies to deliver healthcare when distance is a key barrier [1, 2]. This includes online consultations, remote diagnosis, mobile health tools, and the use of electronic records.

Telemedicine enhances disease prevention, enables early diagnosis, and supports chronic disease management [3, 4]. At the population level, it strengthens disease surveillance, facilitates timely outbreak detection, and improves response capacity [5, 6]. These functions reflect telemedicine's strategic relevance in advancing broader health system objectives, including progress toward Universal Health Coverage (UHC), improved health system resilience, and enhanced emergency preparedness and response capacity [7–9]. In high-income countries, telemedicine is now part of routine care [10–12]. It helps with the management of long-term illnesses and supports public health efforts such as disease tracking and health education. However, countries in Sub-Saharan Africa have adopted telemedicine more slowly. Barriers such as poor infrastructure, weak policies, limited digital skills, and financial constraints continue to hinder progress [13–15]. Yet, the COVID-19 pandemic showed how telemedicine can help maintain access to care during public health emergencies, especially in countries with fragile health systems.

In Sub-Saharan Africa, health systems are often constrained by chronic underinvestment, infrastructure deficits, and human resource shortages [16]. Populations in rural and peri-urban areas frequently face significant geographic and financial barriers to accessing healthcare, while national systems struggle with uneven service delivery, limited surge capacity, and weak referral networks [13, 17, 18]. These structural challenges have created urgent demand for innovative solutions that can bypass conventional access bottlenecks. Within this landscape, telemedicine emerges as a potentially transformative approach enabling decentralized care delivery, improving continuity of care, and enhancing the responsiveness of public health systems, particularly in underserved regions.

This chapter examines how telemedicine is shaping public health in Sub-Saharan Africa with a focus on Ghana and Nigeria. These countries have large populations, diverse health needs, and face similar public health challenges, such as disparities between urban and rural healthcare access. Both share a growing interest in digital health, backed by national policies that promote telemedicine and other innovations [19, 20]. The health systems of these countries offer a valuable opportunity to compare progress, identify common obstacles, and draw lessons for other low- and middle-income countries.

2. Role of telemedicine in public health, adoption and trends

Telemedicine has become a key enabler of public health delivery, helping to overcome structural and geographic challenges in healthcare access. Its relevance has grown with global priorities such as UHC and pandemic resilience. Initially, it was launched through pilot programs linking remote clinics to urban hospitals. Currently, telemedicine has evolved into a structured, policy-aligned component of national health systems. Driven by improvements in mobile connectivity, digital infrastructure, and supportive policies, it now supports core public health functions such as disease surveillance, remote monitoring, infection prevention, and health promotion [3–6]. It is seen not just as a clinical tool but as a strategic intervention to enhance access, equity, and system resilience. In countries like Ghana and Nigeria,

telemedicine has been particularly impactful in rural and underserved areas, addressing shortages in specialist care and easing the burden on higher-level facilities.

2.1 Ghana's telemedicine landscape

Ghana is one of the early adopters of digital health in West Africa. In the early 2000s, Ghanaian health professionals began exploring the use of technology to improve healthcare delivery, especially in remote areas [21]. Between 2000 and 2015, the country introduced several policy initiatives to support this shift. These included the Information Communication Technology (ICT) for Accelerated Development (ICT4AD) Policy, the Health Sector ICT Policy and Strategy, the eHealth Implementation Plan (2007–2011), and the Ghana eHealth Strategy of 2010 [22–24]. The 2010 eHealth Strategy of Ghana identified telemedicine as a key approach to improving service delivery [19]. It aimed to strengthen the regulatory framework for health information systems, build capacity for digital innovation, promote equitable access to care through ICT, and support the shift to paperless health records [22]. After the implementation of this strategy, Ghana has made notable progress. The country has expanded training in health informatics, introduced mobile health interventions, and strengthened its digital health information systems [22]. These developments have improved service delivery, enhanced access in underserved areas, and supported public health goals such as disease surveillance and emergency response.

Since the 2010 eHealth Strategy, Ghana has implemented a range of digital health initiatives involving government, development partners, and private stakeholders. The Sene Smartphone Project involved the use of Pocket Digital Assistants (PDAs) to collect public health service data at the Community-based Health Planning and Services (CHPS) zones (the lowest level of service delivery in Ghana) [25]. Then, Mobile Technology for Community Health (MoTeCH) was also introduced. This innovation relied on short message service (SMS) to support maternal and child health in the communities [26]. Another project that was introduced was the Logistic Management Information System (LMIS) project, which enhanced logistics and supply chain management. The Health Information Systems (HIS) and iHost projects were also initiated with the purpose of strengthening data integration across the Ghana Health Service. Other projects included the National Health Insurance Agency's (NHIA) e-Claims and e-Register. These projects streamlined insurance claims and enrolment processes, respectively. Another important innovation was the introduction of the District Health Information Management System-2 (DHIMS2). This became the national platform for routine health data reporting and analysis. This improved data quality, accessibility, and usability.

Following early national strategies, several innovations and telemedicine initiatives emerged across Ghana's health sector. Among the most notable was the Telemedicine Project (2011–2016) in the Ashanti Region, supported by the Novartis Foundation [27]. This initiative empowered community nurses in remote areas to consult district-level physicians via mobile phones and a centralized call center, bridging service gaps in underserved communities. Building on this momentum, Ghana established four Teleconsultation Centres in 2016 across the Upper East, Central, Volta, and Ashanti regions to provide remote clinical support and improve health service reach [28]. In parallel, private sector-led innovations began to expand the digital health initiatives. For instance, mPharma's Mutti Doctor linked community pharmacies with teleconsultation services, facilitating access to clinical advice directly from retail points. Similarly, the Zipline Ghana

project, though primarily focused on drone-based medical deliveries, integrated with telemedicine teams to support laboratory diagnostics in hard-to-reach areas, extending its impact beyond logistics. Another critical intervention was the implementation of the eTracker system. This digital tool was designed to monitor individuals diagnosed with HIV from the point of diagnosis through long-term care, using unique patient identifiers. Evaluations by the Ghana Health Service reported improved case tracking and treatment continuity, reinforcing the system's potential in managing chronic conditions.

Building on earlier digital health initiatives and lessons learned, Ghana has taken significant steps to institutionalize digital innovation through two major policy frameworks, Ghana's Health Information System Strategic Plan (2022–2025) and National Policy and Strategy on Digital Health (2023–2027) [29, 30]. These policies emphasize the scale-up of proven digital solutions, the integration of telemedicine into the national health system, and the establishment of regulatory and operational frameworks to guide implementation. In line with these strategic shifts, the Policy, Planning, Monitoring, and Evaluation (PPME) Division of the Ghana Health Service recently launched the Ghana Country Innovation Platform (CIP) [31]. This initiative leverages digital technologies to strengthen maternal and newborn health services in selected regions. A key innovation under the CIP is the Digital Live Blackboard (LDB) system, led by the Paediatric Society of Ghana. The LDB enables real-time monitoring of women in labor at peripheral facilities. It connects frontline health workers with district-level specialists who provide timely clinical guidance and support. The system is designed to streamline referrals, reduce delays in recognizing obstetric emergencies, and enable faster interventions during complications. Another innovation introduced under the CIP involves digitally enabled mini ambulances operated by Moving Health. These ambulances are equipped with GPS, USSD, and Internet-based systems that transmit patient information ahead of arrival at referral hospitals. This enhances coordination, reduces delays, and ensures continuity of care from point of pick-up to facility-level intervention. These innovations show a consistent shift from isolated pilot projects to integrated digital health platforms, reinforcing the critical role of telemedicine in improving access, coordination, and quality of care across Ghana's health system.

2.2 Nigeria's telemedicine landscape

Nigeria's adoption of telemedicine has progressed in response to persistent health-care access challenges and growing digital connectivity. Early initiatives focused on extending specialist care to underserved areas. In 2007, the Federal Ministry of Health, in partnership with the National Space Research and Development Agency, launched a national telemedicine pilot [32]. It connected Teaching hospitals and six federal medical centers across geopolitical zones. Intel Corporation also partnered with the ministry that year to link the Federal Medical Centre in Bida with the National Hospital in Abuja via WiMAX for real-time pediatric and surgical consultations. In 2009, the Ondo State government introduced the Abiye (Safe Motherhood) project, distributing mobile phones to pregnant women for direct access to healthcare providers [33]. This contributed to reduced maternal mortality. Also in 2009, Nigeria joined the Pan-African e-Network, an African Union and Indian government initiative, to support telemedicine and tele-education using satellite and fiber-optic infrastructure [34, 35]. These early efforts laid the foundation for integrating telemedicine into Nigeria's health system.

Between 2013 and 2018, private and non-governmental actors advanced digital health solutions. In 2013, DokiLink was introduced as an online platform connecting patients to medical doctors for appointment booking and remote consultations [36, 37]. It expanded its services in 2018 to reach more users across Nigeria. Omowunmi, a GSM-based software, was also developed in 2014 to promote maternal health through mobile health education and reminders [38]. The platform was later integrated into health insurance programs targeting pregnant women. Other projects were also introduced, including LifeBank [39] and Flying Doctors Nigeria [40]. LifeBank was established to improve the delivery of blood and medical supplies using digital logistics solutions. It modernized emergency supply chains for hospitals through mobile and web-based platforms. Flying Doctors Nigeria, an air ambulance service operation, expanded its scope by offering telemedicine consultations for emergency triage and follow-up care.

In 2016, the Federal Government of Nigeria launched the National Health ICT Strategic Framework (2015–2020), formally recognizing telemedicine as a tool for improving health services [41]. Despite this, progress was hindered by weak infrastructure, low Internet coverage, and fragmented coordination [32]. In 2018, the Osun Health Insurance Scheme was introduced with integrated digital tools to streamline enrollment and service delivery [42, 43]. The eHealth Africa (EHA) Clinics also began providing primary care in cities like Kano and Abuja using teleconsultation and electronic medical records [44].

The COVID-19 pandemic in 2020 catalyzed a rapid scale-up of telemedicine. Hospitals implemented telemedicine, and the Federal Ministry of Health issued interim guidelines to support remote care. Private providers such as Wellvis and Helium Health also initiated digital consultations and digital solutions to health challenges [45, 46]. However, rural populations remained underserved due to limited Internet access and high data costs. To improve coordination, the government developed the Nigeria Health Data Repository and expanded digital surveillance using platforms like the District Health Information Software [47]. Telemedicine has since been integrated into maternal and child health and chronic disease programs, though national uptake remains uneven. Nigeria is currently revising its digital health strategy. Key priorities include expanding broadband infrastructure, improving governance, and fostering public-private partnerships. While urban telemedicine use is growing, rural areas continue to face significant barriers.

In summary, the experience of Ghana and Nigeria illustrates that telemedicine is no longer a new or experimental idea. It has become part of how both countries are building stronger public health systems. Initially used for specialist consultations, telemedicine now supports prevention, health promotion, and disease surveillance. This shift reflects changing health needs, growing innovation, and efforts to make health systems more efficient. Adoption in both countries has followed different paths but shares some common features. Policies from governments, support from donors, and private sector involvement have shaped the pace and direction of progress. Ghana's early national strategies helped create a foundation for wider use. Nigeria's adoption was more fragmented at first, but the COVID-19 pandemic pushed it into the mainstream.

In both cases, private companies and community-based innovations have played key roles. Recent trends show a clear move toward integrating telemedicine into national health systems. Digital platforms are now being linked with health insurance schemes and routine data systems. Some programs focus on rural areas, aiming to close long-standing access gaps. Others explore new ways to deliver care, such as mobile consultations and remote diagnostics. These developments show that

telemedicine in Ghana and Nigeria is not just about technology. It is about redesigning public health delivery to respond better to challenges.

3. Impact of telemedicine on healthcare quality and equity

Telemedicine has produced both measurable and observable impacts on public health systems in Ghana and Nigeria, particularly in enhancing access to care, optimizing health service delivery, and supporting health system resilience. While the extent of these impacts varies across contexts, several domains illustrate the tangible benefits and limitations of telemedicine as a public health intervention.

3.1 Improved access and equity

One of the most consistent impacts of telemedicine has been the reduction of geographic and financial barriers to care. In Ghana, community health nurses using teleconsultation platforms in rural areas have reported significantly reduced delays in accessing medical advice, particularly for maternal and neonatal complications [48, 49]. Evaluations of the Ghana Telemedicine Project showed that it reduced unnecessary referrals by 31% [50]. This was achieved by allowing doctors and midwives at the higher-level facilities to support and guide rural health workers through teleconsultation. The project also reduced the need for unnecessary patient transport, thereby lowering the overall cost of care. Also, the use of WhatsApp as a mobile health tool helped increase antenatal care attendance by 5.6% and health facility deliveries by 5.6% in Ghana [51]. In Nigeria, a randomized controlled trial that used SMS appointment reminders for the intervention group improved the return rate of child vaccination by 4.8–6.0% compared to the control group without any reminders [52]. These outcomes reflect telemedicine's potential to improve access and equity regarding care.

3.2 System efficiency and resource optimization

Telemedicine has contributed to greater system efficiency and optimizing human resource utilization. The integration of telemedicine into Ghana's national health information ecosystem (e.g., DHIMS2) allows for timely data transmission, accelerating health service responsiveness and administrative processes. Similarly, in Nigeria, the use of electronic medical consultations in some federal hospitals has helped doctors see more patients and allowed health workers to share tasks more easily in places with limited staff and resources. These efficiency gains are particularly critical in fragile systems facing periodic epidemics and seasonal health surges.

3.3 Strengthens emergency and epidemic response

The COVID-19 pandemic underscored the relevance of telemedicine in sustaining service delivery during emergencies. In both countries, digital health platforms supported remote case assessments, infection control training, and dissemination of risk communication messages. In Nigeria, digital healthcare tools were used to strengthen public health and COVID-19 pandemic preparedness [53]. In Ghana, call centers provided by the Ministry of Health and Ghana Health Service helped individuals to call and ask about their symptoms and seek guidance, reducing in-person visits and potential exposure during the COVID-19 pandemic [54].

3.4 Enhanced health worker support and capacity building

Telemedicine platforms have become critical tools for professional support and continuous learning. In both Ghana and Nigeria, virtual case discussions and remote supervision have helped mitigate the isolation of rural health workers and supported clinical decision-making in real time. In Ghana, WhatsApp platforms used by midwives and nurses as a communication tool were reported to improve early and prompt referral of high-risk obstetric cases [55] and helped improve maternal health case management and patient confidence [51]. In Nigeria, platforms like the video training (VTR) on maternal, newborn, and child health allowed frontline health workers and community health workers to access clinical protocols and communicate with supervisors without traveling to urban areas for training [56]. This facilitated knowledge transfer and reduced costs.

4. Challenges in telemedicine implementation

Although telemedicine is increasingly recognized as a promising approach for improving healthcare access and strengthening public health systems, its implementation in Ghana and Nigeria has not been without challenges. Both countries have made encouraging progress in digital health, including the development of national strategies and the piloting of various telemedicine initiatives. However, the journey from policy to practice has been uneven and faces important obstacles that deserve careful attention. These are not signs of failure, but rather areas where further investment, coordination, and learning are required.

4.1 Governance and regulation

One key challenge is the limited development of governance and regulation. While there are policies in place, the rules that guide the practice of telemedicine are still evolving. In many cases, they do not fully address the realities of delivering healthcare remotely. For example, questions remain about who is allowed to provide care across regions? How is responsibility shared when something goes wrong? How patient information should be protected? These legal uncertainties can make both providers and patients cautious about participating in virtual care.

Closely related to these governance issues are uncertainties concerning the licensing of providers and accreditation. In both Ghana and Nigeria, regulatory frameworks lack clarity on whether practitioners offering remote consultations must be licensed in the patient's jurisdiction or if national licensure suffices. This ambiguity limits the scalability of telemedicine, especially for cross-regional and specialist services. Establishing standardized, enforceable licensing policies is essential to ensuring telemedicine is delivered safely, ethically, and with clear accountability.

Equally critical is the challenge of data privacy and cybersecurity. Although both countries have national data protection laws, enforcement within the health sector remains weak. Many healthcare workers and institutions lack awareness of or training on protocols for securing electronic patient information. Given that telemedicine relies heavily on the storage and transmission of sensitive health data via digital platforms, vulnerabilities to breaches and unauthorized access increase. To build public trust and safeguard confidentiality, it is vital to implement robust digital security standards such as end-to-end encryption, secure authentication, role-based

access controls, and regular system audits. This will ensure that telemedicine services are safe, fair, and accountable.

4.2 Infrastructure and capacity challenges

The effectiveness and equity of telemedicine in Ghana and Nigeria are fundamentally constrained by significant disparities in digital infrastructure and human capacity, which collectively perpetuate existing health inequities. Urban centers in both countries typically benefit from relatively stable, high-speed Internet connectivity and widespread mobile phone ownership, creating favorable conditions for telemedicine adoption. In contrast, rural and underserved regions face inconsistent or insufficient bandwidth, unreliable electricity supply, and limited access to smartphones or other digital devices. These infrastructural deficiencies impede real-time data exchange, and video-based consultation modalities are often essential for high-quality clinical assessment and patient engagement.

While asynchronous telemedicine models offer some mitigation by enabling delayed communication that requires less bandwidth, such adaptations alone are insufficient to bridge the broader digital divide. Addressing these structural disparities demands targeted, sustained investments in broadband expansion and electricity supply, particularly in rural areas where digital exclusion mirrors entrenched social and health inequalities.

Equally critical to overcoming the digital divide is addressing the pronounced inequity in digital literacy and skills. The mere availability of technology does not guarantee effective utilization. Many individuals in remote communities lack the competencies needed to navigate telemedicine platforms confidently and safely. This skills gap risks exacerbating disparities by privileging digitally literate populations, primarily urban and wealthier groups, while marginalizing those already underserved. Therefore, digital infrastructure expansion must be complemented by comprehensive education and training initiatives aimed at enhancing digital literacy at the community level. Empowering patients and caregivers with the knowledge and confidence to engage in virtual care is imperative for realizing the inclusive potential of telemedicine.

Complementing these patient-centered challenges, the quality of care delivered through telemedicine hinges substantially on the preparedness and competencies of healthcare providers. Although health workers generally demonstrate willingness to incorporate digital tools, most have not received formal, structured training on remote care delivery. Essential skills including establishing therapeutic rapport in virtual settings, conducting symptom assessments without physical examination, and managing privacy and confidentiality concerns are frequently absent from standard medical and nursing curricula. This gap in provider capacity risks undermining the clinical effectiveness and safety of telemedicine services. Without rigorous training programs and evidence-based guidelines tailored to virtual care contexts, even well-intentioned initiatives may fall short of expected quality standards and could inadvertently compromise patient outcomes. Therefore, investment in professional development and the institutionalization of clear, context-appropriate protocols are critical to ensuring consistent, high-quality telemedicine services.

4.3 Financing

Financing is another area that presents risks for long-term sustainability. Many telemedicine platforms have been launched through donor funding or start-up

capital, which can provide useful early momentum. However, when these external sources of support end, it becomes difficult to maintain and expand the services. Without a clear plan for how telemedicine fits into national health budgets, or how patients will be supported to use these services, it is hard to ensure that the benefits of digital care reach all communities. It is also important to explore whether national insurance schemes and health financing systems can help cover the cost of virtual consultations, especially for people who may not afford out-of-pocket payments.

4.4 Coordination challenges

A major challenge in telemedicine is the lack of coordination among the many actors involved. Many projects operate in different parts of Ghana and Nigeria, but they use different technologies, patient identification methods, and data recording systems. This makes it difficult to connect these efforts into one strong and unified system. Lessons learned in one area may not be shared with others. Resources may be used in ways that do not support long-term goals. Having a shared vision and a clear structure for collaboration can help avoid duplication, reduce waste, and make better use of local knowledge.

In addition, delays in decision-making and weak coordination across government sectors also slow down progress. Although digital health is included in national health strategies, putting these plans into action is often delayed by complex procurement processes, unclear responsibilities, and poor cooperation between health ministries and other key sectors like telecommunications, education, and infrastructure. Telemedicine does not work alone. It depends on many parts of the system working together. Progress happens faster when all these parts are coordinated and moving in the same direction.

5. Prospects and policy considerations to boost telemedicine

Telemedicine offers more than just convenience. It represents a new way of thinking about how health services are delivered, especially in places where healthcare workers, facilities, and resources are limited. It brings forward a chance to address long-standing inequalities in access to care. But opportunities alone do not lead to change. They must be supported by decisions that are thoughtful, inclusive, and grounded in context.

The early steps taken by Ghana and Nigeria are promising. National strategies show that leaders are paying attention, and several pilot programs are already underway. However, pilots are not the end goal. The aim should be to make telemedicine a normal part of the health system. It must be available, affordable, and trusted by the public. Reaching that point will require action in a few key areas.

5.1 Reimagining health financing and strengthening governance

For telemedicine to thrive, it must be backed by strong financing and governance systems. These are not just administrative needs, but they are pillars of sustainability. Funding for digital health should be seen not simply as a cost, but as a long-term investment in public health. Relying on donor support or short-term projects is not enough. National health financing strategies must evolve to support digital transformation. This includes integrating telemedicine into health insurance schemes, increasing domestic

funding, and building meaningful partnerships between the public and private sectors. When governments and private actors work together, the benefits can reach more people and last longer. However, this collaboration must be well designed. It must protect public interests, promote fairness, and ensure transparency. Poorly regulated partnerships can widen inequalities or compromise patient safety.

At the same time, the laws and ethical standards that govern healthcare must catch up with the rise of virtual care. Many existing rules were created with face-to-face care in mind. Applying them directly to teleconsultations, remote diagnostics, or cross-border services without review can lead to confusion or even harm. For instance, who is responsible if something goes wrong during a video consultation? How can we ensure that patient information stays private in a digital space? These questions need answers that reflect today's realities. Ghana and Nigeria should aim to create clear, adaptive legislation, which defines licensure, scope of virtual practice, reimbursement structures, clinical liability, and data protection. Importantly, reforms should not be isolated efforts. They must be institutionalized and harmonized across jurisdictions to enable scalable and safe digital service delivery. There should be harmony in licensing standards for telemedicine practitioners across regions. This can reduce bureaucratic bottlenecks, facilitate specialist care access, and uphold quality assurance in virtual services.

5.2 Investing in human capacity and digital literacy for providers

The success of telemedicine depends not only on technology, but on the people who use it. Health workers are central to its effectiveness. Digital tools may change how care is delivered, but without the skills and confidence of the health workforce, telemedicine cannot succeed. Virtual care changes how providers assess patients, keep records, and communicate. If health professionals are not well prepared, they may resist these changes or use them poorly putting care quality at risk.

To prevent this, digital literacy and clinical readiness for virtual care must become part of health professional training. These skills should be introduced early in pre-service education and strengthened through regular in-service training. Healthcare workers need to learn more than just how to use digital platforms. They also need to master tele-triage, remote patient monitoring, digital ethics, and how to navigate virtual care systems. Equally essential are the interpersonal and communication skills required to build patient rapport through screens, maintain professionalism in virtual settings, and manage digital records with clarity.

If we expect health workers to deliver care in new ways, we must train and support them accordingly. This is especially urgent at the primary care level, where many services are delivered and where gaps in staffing are common. Here, digital tools can help by allowing task-sharing and enabling frontline workers to get real-time support from remote specialists. To bridge urban-rural gaps in the health workforce, investments should prioritize tele-mentorship, digital education, and decision-support systems.

5.3 Digital infrastructure, platform interoperability, and cybersecurity

Telemedicine will not grow on technology alone. It needs strong digital foundations. These include steady Internet, reliable electricity, sufficient bandwidth, and digital tools, especially in rural and underserved areas where the needs are high, but resources are few. Without these, virtual care cannot reach those who need it most. Governments must treat broadband access, bandwidth capacity, and digital systems

as core parts of national health development. Weak connectivity or limited bandwidth makes telemedicine unreliable and frustrating for both patients and providers. That is why national plans must set clear targets for digital infrastructure within broader health strategies. Public funding is important, but private sector support will also be key. Together, these efforts can close the digital gap.

Ghana and Nigeria are making important progress. Ghana's Eastern Corridor Fiber Optic Backbone now links Ho to Bawku, with branches reaching Yendi and Tamale. This helps connect the north, where health access is more limited. MTN Ghana's move to extend over 130 kilometers of fiber shows that private actors are also stepping in to support digital goals.

Nigeria is taking bold steps too. Its National Broadband Plan aims to cover 90% of the population by 2025. Project "Building Resilient Digital Infrastructure for Growth (BRIDGE)," which plans to lay 90,000 kilometers of fiber cable, will create a strong base for ICT services. States like Edo are also leading locally by using existing broadband to support digital health and telemedicine services.

These are more than just tech upgrades; they are steps toward better health for all. If Ghana and Nigeria keep investing in infrastructure and bandwidth, they can expand telemedicine to scale, speed, and equity. But access alone is not enough. The platforms that carry telemedicine must also be safe, connected, and trusted. Systems should cross-connect with each other; that is, they must be interoperable. They must also follow strict rules for security. This means adopting end-to-end encryption, secure user authentication, role-based access controls, and conducting regular security audits. Cybersecurity cannot be an afterthought. It must be part of how we protect patients, just like infection control in clinics. Policies must prioritize educating both healthcare providers and patients on best practices for digital safety. Ghana and Nigeria could make digital health infrastructure part of national development goals, ensure that platforms work across systems, and treat cybersecurity as essential. These are not optional steps. They are the base on which safe, fair, and lasting digital health will be built.

5.4 Cross-sectoral and regional coordination

Scaling up telemedicine is not a task for the health sector alone. It requires joined-up action across government bodies. Ministries responsible for digital infrastructure, education, finance, and communications must work hand in hand with health authorities. This alignment helps ensure that policies, budgets, and implementation plans support one another rather than work at cross-purposes.

To make this happen, countries need inter-ministerial coordination platforms—formal ways for ministries to work together, share updates, and make joint decisions. These structures break down silos and help build shared ownership of digital health. Just as important, voices outside of government should be heard. Technology start-ups, universities, civil society groups, and patient advocates bring fresh ideas, technical know-how, and practical insights. Their involvement will help shape policies that are realistic, inclusive, and responsive to real-world needs.

Looking beyond national borders, regional cooperation offers even greater potential. In West Africa, countries face many of the same challenges and opportunities in digital health. Working together can speed up progress and avoid repeating mistakes. Regional bodies such as the West African Health Organization (WAHO) and the Economic Community of West African States (ECOWAS) must take a stronger lead in this space. These institutions can help countries harmonize regulations, agree on technical standards, and pool investments in shared digital infrastructure. They can

also support the creation of regional centers of excellence in virtual care places where health professionals, technicians, and researchers from across the region can train, innovate, and lead.

Regional solutions are especially useful for cross-border challenges. For example, a patient in one country may receive virtual consultation from a specialist in another. This raises important questions: Can health professionals practice across borders? Which country's laws apply? Who is responsible for patient safety? To address this, countries can work together to develop regional licensing systems, shared teleconsultation protocols, and common frameworks for data protection.

By fostering this level of coordination, both within countries and across the region of West Africa can move faster, invest smarter, and deliver more equitable digital health services. Telemedicine, when supported by strong governance, becomes not just a tool for convenience but a powerful force for health equity and regional solidarity.

5.5 Equity, affordability, and cultural acceptance

For telemedicine to truly deliver on its promise, it must be built around the needs of its users, which are the patients, families, and communities. The success of telemedicine depends on how people experience and engage with virtual care. If services are hard to use, costly, or unfamiliar, they will not reach those who need them most. This means policymakers must go beyond infrastructure and address the social and financial barriers that limit access. In many places, especially in rural and underserved communities, people face real obstacles. The cost of mobile data, limited access to smartphones, and low digital literacy are just a few examples.

To reduce these barriers, national health insurance schemes should consider covering telemedicine services, and targeted subsidies could help those who cannot afford digital access. Financial protection is not a luxury; it is a necessity for equitable digital health.

At the same time, cultural sensitivity must guide the design and delivery of telemedicine. Both Ghana and Nigeria are richly diverse countries where health beliefs, languages, and customs vary widely. Telemedicine platforms must reflect this diversity. Interfaces should be easy to use, offered in local languages, and grounded in cultural norms that people trust. Community involvement is key. When communities are engaged early and meaningfully, they are more likely to accept and support virtual care.

Public awareness campaigns, patient education, and peer-to-peer engagement can build trust and familiarity. Digital health literacy should not be limited to health workers. Patients and caregivers also need to understand how to use telehealth services, how their data is protected, and what to expect from virtual consultations.

Without this human focus, without understanding and addressing the real-life context in which people live, telemedicine risks becoming a missed opportunity. It may exist on paper or in policy but remain unused in practice. On the other hand, when users are empowered, protected, and respected, telemedicine can expand access, strengthen health systems, and move both Ghana and Nigeria closer to health for all.

6. Conclusion

In conclusion, this chapter examined the role of telemedicine in the public health systems of Ghana and Nigeria. It has highlighted its potential to improve access to

healthcare, enhance quality of services, and strengthen health system responsiveness. However, its effective implementation depends not only on technological advancement but also on coherent policy reforms, capacity development, and institutional commitment. As we look ahead, the path forward is not guaranteed. It will depend on how decisions are made, whose voices are heard, and how well digital tools are matched to real-world needs. Telemedicine should not become a solution to looking for a problem. It should respond to the challenges that people already face in getting care: distance, cost, time, and shortage of providers. If this goal remains at the center of policymaking, then telemedicine can move from promise to impact, helping build stronger, fairer, and more responsive health systems in both Ghana and Nigeria.

Conflict of interest

We have no conflict of interest regarding this work.

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Perspective Chapter: Exploring the Practical Implications of Emerging Technologies in Pediatric Telehealth and Telemedicine

Lingrui Yang, Yize Zhao, Yajiao Tan, Song Zuo and Xin Sun

Abstract

In this chapter, children's proactive health is explored within the framework of telemedicine and telehealth, utilizing new technologies such as artificial intelligence (AI)/Large Language Models (LLMs), Internet of Things (IoT), 5G, augmented reality (AR)/virtual reality (VR), and big data to create a full-cycle health management system for children. Proactive health starts at home, with roots in lifestyle medicine and early childhood comprehensive development. In addition to creating the Children's Proactive Health Index, the Xinhua Hospital project team constructed a child health portrait based on the Index, where wearables with Internet of Things capabilities continuously track parameters like nutrition, sleep patterns, and physical activity. Dynamic health profiles are produced using real-time data, allowing for timely risk alarms, individualized prevention, and early anomaly identification. Caregivers can use Intelligent Digital General Practitioner—guided home-based treatments to address health issues. These interventions offer personalized guidance for child care, diseases and lifestyle changes. Internet hospitals fulfill the essential approach for telemedicine. An effective intelligent triage system refers caregivers to the right medical specialists, either in person or online, for cases that need professional attention. Online consultations that can assist with smart pre-consultation, facilitate diagnosis, incorporate digital therapies provide prescription administration, and permit remote follow-ups, may guarantee smooth continuity of healthcare services for the patient. Bridging the gap between prevention and treatment, in an integrated approach, creates a new paradigm for the management and intervention of children's health by optimizing pediatric health outcomes through proactive, technology-driven care.

Keywords: artificial intelligence, pediatric healthcare, proactive health, Children's Proactive Health Index, digital general practitioners, intelligent triage, child health management, telemedicine, telehealth, healthcare innovation

1. Introduction

The rapid evolution of information and communication technologies has catalyzed a paradigm shift in healthcare delivery, enabling the emergence of remote health and telemedicine as transformative modalities. The integration of cutting-edge technology, including cloud computing, big data analytics, the Internet of Things (IoT), and artificial intelligence (AI), to provide remote real-time health monitoring, illness prevention and early detection, and personalized care outside of conventional clinical settings is known as remote health [1–4]. With services ranging from remote diagnosis and consultation to AI-assisted surgical guidance [5], telemedicine uses these technologies to ameliorate geographic and temporal gaps in the distribution of medical resources.

The World Health Organization (WHO) defines health as “not only the absence of disease, but also physical, mental, socially well-adjusted and morally healthy” [6]. The emergence of lifestyle medicine has prompted a paradigm shift in health conceptualization, challenging the traditional disease-centric model and emphasizing the enhancement of psychological well-being and quality of life as fundamental components of holistic health [7]. This approach encourages a comprehensive understanding of health that considers social, emotional, and physical well-being. “Healthy lifestyle management” is the cornerstone of the future of health, which facilitates a holistic transformation of health management into intelligent and personalized solutions using emerging technologies. The transition from “passive treatment” to “active health management” is made achievable by cutting-edge technologies like AI, big data, and cloud computing. Guided by China’s “Healthy Children 2030” strategy [8] and the implementation of children’s proactive health, it integrates data-driven health assessment and intervention strategies, covers the entire “prevention, treatment, and rehabilitation” process, breaks down socioeconomic and geographic barriers, and increases access to high-quality medical resources. Using technology integration, integrated medicine, and policy support, the proactive health system will be intelligent and borderless, fostering the growth of telehealth and telemedicine, optimizing resource allocation, enhancing patient experience, and offering a novel approach to managing global health.

This chapter introduces an innovative framework for pediatric active health management and intervention based on the Children’s Proactive Health Index, which seeks to implement telehealth-based active health management and intervention for children. The project team trains AI pediatric general practitioners to address a number of guardians’ concerns regarding children’s healthcare, including providing health education, promoting health consultation, offering cultivating healthy lifestyles development, guiding home treatment for common and frequent diseases, and timely guidance for medical treatment. Various functions are implemented in Internet hospital, which additionally offers online consultation services in an effort to minimize needless offline visits and maximize the use of medical resources. Through bridging the gap between prevention and treatment, this integrated health management approach fosters initiative, accuracy, and efficiency in child health management, optimizes child health outcomes in a technology-driven manner, and establishes a new paradigm for child health management.

2. Telehealth

Against the backdrop of the continuous development of digital healthcare, telemedicine and telehealth have become an important part of the drive to improve

the accessibility and efficiency of healthcare services. Telemedicine mainly refers to the provision of clinical services such as remote diagnosis, treatment and consultation by medical professionals to patients in different locations through information and communication technologies, with the core focus on realizing the spatial extension of medical behaviors. Telehealth, on the other hand, not only covers telemedicine itself but also includes non-clinical services such as health monitoring, health education, chronic disease management, and rehabilitation guidance. The common goal of the two is to enhance the accessibility and continuity of healthcare services with the help of technological means, which complement each other in practical application and jointly promote the development of the healthcare system in the direction of being more intelligent, efficient and people-centered.

2.1 Future Health

Future Health is a comprehensive innovation in the concept and practice of human health lifestyle management. It not only focuses on the treatment and control of diseases but also on improving the overall health of individuals through prevention, early intervention, and continuous management. Against the backdrop of technological progress, social change, and evolving medical needs, Future Health represents the direction and goal of development in the health field. It is not only a renewal of concepts, but also a reconstruction of practice pathways [9, 10].

With digital empowerment and integration and innovation as its core features, Future Health utilizes technologies such as big data, AI, and the IoT to achieve real-time monitoring and in-depth analysis of individual health status. Its system construction relies on three cornerstones: (1) environment, (2) biomedical technology and (3) lifestyle. A good environment can reduce the impact of external harmful factors on children's health; biomedical technology, especially the development of genetic testing and precision medicine, provides individuals with more targeted health protection; and scientific lifestyle management strengthens children's immunity and resistance to disease through a reasonable diet, moderate exercise and mental health support [11].

The realization of Future Health entails a dual transformation in both concept and technology—marking a shift from the traditional “passive health” model to a “proactive health” approach. In the past, health management primarily focused on treatment and intervention after the onset of disease. In contrast, Future Health leverages technological empowerment to shift the focus forward, emphasizing risk prediction, active monitoring, and early intervention, thereby truly building a proactive health system that covers the entire process of prevention, monitoring, and intervention.

2.2 The concept of proactive health

In 2015, China's Ministry of Science and Technology introduced the innovative concept of “proactive health” for the first time in its 13th Five-Year Plan on “Digital Healthcare and Health Promotion”. Proactive health is a human-centered health concept that emphasizes prevention, active individual participation and whole-life management. It advocates a shift from passive acceptance of treatment to active action to maintain health, including disease prevention, healthy lifestyle development and active access to and application of health information. Proactive health emphasizes interdisciplinary cooperation and the integration of various resources, such as medical care, sports and education, in order to improve the health literacy and quality of life of all people [12, 13].

2.3 Health model transformation

The traditional health management model has long been “disease-centered”, focusing on diagnosis and treatment after symptoms appear. This model tends to lag behind, ignoring the many preventable and intervenable risk factors in children’s healthy development. The health service system established on this basis assumes the role of “rescuer” rather than “guardian” [12].

With the continuous improvement of people’s health concepts and the rapid development of scientific and technological means, the traditional passive health model, which focuses on disease treatment, is changing to a proactive health model, which is prevention-oriented and characterized by full-cycle management [14]. This model emphasizes “health-centeredness” and shifts the focus of attention to risk warning, daily intervention and behavioral guidance, especially for children, a group with rapid physical and mental development and a concentrated sensitive period for intervention.

Childhood is a critical stage of physical and mental development and is the foundation for health throughout the life cycle. Early health status has a profound impact on cognitive ability, chronic disease risk and psychological quality in adulthood. If health problems are not detected and intervened in time during childhood, it may lead to delayed development of diseases and even irreversible health damage. Therefore, it is necessary to build a new model of children’s health management and intervention centered on the concept of active health to achieve all-round and systematic health intervention to ensure the healthy growth of children [15, 16].

Guided by this concept, the team constructed a proactive health management and intervention model for the children’s population. The model is based on the Children’s Proactive Health Index and integrates advanced technologies such as big data, AI and the IoT to realize dynamic monitoring and intelligent analysis of children’s multidimensional health status. It not only provides personalized intervention recommendations but also establishes a multi-party mechanism of “society-family-school-medical care”, forming a closed-loop proactive health support system that covers the entire cycle of children’s growth, and truly realizes the sustainability and accuracy of health management.

2.4 Realization of proactive health management and intervention for children

The realization of proactive health management and intervention for children cannot be separated from the deep integration and synergistic empowerment of emerging technologies [17]. Frontier technologies such as AI, big data, cloud computing, IoT, 5G, smart wearable devices and natural language processing have built a service system combining multi-dimensional data perception, intelligent analysis and personalized interventions, which provides solid technical support and innovative power for children’s health management [18].

2.4.1 Construction of the Children’s Proactive Health Index

The Children’s Proactive Health Index is a comprehensive multi-dimensional evaluation system for systematically assessing the overall health status of children. It reflects the health level and potential risks of children during the critical period of growth and development by quantifying multi-dimensional indicators such as physiology, psychology, social adaptation and environmental support. Unlike adult

health assessment, the core of the Children's Proactive Health Index lies in dynamic monitoring of developmental trajectories rather than purely diagnosing diseases.

The team has established a scientific, systematic, and quantifiable Children's Proactive Health Index, see **Figure 1**. It covers seven age stages of a child's development (1) fetal stage, (2) neonatal stage, (3) infant stage, (4) early childhood stage, (5) preschool stage, (6) school age and (7) adolescence. Based on the growth patterns and health risks of different age groups, the construction of the Children's Proactive Health Index sets up differentiated and dynamic evaluation indicators, with core dimensions including but not limited to growth and development (e.g., height, weight, Body Mass Index [BMI]), physiological indicators (e.g., vision, hearing), mental health (e.g., emotion, social interaction), and behavioral habits (e.g., diet, exercise, rest and relaxation), etc. The Children's Proactive Health Index is based on a set of standardized data collection and standardized assessment [19].

Through continuous data collection, standardized assessment and dynamic modeling, the Children's Proactive Health Index can help parents and professionals have a comprehensive understanding of children's health status and provide an important basis for predicting potential risks and developing personalized intervention strategies.

2.4.2 Personal electronic health records

Children's personal electronic health record is a digital file system that records and manages all kinds of health-related information of children in the process of growth and

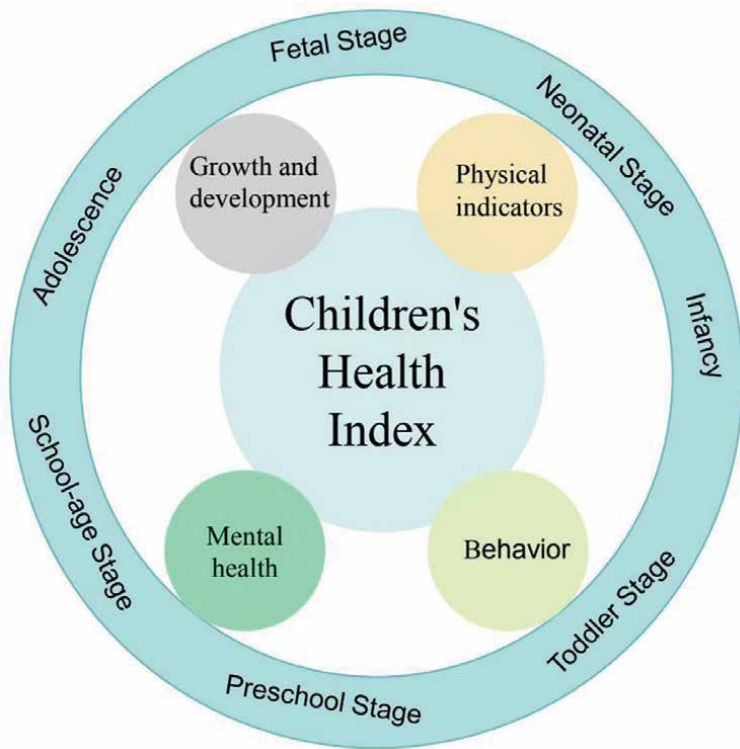


Figure 1.
Architecture of the Children's Proactive Health Index.

development by means of information technology. In the practice of proactive health management and intervention for children, a comprehensive and dynamic children's electronic health file is constructed by combining technical means such as the Internet, the IoT, big data and AI and integrating multi-dimensional data such as children's basic information, diagnostic and therapeutic information, lifestyles and social behaviors. It will realize real-time updating and sharing of information, and provide a convenient and efficient health management tool for doctors, parents and administrators.

2.4.3 Dynamic electronic child health portrait

Based on Children's Proactive Index, and by integrating wearable devices and digital twin technology, real-time and continuous health data can be collected to create a panoramic, dynamic portrait of children's health. This comprehensive profile will reflect children's lifestyles, health conditions, and potential health risks. It will provide doctors with more accurate grounds for diagnosis and treatment, and offer parents more scientific guidance for child-rearing. At the same time, algorithms and models are used to evaluate children's current health status based on objective indicators. When certain health metrics reach critical thresholds, the platform will automatically issue alerts, notifying parents and doctors to take timely intervention measures. This early warning mechanism will greatly enhance the timeliness and effectiveness of children's health management.

2.4.4 AI pediatric general practitioner

Digital empowerment has significantly improved the convenience and accessibility of children's health services. With the help of intelligent technologies, healthcare services are no longer bound by geographic or time constraints—children can now access high-quality medical support anytime and anywhere. This technology-driven model of healthcare delivery has greatly enhanced the responsiveness and accessibility of health interventions, steering children's health management toward greater intelligence and precision.

In this process, the application of children's AI general practitioners is particularly critical. It integrates multi-source data analysis, intelligent diagnosis and personalized advice, and deeply integrates intelligent diagnosis engine, disease prediction model and emerging front-end technologies. It starts an intelligent dialog with parents through natural language interaction and provides scientific home care advice. It is able to monitor and provide feedback on a child's health status in a 24/7, all-round way, and guide them to seek medical treatment when necessary, helping parents to make more reasonable health decisions. This not only greatly improves the efficiency and quality of medical services but also reduces medical costs, realizes personalized medical treatment, accurate management and dynamic adjustment of children, and promotes children's health management into a new era of "technology-led, intelligent intervention".

3. Telemedicine

3.1 Introduction of telemedicine

While telehealth encompasses a broad spectrum of digital health activities across the entire continuum of care, telemedicine specifically refers to the use

of telecommunications technology to deliver clinical medical services remotely. Telemedicine aims to overcome geographical barriers and improve access to medical care, particularly for individuals in remote or underserved areas. By utilizing technologies such as video conferencing, mobile health applications, remote monitoring devices, and electronic health records, telemedicine facilitates seamless communication between patients and healthcare providers, focusing on the diagnosis, treatment, and management of medical conditions [20].

The primary functions of telemedicine include remote consultations, multidisciplinary online consultation, prescription renewal, chronic disease management, medical follow-ups, and health education. It has significantly improved the efficiency and accessibility of telemedicine by integrating medical resources and optimizing service processes, particularly beneficial in rural and remote areas, where access to healthcare facilities is limited, and in managing chronic conditions that require ongoing care. Telemedicine facilitates immediate medical consultation and triage, while also demonstrating significant utility in emergency healthcare scenarios like COVID-19 [21].

The core advantage of telemedicine lies in “digitalization of medical services, intelligent process management, and precise data utilization”. In terms of functionality, telemedicine not only support the initial and subsequent diagnosis and treatment of common and frequent diseases but also realize the long-term management and follow-up of chronic diseases. Furthermore, relying on medical big data and AI technology, telemedicine can also provide personalized health advice, intelligent diagnostic guidance, and disease warning services. In addition, telemedicine also realizes the seamless connection between medical and pharmaceutical services, enabling patients to conveniently obtain medicines after completing consultation, which is of wide application value, especially among the elderly population and patients with chronic diseases and physical disabilities. However, it also faces challenges, such as the need for reliable Internet connectivity, technical literacy, and concerns over data privacy. Additionally, the inability to conduct physical examinations can limit its effectiveness for certain conditions.

3.2 Internet hospital

3.2.1 Introduction of Internet hospital

Internet hospitals represent a critical modality for realizing telemedicine, functioning as both a practical implementation of telemedicine principles and a technological support. They extend the functional capabilities of physical hospitals into the digital realm, creating a novel medical service platform. Patients can remotely access comprehensive healthcare services via mobile applications, web portals, mini programs, and other digital interfaces of this platform, enabling them to schedule appointments, consult with healthcare providers, assess for diagnoses, obtain electronic prescriptions, and receive home-delivered medications—all from the comfort of their homes, without geographical restrictions. This platform not only enhances accessibility and convenience for patients but also optimizes the efficiency of healthcare delivery by leveraging digital technology to streamline processes and improve patient outcomes [22].

Compared with traditional hospitals, Internet hospitals present obvious differences in terms of service model, operation mechanism and technology application. Traditional hospitals rely on physical space and face-to-face diagnosis and treatment,

emphasizing the direct contact between doctors and patients, which has irreplaceable advantages in the resuscitation of serious illnesses, the treatment of acute illnesses, and complex surgeries. However, it also has drawbacks, particularly in tertiary hospitals, like unequal resource distribution, prolonged patient wait times, and unsatisfactory consultation experiences. From a public health standpoint, the inherent risk of cross-infection and nosocomial transmission—exemplified by the COVID-19 pandemic—further amplifies the overall disease burden and underscores the limitations of traditional care models. Internet hospitals, on the other hand, emphasize the integration of “online + offline”, which reconstructs the way of providing medical services [23]. Through the digital platform, patients can initiate consultation requests at any time, and doctors can complete consultations and prescriptions remotely, greatly enhancing the convenience and efficiency of services.

The development of Internet hospitals around the world has shown a diversified trend, with each country adopting different development paths according to its own healthcare system and technology level. For instance, in the United States (U.S.), the development of Internet hospitals is mainly market-driven, with technological innovations and insurance policies being important drivers of their development. Internet hospitals in the U.S. are usually operated by private companies, providing services such as remote medical consultation, chronic disease management, mental health support, etc. Companies such as Teladoc and Mediguid occupy an important position in the U.S. market. Internet hospitals in the U.S. focus on technological innovation and multi-agency collaboration to improve the accuracy and efficiency of diagnosis and treatment through artificial intelligence and big data analysis. Additionally, U.S. insurance companies are gradually incorporating telemedicine into their insurance coverage, further promoting the development of Internet hospitals [21].

In China, the development of Internet hospitals is strongly supported by government policies. In recent years, China has introduced a series of policies to encourage the development of Internet hospitals in order to alleviate the problem of uneven distribution of medical resources. Internet hospitals in China usually rely on large public hospitals and provide services such as remote diagnosis and treatment, health consulting, and e-prescription through online platforms. Internet companies such as Ali Health and Ping An Health have also been actively involved, driving the rapid development of Internet hospitals. Especially during the COVID-19 pandemic, Internet hospitals played an important role in providing patients with safe and convenient medical services [24]. As of September 2024, there were over 3340 Internet hospitals in China, providing Internet diagnosis and treatment services to more than 100 million people every year [25].

3.3 Practices of internet hospital

In China, most Internet hospitals act as extensions and supplements to physical hospitals. Their functions are similarly divided into pre-consultation, during-consultation, and post-consultation stages. The following sections will provide a detailed introduction to each of these stages.

3.3.1 Pre-consultation

In the pre-consultation stage, Internet hospitals help patients with health management and appointment scheduling through functions such as online health assessment and consultation appointments. When a patient experiences discomfort and visiting

a hospital is inconvenient or time-constrained, they can remotely access the Internet hospital platform through the hospital's WeChat official account. There are two primary features at this phase: Smart Pre-consultation System and Intelligent Triage System. When the patients experience discomfort yet are uncertain of its implications, they can describe their symptoms to the intelligent triage system and the system will suggest which specialty diseases the patient belongs to and what department he should go to, based on the analysis using its AI model and knowledge base. Then the patient will be directed to the smart pre-consultation system where they are asked about their detailed symptoms. A structured pre-electronic medical record (EMR) will be constructed and sent to the patient's assigned doctor so that they can get familiar with the symptoms before the consultation and prepare for them accordingly. After these steps, patients can schedule the consultations or tests they need through the platform and get all the notifications and reminders via the WeChat official account. See **Figure 2** for the workflow of pre-consultation and during-consultation.

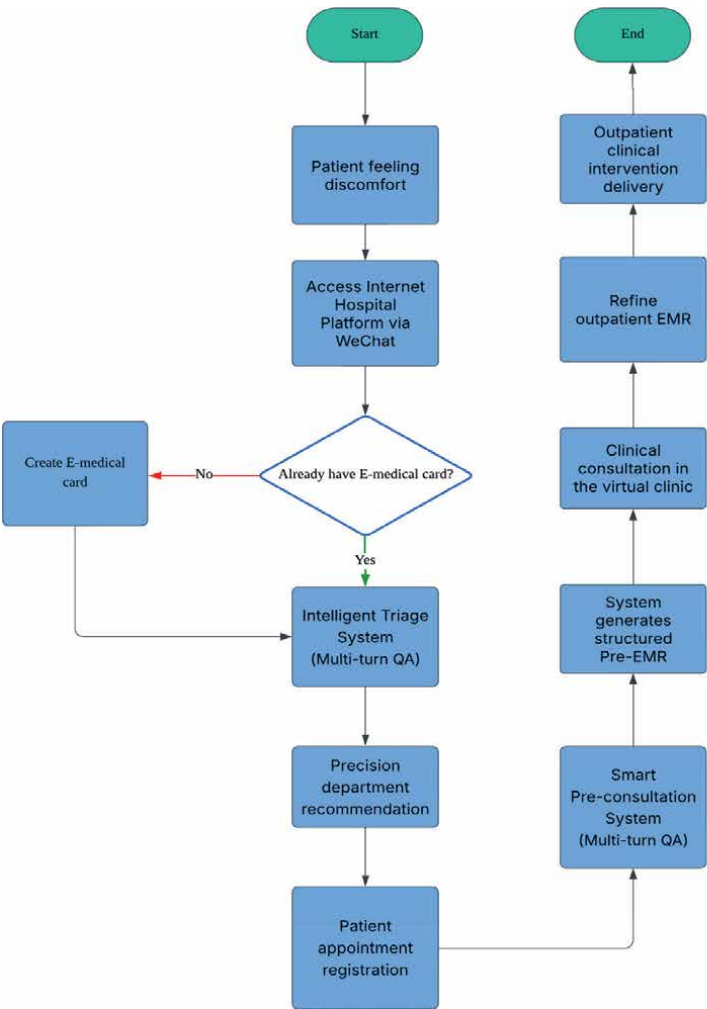


Figure 2.
Pre-consultation and during-consultation workflow.

By reconstructing the initial touchpoints of the patient medical care-seeking procedure through these systems, the Internet hospital provides a solution for the pervasive challenge of “uncertainty in seeking appropriate medical care” inherent in traditional healthcare systems. The implementation of intelligent triage systems enables patients to reduce registration errors stemming from mis-triage while simultaneously optimizing institutional resource allocation by directing specialist physicians’ expertise toward complex cases. Based on the multi-round interactive consultation mechanism realized by AI technology, the intelligent pre-consultation system realizes the automatic collection and structured processing of patient symptom information in the pre-clinical diagnosis and treatment stage, and generates electronic medical record documents that meet medical standards. The core function of the system is to systematically optimize the traditional diagnosis and treatment process through the pre-deployment of the intelligent consultation process, reduce the workload of clinical medical staff, and provide auxiliary decision-making support based on symptom characteristic analysis.

Furthermore, a domain-adapted large-scale AI model is trained exclusively on pediatric disease data to assist in the diagnosis of childhood conditions, ensuring that every pediatric patient receives a precise and tailored evaluation. These innovative medical information technology applications have significantly improved the overall operational efficiency of the medical service system and patient satisfaction under the premise of ensuring the accuracy of clinical data collection. This foundational infrastructure ensures structured clinical workflows and evidence-based decision-making for subsequent diagnostic and therapeutic interventions, thereby enhancing systemic efficiency by reducing unnecessary referrals and improving first-visit diagnostic accuracy.

3.3.2 During-consultation

In the during-consultation stage, Internet hospitals provide patients with comprehensive medical services through remote consultation, multidisciplinary consultation, electronic medical record sharing, and the innovative Remote Medical Accompaniment System.

The cloud-based consultation platform facilitates multimodal physician-patient interactions through text, audio, and video communication channels, while also facilitating structured follow-up visit scheduling, renewing electronic prescriptions for patients with chronic or recurring conditions, and achieving online multidisciplinary consultation for patients with complex diseases. The integration of these features within the during-consultation stage of Internet hospitals signifies a transformative shift in healthcare delivery. The platform enhances clinical accessibility and operational efficiency by enabling remote diagnostic and therapeutic interventions, seamless care coordination among providers, and continuous patient-provider engagement. These capabilities are particularly impactful for managing longitudinal care pathways in chronic disease populations, demonstrating the potential of Internet hospitals to transform conventional care models through technology-mediated service delivery.

A medical record center is available for patients to keep track of the online consultations, prescriptions, laboratory test results, and other relevant medical data. The prescription medications can be delivered directly to the patients’ residences and the payment system is integrated to ensure a satisfying patient experience. The EMR sharing ensures that patients receive comprehensive and coordinated care, improving

diagnostic accuracy and therapeutic outcomes. Moreover, the integration of the medical record center and payment system streamlines the patient experience, alleviating administrative burdens and allowing patients to gain a comprehensive understanding of their consultation statuses. All these features together further exemplify the commitment to patient-centered care, minimizing the need for physical visits and enhancing adherence to treatment plans.

In order to make the consultation process more convenient, a Remote Medical Accompaniment System was created, which is a collaboration model between the patient and his “online companions”. During the medical process, remote video calls, shared workflows, and bill payment assistance are shared with the online companion to help patients complete complex medical procedures. By providing these features, the system ensures that all patients can complete complex medical processes with confidence. For pediatric patients, parents are no longer limited by geographic constraints and can participate in medical consultations with their child remotely. They can join virtual consultation rooms from their workplace, facilitating medical decision-making and managing payments or lab test appointments. Additionally, for the elderly unfamiliar with technology and individuals with visual or hearing impairments, this system provides valuable support, enabling family members or social workers to assist with medical procedures. The collaborative model between patients and their online companions fosters a sense of community and support, bridging the gap between technology and human interaction, which underscores the critical role of adaptive technologies in ensuring equitable access to medical services for vulnerable populations.

The advancements in the during-consultation phase not only enhance healthcare efficiency but also embody a harmonious blend of technological innovation and humanistic care. They represent a significant step forward in creating a more equitable and patient-centered healthcare system, where technology serves as an enabler of compassionate and comprehensive care.

3.3.3 Post-consultation

In the post-consultation phase, Internet hospitals leverage their platforms to facilitate follow-up care and chronic disease management, providing patients with continuous medical support.

Regarding follow-up care, Internet hospitals utilize online platforms to enable physicians to regularly monitor patients’ recovery progress and access their wearable monitor data. Through multimodal follow-up mechanisms, including structured questionnaires, telephonic consultations, and asynchronous messaging, healthcare professionals can efficiently track clinical progress and modify therapeutic interventions as needed. This online follow-up not only enhances the efficiency of medical services but also reduces the burden of in-person visits for patients.

In terms of chronic disease management, the platform focuses on implementing follow-up care for several common chronic diseases, including non-alcoholic fatty liver disease and pediatric oncology. Internet hospitals offer personalized health management plans through which patients receive tailored health advice and lifestyle guidance to better manage their conditions. They also provide medication management services, including medication reminders and delivery, ensuring adherence to prescribed regimens and preventing missed or incorrect dosages. The integration of these services not only enhances the effectiveness of chronic disease management but also significantly improves patients’ quality of life.

The implementation of these post-consultation features within Internet hospitals represents a pivotal advancement in telemedicine. By facilitating continuous follow-up care and chronic disease management, this platform ensures that patients receive ongoing support beyond the initial consultation. This continuity of care is crucial for optimizing rehabilitation outcomes and maintaining patient engagement in their health journey [26]. The integration of these post-consultation services within Internet hospitals not only enhances the efficiency and effectiveness of healthcare delivery but also embodies a holistic approach to patient care.

3.4 Telemedicine in the future

In the future, telemedicine is poised to revolutionize healthcare delivery through innovative concepts such as virtual wards, AI hospital, and remote surgeries. Virtual wards will enable patients to receive hospital-level care within the comfort of their homes, monitored by healthcare professionals through advanced telehealth technologies like IoT, AR/VR, and 5G [27]. There are currently 20 virtual ward beds per 100,000 GP-registered people in England, and it was proven to enhance clinical outcomes and patient satisfaction by preventing hospital admissions and shortening the duration of hospital stays [28]. With advancements in AI agents, initiatives such as Stanford's AI-town "Smallville" and Tsinghua's Agent Hospital demonstrate the feasibility of fully AI-driven hospitals. These AI hospitals offer significant benefits, including enhanced diagnostic accuracy, streamlined operations, and personalized patient care, ultimately leading to improved healthcare efficiency and accessibility [29, 30]. Remote surgery, in particular, offers significant advantages, including access to specialized surgical expertise regardless of location, reduced patient travel, and the potential for quicker response times in critical situations.

Currently, robotic surgery systems such as the da Vinci Surgical System are widely utilized. With advancements in robotics and communication technology, these systems will achieve greater precision and be applicable in a broader range of scenarios [31]. Additionally, while China's Internet hospitals are currently mostly single-centered, the future may see them evolving into multi-hospital networks or even integrating with international healthcare systems. This transformation will transcend national boundaries, facilitating the sharing of global medical resources and enabling patients to receive diagnostic opinions from international experts, thereby accessing high-quality medical services worldwide. The realization of these innovative scenarios and functions will make future telemedicine more efficient, convenient, and globalized, offering patients superior medical services. With continuous technological advancements and policy support, telemedicine will play an increasingly important role in future healthcare systems.

4. Conclusion

This chapter proposes an innovative paradigm of children's active health management and intervention that integrates telehealth and telemedicine services with new cutting-edge technology. This paradigm realizes the innovation of the whole life cycle health management of children aged 0–18 using an "AI digital general practitioner-Internet hospital" collaborative system, promoting comprehensive early childhood development [32].

This system creates a digital management and intervention network that includes early screening, disease prevention, and developmental assessment by utilizing

children's dynamic health profiles that conducts remote monitoring. Multi-Features like online medical treatment, online medication prescriptions, online consultations, and online hospital platform examinations have been made possible on the Internet hospital platform [22, 33]. Intelligent pre-consultation and 24/7 intelligent triage enable accurate registration through analyzing the patient's symptom descriptions [34, 35]. Using on the organic integration of telehealth and telemedicine, this study established a sustainable medical service system for children and caregivers and offered creative and long-lasting solutions to address the issue of unequal distribution of medical resources. The approach has successfully implemented the children's family doctor system through technology empowerment, enabling high-quality medical resources to transcend geographic boundaries and serve more children [20, 36]. With technological advancements, emerging technologies such as augmented reality (AR) and virtual reality (VR) are being increasingly integrated into telehealth and telemedicine fields to enhance medical services' accessibility, interactivity, and clinical outcomes.

In summary, the integration of telemedicine and telehealth represents a significant advancement in the idea of health management and the equitable distribution of medical resources, in addition to a technological advancement in the field of medicine. By bridging the gap between prevention and treatment, this integrated strategy optimizes pediatric health outcomes through technology-driven proactive healthcare, creating a new paradigm for the management and intervention of children's health. The project serves and concentrates on the child population, which makes up 20% of the population and represents 100% of humanity's future.

Acknowledgements

This study was supported by Noncommunicable Chronic Diseases-National Science and Technology Major Project (2023ZD0508705). The authors acknowledge the use of ChatGPT, Deepseek, and QuillBot AI for language polishing of this manuscript, with the entire process supervised and refined by the authors.

Conflict of interest

The authors declare no conflict of interest.

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Section 3

Emerging Concepts in Digital Health

The Role of Tertiary Care in the Digital and Green Transformation of Health Systems

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Abstract

Tertiary care centers play a crucial role in the digital and green transformation of healthcare systems, especially in the context of controlling infectious diseases. The integration of digital technologies, such as telemedicine and artificial intelligence (AI), enhances disease surveillance, diagnosis, and patient management, thereby improving responsiveness to infectious outbreaks. Telemedicine facilitates remote consultations, reducing hospital crowding and exposure risks, while AI-driven systems enable faster and more accurate detection of infectious diseases, optimizing treatment protocols. Simultaneously, green practices, including energy-efficient infrastructure, sustainable waste management, and water conservation, reduce the environmental impact of healthcare facilities and minimize the spread of infection. The synergy between digital and green strategies strengthens the overall resilience of tertiary care in managing infectious diseases, fostering both healthcare efficiency and sustainability. This combined approach not only improves infection control but also contributes to the long-term sustainability and effectiveness of health systems globally.

Keywords: tertiary care, digital transformation, telemedicine, artificial intelligence, green transformation, infectious diseases, sustainability, healthcare systems, disease surveillance, infection control

1. Introduction

Tertiary care represents the pinnacle of healthcare delivery systems, focusing on specialized and complex medical services provided by highly trained specialists in advanced facilities. These institutions manage the most challenging cases, including severe illnesses, rare conditions, and complicated surgical interventions, forming the backbone of healthcare in both developed and developing countries [1–3]. In the broader health ecosystem, tertiary care plays a critical role not only in patient care but also in research, education, and system-wide innovation. It serves as a hub for technological advancement and quality improvement in healthcare practices [1–5].

Globally, the healthcare landscape is undergoing significant transformations, marked by two overarching trends: digital innovation and sustainability. Digital transformation encompasses the integration of cutting-edge technologies, such as artificial intelligence (AI), big data analytics, telemedicine, and electronic health records (EHR), which collectively aim to improve patient outcomes, enhance operational efficiency, and increase accessibility. Concurrently, sustainability has emerged as a pressing concern, driven by the need to reduce the environmental impact of healthcare delivery [4, 6]. Hospitals and healthcare systems are now embracing green practices, from renewable energy use to sustainable waste management, recognizing their responsibility in combating climate change.

Tertiary care facilities, given their size, resources, and influence, are uniquely positioned to lead these dual transformations. These institutions often act as centers of excellence, piloting new technologies and implementing sustainable practices that set benchmarks for the broader healthcare system. For instance, the adoption of telemedicine platforms in tertiary care has not only streamlined specialist consultations but has also reduced the carbon footprint associated with patient travel. Similarly, green building designs and energy-efficient infrastructures in tertiary hospitals are shaping a more sustainable approach to healthcare delivery [5–7].

The relevance of tertiary care in adapting to these changes cannot be overstated. In the realm of digital transformation, tertiary hospitals are at the forefront of integrating AI in diagnostics, using big data for predictive analytics, and personalizing medicine through genomics. These advancements not only improve patient care but also influence secondary and primary care providers, creating a ripple effect of innovation. On the sustainability front, tertiary care institutions are addressing healthcare's environmental impact through initiatives such as reducing waste, minimizing energy consumption, and promoting awareness of the health implications of climate change [1, 5–7].

However, the dual challenge of digital and green transformation is not without obstacles. High implementation costs, the need for workforce training, and ensuring equitable access to advanced care are some of the barriers faced by tertiary institutions. Despite these challenges, their central role in healthcare systems makes them indispensable in driving these changes. By aligning with global trends and leveraging their expertise, tertiary care facilities are poised to lead the healthcare sector into a future that is both technologically advanced and environmentally sustainable [7–9].

This chapter explores the intersection of digital and green transformation within tertiary care, emphasizing its critical role in reshaping health systems for the modern era.

2. The current landscape of tertiary care

Tertiary care represents the highest level of specialized medical services within a healthcare system, focusing on complex cases that require advanced technology, expertise, and infrastructure. It plays a critical role in managing severe diseases, offering advanced diagnostics, performing intricate surgical interventions, and providing critical care for life-threatening conditions. Despite its pivotal role, tertiary care is resource-intensive and poses significant challenges in terms of sustainability and operational efficiency. However, the landscape of tertiary care is evolving, driven by opportunities for digital transformation and green innovation, which promise to reshape its operations and reduce its environmental footprint [9].

2.1 Role in providing specialized, advanced care

Tertiary care is essential for addressing the most challenging and intricate health conditions that go beyond the capabilities of primary and secondary care. Its primary function is to offer specialized services that rely on advanced technology and highly skilled professionals. This includes:

2.1.1 Cutting-edge diagnostic services

Tertiary care facilities are equipped with state-of-the-art diagnostic tools such as MRI, CT, and PET scanners, along with molecular and genetic testing capabilities. These tools allow for the precise identification of diseases like cancer, neurological disorders, and cardiovascular conditions, enabling the creation of tailored treatment plans that improve patient outcomes [4, 7, 10].

2.1.2 Sophisticated surgical interventions

Hospitals at the tertiary level perform highly specialized surgeries, such as organ transplants, cardiac surgeries, and robotic-assisted procedures. These surgeries require advanced equipment and expert teams, often employing technologies like 3D imaging, virtual reality simulations, and minimally invasive techniques to improve surgical precision and reduce recovery times.

2.1.3 Critical care for severe cases

Intensive care units (ICUs) in tertiary hospitals are designed to handle the most critical patients, offering advanced monitoring systems, ventilators, and life-support technologies. These units cater to conditions such as severe trauma, multi-organ failure, and acute respiratory distress syndrome, providing life-saving interventions around the clock [11–13].

2.1.4 Management of chronic and rare diseases

Tertiary care also excels in the long-term management of chronic illnesses, such as diabetes, cancer, and heart failure, as well as rare diseases that require multidisciplinary teams and experimental therapies. Clinical trials and research at tertiary centers often provide hope for patients with conditions that lack standardized treatments [4, 6, 9].

These functions underscore the indispensable role of tertiary care in modern healthcare systems. However, its extensive reliance on advanced technologies, infrastructure, and personnel brings about challenges that demand immediate attention and innovative solutions.

3. The role of telemedicine in tertiary care

Telemedicine has emerged as a transformative force in modern healthcare, particularly in tertiary care, where it offers advanced and specialized medical services. By leveraging technology to deliver healthcare remotely, telemedicine not only enhances access to specialized care but also streamlines operations, reduces costs,

and minimizes environmental impact. Telemedicine has become an indispensable component of tertiary care, bridging critical gaps in access to specialized services while enhancing operational efficiency and reducing costs. By enabling remote consultations, it empowers patients in underserved regions to connect with expert care, improves the management of postoperative and chronic conditions, and reduces the environmental impact of healthcare delivery [13–16].

Incorporating telemedicine into tertiary care is not just a technological advancement but a paradigm shift that aligns with the goals of equitable, efficient, and sustainable healthcare. As telemedicine continues to evolve, its integration with emerging technologies such as artificial intelligence and remote monitoring devices will further enhance its potential, making it an essential tool for addressing the complex challenges of modern healthcare systems [16–18].

3.1 Expanding access to specialized care

3.1.1 How telemedicine bridges gaps for remote and underserved populations

Access to specialized care has traditionally been a challenge for patients in remote, rural, or underserved regions. Tertiary care facilities, often concentrated in urban centers, are not easily accessible to these populations due to geographical, financial, or infrastructural barriers. Telemedicine addresses this disparity by connecting patients with specialists through virtual platforms [13–15].

For instance, telemedicine enables consultations with cardiologists, neurologists, and oncologists without requiring patients to travel long distances. This is especially critical for individuals in remote areas where such expertise is otherwise unavailable. By eliminating the need for physical presence, telemedicine reduces the time, cost, and logistical challenges associated with accessing advanced care. Furthermore, it empowers local healthcare providers by offering real-time access to expert guidance, allowing them to deliver better care at the community level [13–19].

Additionally, telemedicine can play a significant role in emergency situations. For example, telestroke programs have been implemented in many tertiary care systems to ensure timely treatment for stroke patients in rural hospitals. Through video consultations, specialists can quickly assess patients, recommend interventions, and facilitate transfers if needed, significantly improving outcomes [19–22].

3.1.2 Telemedicine and infectious disease control

Telemedicine is a cornerstone of digital transformation in healthcare and plays a pivotal role in infectious disease management. It allows for real-time remote consultations, reducing the need for patients to visit hospitals and thus preventing potential exposure to infectious diseases in crowded clinical settings. During pandemics like COVID-19, telemedicine has enabled healthcare professionals in tertiary care centers to continue monitoring patients, providing timely medical advice, and diagnosing symptoms without requiring direct contact, thus limiting the spread of infection [13].

Furthermore, telemedicine facilitates global outreach, enabling tertiary care facilities to offer expertise to underserved or remote areas, which is critical in managing infectious diseases that may otherwise go unnoticed or untreated in these regions. Through teleconsultations, healthcare providers can assist in diagnosing and treating infectious diseases, preventing outbreaks from spreading beyond the local level [15].

3.1.3 Virtual consultations for post-operative care and chronic disease management

Tertiary care facilities often handle complex surgical procedures and advanced treatments for chronic diseases. Post-operative care and the management of chronic conditions such as diabetes, heart failure, and cancer require ongoing monitoring and follow-up, which can be burdensome for patients and healthcare systems [3–5, 9–12, 18].

Telemedicine provides a solution through virtual consultations, enabling patients to receive high-quality follow-up care from the comfort of their homes. For instance, post-operative patients can connect with their surgeons or care teams to discuss recovery progress, address concerns, and receive guidance without making repeated trips to the hospital. This reduces the physical and emotional strain on patients, particularly those who may still be in recovery [17].

Similarly, for chronic disease management, telemedicine facilitates regular check-ins with specialists, medication reviews, and lifestyle counseling. Remote monitoring technologies, such as wearable devices and mobile health apps, can transmit real-time health data (e.g., blood pressure and glucose levels) to tertiary care teams, allowing for proactive interventions. This not only enhances patient engagement and adherence but also helps prevent complications, reducing the need for emergency visits or hospital readmissions [18].

3.2 Efficiency and cost reduction

3.2.1 Reducing patient travel emissions and healthcare facility congestion

Telemedicine has significant environmental and operational benefits, making it a key driver of efficiency in tertiary care. One of its most notable advantages is the reduction of patient travel emissions. Traditional healthcare delivery models often require patients to travel long distances to access tertiary care services, contributing to carbon emissions and environmental degradation. Telemedicine eliminates the need for many of these journeys by enabling remote consultations [20].

For example, studies have shown that replacing in-person visits with telemedicine consultations can significantly reduce greenhouse gas emissions associated with patient transportation. This is particularly relevant in countries where healthcare facilities are centralized, and patients routinely travel hundreds of kilometers for specialist care. By reducing these emissions, telemedicine contributes to the broader goal of creating sustainable healthcare systems [21].

Furthermore, telemedicine alleviates congestion in healthcare facilities. Tertiary care centers are often overburdened with high patient volumes, leading to long waiting times and strained resources. Virtual consultations help streamline workflows by triaging patients more effectively and prioritizing those who require in-person care. This allows healthcare providers to allocate their time and resources more efficiently, improving the overall quality of care.

Telemedicine also reduces the indirect costs associated with hospital visits, such as missed workdays and childcare expenses for patients and their families. For healthcare systems, the decreased demand for physical infrastructure—such as waiting rooms, parking spaces, and administrative staff—translates into cost savings. These efficiencies are especially important as tertiary care systems face increasing financial pressures and growing patient populations [22].

4. Artificial intelligence in tertiary care

Artificial intelligence (AI) is transforming the landscape of tertiary healthcare by enabling precision, efficiency, and sustainability. Tertiary care, which provides advanced medical treatments such as specialized surgeries, oncology services, and critical care, is often resource-intensive [18]. The integration of AI offers innovative solutions to address these challenges while enhancing patient outcomes and promoting operational sustainability. Artificial intelligence is revolutionizing tertiary care, enabling predictive analytics, operational efficiencies, enhanced patient outcomes, and sustainable practices. By leveraging AI, tertiary care facilities can not only improve their ability to manage complex cases but also contribute to the broader goals of healthcare efficiency and environmental stewardship. As technology continues to evolve, the integration of AI in tertiary care will remain a cornerstone of modern healthcare systems, driving innovation and sustainability in equal measure [23].

Below, we explore the critical applications of AI in predictive analytics, operational efficiencies, precision medicine, and sustainable healthcare practices.

4.1 Predictive analytics and decision support

One of AI's most transformative contributions to tertiary care is its role in predictive analytics and clinical decision support. Tertiary care facilities often manage complex patient cases where early and accurate diagnosis can significantly improve outcomes. AI algorithms, particularly those powered by machine learning, analyze vast amounts of patient data to identify patterns that may not be immediately apparent to human clinicians [24].

4.2 Early detection of diseases

Cancer: AI-powered tools, such as those using convolutional neural networks (CNNs), are revolutionizing early cancer detection by analyzing radiological images like X-rays, CT scans, and MRIs with remarkable accuracy. For example, AI systems can identify lung nodules or breast lesions with a sensitivity and specificity comparable to or exceeding that of experienced radiologists. This early detection reduces the burden on tertiary care by allowing for timely intervention [25].

Sepsis: In critical care settings, sepsis is a leading cause of mortality. AI algorithms can monitor vital signs and laboratory results in real time, predicting the onset of sepsis hours before clinical symptoms manifest. This early warning enables rapid intervention, significantly improving survival rates.

4.3 Artificial intelligence in infectious disease surveillance and diagnosis

AI is another transformative tool with significant implications for controlling infectious diseases. AI-powered systems can process vast amounts of data to detect early warning signs of infectious disease outbreaks. By analyzing patterns in health data, AI can predict potential hotspots for disease transmission, allowing healthcare providers to allocate resources efficiently and initiate preventive measures. In the context of tertiary care, AI tools can enhance diagnostics by analyzing imaging, laboratory results, and patient data, enabling faster and more accurate identification of infectious diseases like tuberculosis, pneumonia, or emerging pathogens [26].

Moreover, AI-driven algorithms can help in tracking disease progression in patients, providing real-time insights into patient conditions. This helps in decision-making, ensuring that patients receive timely interventions and reducing the risk of disease spread within hospitals and other healthcare settings. AI can also be leveraged to personalize treatments, making healthcare responses more effective in managing infectious diseases in diverse populations [27].

4.4 Decision support systems

AI assists clinicians by offering evidence-based recommendations tailored to individual patients. For instance, decision-support systems in oncology can propose personalized treatment plans based on tumor genetics, patient history, and clinical guidelines. This reduces variability in care delivery and ensures that patients receive the most effective therapies [28].

4.5 Operational efficiencies

Tertiary care centers are often large, complex institutions that require meticulous management of resources, staff, and infrastructure. AI-driven solutions are streamlining these processes, enhancing operational efficiencies, and reducing costs [28].

4.6 Resource management

AI can predict resource demand, such as the availability of ICU beds, medical equipment, or blood supplies, by analyzing historical data and current trends. This ensures that resources are allocated optimally, preventing shortages or waste [29].

4.7 Staff scheduling

Workforce management is a significant challenge in tertiary care, where staff shortages or overstaffing can impact both care quality and costs. AI-driven scheduling tools use predictive algorithms to forecast patient volumes and adjust staff schedules accordingly. This ensures adequate staffing levels while minimizing burnout and inefficiencies [30–34].

4.8 Energy usage optimization

Hospitals are among the largest consumers of energy, contributing to significant operational costs and environmental impact. AI systems can monitor and control energy usage by analyzing data from heating, ventilation, and air conditioning (HVAC) systems, lighting, and medical equipment. For example, AI can optimize heating and cooling systems in real time, ensuring patient comfort while minimizing energy consumption.

4.9 Enhancing patient outcomes

AI is playing a pivotal role in advancing patient outcomes in tertiary care by driving innovation in precision medicine, robotic surgery, and personalized treatment planning.

4.10 Precision medicine

Precision medicine, which tailors treatments to individual patients based on genetic, environmental, and lifestyle factors, is a cornerstone of tertiary care. AI accelerates this approach by analyzing large-scale genomic data to identify genetic mutations associated with diseases. For instance, AI tools can help oncologists match cancer patients with the most effective targeted therapies, improving survival rates and reducing unnecessary treatments [31].

4.11 Robotic surgeries

Robotic-assisted surgeries, powered by AI, enhance surgical precision and minimize risks. These systems provide real-time feedback to surgeons, enabling them to perform complex procedures with unparalleled accuracy. For example, robotic platforms like the da Vinci Surgical System are used in urological, gynecological, and cardiac surgeries, reducing complications and speeding up recovery times.

4.12 Tailored treatment plans

AI algorithms integrate diverse data sources—such as EHRs, imaging studies, and lab results—to create personalized treatment plans. For example, in cardiology, AI systems can predict the likelihood of adverse events like heart attacks or strokes, guiding clinicians in tailoring interventions to mitigate risks.

4.13 AI for sustainability

Sustainability in healthcare is an increasingly critical goal, and AI offers innovative solutions to reduce the environmental impact of tertiary care facilities.

4.14 Energy efficiency and waste reduction

As mentioned earlier, AI optimizes energy consumption by monitoring and adjusting hospital systems in real time. Hospitals leveraging AI for energy management have reported significant reductions in their carbon footprints without compromising patient care. Tertiary care generates substantial waste, including single-use medical supplies and packaging. AI-powered systems can analyze procurement and usage patterns to minimize waste, promoting a circular economy. For instance, algorithms can recommend reprocessing of medical devices where safe and feasible. AI tools help hospitals identify eco-friendly suppliers and products by evaluating lifecycle data on medical equipment and consumables. This enables tertiary care centers to adopt greener practices while maintaining quality standards.

4.15 Optimizing energy consumption, waste reduction, and green logistics in tertiary care

Healthcare supply chains are complex and often inefficient. AI-driven logistics platforms can optimize supply chain operations by predicting demand, reducing

unnecessary shipments, and minimizing the environmental impact of transportation. Energy usage in tertiary care facilities accounts for a significant portion of operational costs and environmental impact. AI-powered energy management systems analyze data from various sources, such as building sensors, patient flow, and weather conditions, to optimize energy usage in real time [35–38]. AI can manage HVAC systems to adjust temperatures and ventilation based on occupancy levels and weather forecasts. For instance, AI algorithms can ensure that only occupied areas are heated or cooled, reducing wastage. AI helps manage energy inputs from renewable sources like solar panels by balancing the grid load and minimizing reliance on non-renewable energy during peak hours. Medical waste is a critical issue in tertiary care, contributing to environmental degradation and public health risks. AI offers solutions for waste management. AI systems analyze consumption patterns of medical supplies and forecast future demand, preventing over-ordering and reducing unused inventory waste. AI-powered waste segregation systems use computer vision to identify and sort recyclable, hazardous, and general waste, improving recycling rates and reducing landfill contributions [39–42]. AI tools can identify which single-use medical devices can safely be reprocessed and reused, ensuring compliance with safety protocols. AI is transforming logistics by streamlining supply chain operations and reducing the carbon footprint associated with medical equipment, pharmaceuticals, and consumables. Also, it optimizes delivery routes for medical supplies, reducing fuel consumption and emissions. AI predicts stock requirements accurately, preventing excess deliveries and storage inefficiencies. AI helps tertiary care facilities collaborate with green logistics providers that utilize electric or low-emission vehicles [43, 44].

4.16 Green practices in managing infectious disease spread

Green transformation, which focuses on sustainability, is also integral to controlling infectious diseases. Hospitals and healthcare settings are often energy-intensive environments, contributing to pollution and carbon emissions [45–59]. However, adopting green practices—such as utilizing renewable energy sources, reducing medical waste, and improving waste management systems—can create a cleaner and safer environment, minimizing the spread of infection [45–69].

Green practices also extend to water management, which is critical in preventing waterborne diseases. Hospitals that incorporate water-efficient technologies and sustainable infrastructure can reduce the risk of contamination through inadequate sanitation systems. Furthermore, eco-friendly procurement policies that focus on sustainable, non-toxic medical supplies ensure that hazardous chemicals and materials do not contribute to harmful environmental impacts or increase the risk of infections [69–79].

5. Digital transformation in tertiary care

Digital transformation in tertiary care is reshaping the delivery of specialized healthcare by integrating advanced technologies. This paradigm shift enhances the efficiency, accessibility, and sustainability of health services. Digital transformation in tertiary care, driven by technologies like EHRs, automation, robotics, Virtual Reality (VR), Augmented Reality (AR), and big data analytics, is redefining the landscape of advanced healthcare. These innovations not only enhance clinical outcomes and

operational efficiency but also contribute to the sustainability of health systems [80–88]. By integrating EHRs with interoperable systems, tertiary care facilities improve patient safety and reduce administrative burdens. Automation and robotics streamline workflows and elevate surgical precision, while VR and AR revolutionize training and rehabilitation. Meanwhile, big data analytics unlocks insights that optimize treatment protocols and resource management. As digital technologies continue to evolve, their role in tertiary care will expand, driving advancements in patient care, staff training, and sustainability. Embracing these innovations ensures that tertiary care remains at the forefront of healthcare transformation, addressing the growing demands of an aging population, complex medical conditions, and the need for eco-friendly practices.

Central to this transformation are key tools such as electronic health records (EHR), automation, robotics, Virtual Reality (VR), Augmented Reality (AR), and big data analytics. These technologies empower tertiary care facilities to improve patient outcomes, optimize workflows, and reduce operational costs.

5.1 Electronic health records (EHR) and interoperability

5.1.1 Benefits of integrated health information systems

EHRs are a cornerstone of digital transformation in tertiary care, enabling comprehensive, accessible, and secure documentation of patient data. Unlike traditional paper-based systems, EHRs facilitate real-time access to medical records, improving coordination among healthcare providers.

Interoperability, the ability of different healthcare systems to share and use information seamlessly, magnifies the benefits of EHRs. In tertiary care settings, where patients often require input from multiple specialists, interoperable systems ensure continuity of care. For instance, a cardiologist, oncologist, and surgeon treating a single patient can access the same up-to-date medical records, reducing the risk of redundant tests or conflicting treatments [33].

Integrated EHR systems also enhance patient safety. Automated alerts within these systems flag potential drug interactions, allergies, or deviations from standard treatment protocols. Furthermore, they support telemedicine by enabling remote providers to access patient histories during virtual consultations. The use of EHRs and interoperable systems has economic advantages. By reducing administrative burdens, eliminating unnecessary procedures, and minimizing errors, hospitals can allocate resources more efficiently. This is particularly crucial in tertiary care, where the costs and complexity of treatments are higher than in primary or secondary care settings [28].

5.1.2 Automation and robotics: Streamlining repetitive tasks and enhancing surgical precision

Automation and robotics play a transformative role in tertiary care by improving operational efficiency and clinical outcomes. Automation systems streamline repetitive tasks such as patient scheduling, billing, and supply chain management. These efficiencies free up healthcare staff to focus on direct patient care. For example, automated medication dispensing systems in tertiary hospitals reduce errors and ensure timely delivery of prescriptions [67].

In clinical settings, robotics has revolutionized surgical procedures. Robotic-assisted surgeries, such as those performed with the da Vinci Surgical System, offer

unparalleled precision, reduced recovery times, and lower risks of complications. These systems allow surgeons to perform minimally invasive procedures with greater dexterity and control, translating into better patient outcomes. Robotics also contributes to rehabilitation in tertiary care. For instance, robotic exoskeletons are increasingly used to help patients regain mobility after spinal cord injuries or strokes. Additionally, robotic technologies are being employed in diagnostics, such as automated pathology scanners that analyze tissue samples with high accuracy and speed. By automating routine and repetitive tasks, tertiary care facilities can reduce operational costs and enhance overall efficiency. Robotics not only improves the quality of care but also supports sustainability by optimizing resource usage, such as energy and materials, in healthcare processes [23–33].

5.1.3 Virtual reality (VR) and augmented reality (AR)

Virtual Reality (VR) and Augmented Reality (AR) are groundbreaking technologies that have found significant applications in tertiary care. These tools are particularly valuable for medical training, surgical planning, and patient education.

In training, VR creates immersive, simulated environments where healthcare professionals can practice complex procedures without risks to real patients. For example, surgeons can use VR to rehearse intricate operations, such as organ transplants or neurosurgery, in a controlled setting. This hands-on experience improves their skills and confidence before performing procedures in real life.

AR enhances real-time guidance during surgeries. By overlaying digital images onto the physical surgical field, AR provides surgeons with critical information, such as anatomical structures, tumor margins, or blood vessel pathways, without the need to look away from the operative area. This technology has been successfully used in orthopedic surgeries, where precise alignment of bones and implants is crucial.

Beyond training and surgery, VR and AR play a role in patient rehabilitation and education. Patients undergoing physical therapy can use VR systems to engage in interactive exercises, improving motivation and adherence to treatment plans. AR applications can also help patients understand their conditions better by visualizing their anatomy and treatment options in a user-friendly manner.

The adoption of VR and AR in tertiary care not only improves clinical outcomes but also enhances the learning curve for new technologies, making healthcare systems more adaptive to future innovations.

6. Big data analytics: Using data to optimize treatment protocols and operational workflows

Big data analytics is a game-changer in tertiary care, offering the ability to process and analyze vast amounts of healthcare data to generate actionable insights. Tertiary care facilities generate enormous volumes of data from EHRs, imaging systems, laboratory results, and wearable devices. Harnessing this data helps optimize treatment protocols and streamline operations [13–16]. In clinical decision-making, big data analytics enables predictive modeling, identifying patients at risk for complications or readmissions. For example, algorithms can analyze trends in a patient's vitals to predict the onset of sepsis, allowing for timely interventions. Similarly, cancer treatment protocols can be tailored using data-driven insights from genomic analyses and

clinical trial results, paving the way for personalized medicine. Operationally, big data analytics improves resource allocation. By analyzing historical patient admissions and procedure trends, hospitals can predict staffing needs, bed availability, and equipment usage. This ensures that resources are used efficiently, reducing waste and improving patient flow. Analytics also supports population health management by identifying patterns in chronic disease prevalence, enabling tertiary care facilities to design targeted outreach programs. For instance, analyzing data from patients with diabetes can reveal gaps in care, prompting early interventions to prevent complications [8, 12–15].

Moreover, big data contributes to sustainability. By optimizing workflows and reducing redundancies, analytics can minimize the carbon footprint of tertiary care operations. For example, data-driven energy management systems can identify peak usage times and adjust power consumption accordingly, reducing environmental impact.

6.1 Green transformation in tertiary care

The healthcare sector, especially tertiary care facilities, is a critical player in the transition toward sustainability. Hospitals and tertiary care centers are energy-intensive and resource-demanding environments, leading to significant ecological footprints. However, the global emphasis on sustainability and environmental stewardship has prompted many healthcare providers to adopt “green” practices to reduce their environmental impact. The green transformation of tertiary care focuses on sustainable hospital infrastructure, efficient resource utilization, eco-friendly supply chains, and effective waste management. These practices not only support environmental health but also enhance the operational efficiency and long-term viability of healthcare institutions [15–18].

6.1.1 Sustainable hospital infrastructure

Sustainable hospital infrastructure is a cornerstone of green transformation in tertiary care. Tertiary hospitals often have complex, large-scale operations that consume vast amounts of energy, water, and resources. The goal of incorporating sustainable infrastructure is to minimize environmental impact while maintaining a high level of patient care.

6.1.1.1 Incorporating renewable energy sources

A key strategy for sustainable hospital infrastructure is the use of renewable energy sources. Hospitals have a continuous demand for energy due to their 24/7 operations, which include critical care units, imaging systems, and lighting. Integrating renewable energy sources, such as solar panels, wind turbines, and geothermal systems, into hospital design can significantly reduce reliance on non-renewable, grid-based electricity. For instance, the installation of solar photovoltaic systems on rooftops or parking structures can help hospitals generate their own clean energy, offsetting the use of fossil fuels. Geothermal energy can be employed for heating and cooling systems, reducing energy consumption in a cost-effective and environmentally friendly manner [6, 8, 9].

Hospitals can also explore energy storage systems, such as battery storage, to ensure consistent energy availability even during peak demand or times of low

renewable energy generation. These systems help hospitals reduce their carbon footprint by relying on clean energy sources while reducing their dependence on conventional power grids that may have a high carbon intensity.

6.1.1.2 Eco-friendly building designs

Eco-friendly building designs are another vital aspect of sustainable hospital infrastructure. Hospitals designed with green building principles in mind, such as those certified by LEED (Leadership in Energy and Environmental Design), prioritize energy and water conservation, natural lighting, indoor air quality, and the use of sustainable materials. For instance, buildings with improved insulation and high-efficiency windows reduce heating and cooling demands, leading to lower energy consumption. The use of low-VOC (volatile organic compound) paints, materials, and finishes ensures better indoor air quality for patients and healthcare workers.

Hospitals are also adopting green roofs and urban greening initiatives that help manage stormwater runoff, improve air quality, and provide natural spaces for patients and staff to relax and recover. These environmentally sustainable designs contribute to the health and well-being of both patients and the surrounding community.

6.1.2 Efficient resource utilization

Efficient resource utilization is critical in tertiary care settings, where the consumption of resources such as water, energy, and raw materials is high. Implementing energy-efficient and water-conserving technologies can drastically reduce a hospital's environmental footprint.

6.1.2.1 Water conservation

Water is a vital resource for healthcare facilities, used in various medical procedures, sanitation, and even for patient care. Hospitals are major consumers of water, and given the increasing global water scarcity, hospitals must adopt water conservation strategies. One approach is the installation of water-efficient fixtures, such as low-flow faucets, showerheads, and toilets, which can significantly reduce water consumption without compromising functionality. Hospitals can also implement water recycling systems, such as graywater reuse systems, that treat and recycle water from sinks and showers for non-potable uses like landscape irrigation or cooling systems. Rainwater harvesting systems are another sustainable practice where rainwater is collected, filtered, and stored for use in non-critical applications. Energy-efficient water heating systems, such as solar water heaters or heat pump systems, can be used to reduce the energy consumption associated with water heating. These technologies help tertiary care facilities reduce both water and energy use simultaneously, lowering operational costs and reducing environmental impact.

6.1.2.2 Energy-efficient systems

Hospitals are often characterized by high energy demands, especially in tertiary care centers with multiple specialty units, operating rooms, and diagnostic imaging equipment. Energy-efficient technologies are crucial in minimizing this energy

consumption and reducing greenhouse gas emissions. Hospitals can integrate building management systems (BMS) that optimize heating, ventilation, and air conditioning (HVAC) systems. Smart sensors and automation allow for more efficient temperature regulation by adjusting heating and cooling levels based on occupancy, external weather conditions, and time of day. LED lighting systems with motion sensors can also contribute to energy savings by ensuring that lights are on only when needed. Additionally, energy-efficient medical equipment and appliances, such as low-power MRI machines and energy-saving sterilization units, can significantly reduce the overall energy demand of a hospital.

6.1.3 Green supply chain and procurement

A hospital's supply chain plays a critical role in its sustainability efforts, as procurement decisions can have significant environmental impacts. By prioritizing eco-friendly procurement practices, hospitals can reduce their environmental footprint and support sustainable industries.

6.1.3.1 Eco-friendly medical supplies

One of the most impactful strategies for creating a green supply chain is the procurement of eco-friendly medical supplies. Hospitals can shift toward buying products made from sustainable, recyclable, and biodegradable materials. For example, reusable medical devices like surgical instruments and examination tools can reduce waste compared to disposable alternatives. Hospitals can also invest in medical supplies that are produced with less environmental impact, such as packaging made from recycled materials or products manufactured using energy-efficient processes.

Additionally, sourcing pharmaceuticals from companies that employ environmentally responsible manufacturing and packaging practices can contribute to a hospital's green procurement goals. Reducing single-use plastics in hospital settings is also a critical step toward reducing the overall environmental burden of medical supply chains.

6.1.3.2 Minimizing transportation emissions

The transportation of goods, including medical supplies, equipment, and pharmaceuticals, contributes to the carbon footprint of hospitals. Reducing transportation emissions involves sourcing products locally whenever possible to minimize long-distance shipping and its associated environmental costs. Hospitals can also work with suppliers that use electric or low-emission vehicles for deliveries, further reducing the transportation-related carbon footprint.

Hospitals can explore centralized purchasing models that streamline supply chains and reduce unnecessary deliveries, ensuring that products are delivered in bulk or in more efficient, consolidated shipments.

6.1.4 Waste management

Effective waste management is a significant part of any green transformation strategy in healthcare. Tertiary care centers generate a variety of waste, including hazardous waste (e.g., infectious materials), non-hazardous waste (e.g., medical

packaging), and general waste from daily operations. A comprehensive waste management strategy aims to minimize waste generation, maximize recycling, and ensure the safe disposal of hazardous materials.

6.1.4.1 Recycling

Recycling programs in hospitals can divert a significant amount of waste from landfills. Hospitals can establish recycling stations in common areas, making it easier for staff to separate recyclable materials from non-recyclables. Cardboard, paper, glass, and plastic can be sorted and sent to recycling facilities, while metals like aluminum can be collected and repurposed for other uses. Hospitals can also ensure that medical packaging, such as glass vials or plastic bottles, is properly sorted and recycled.

6.1.4.2 Reducing hazardous waste

Hazardous waste, such as used needles, contaminated gloves, and certain pharmaceutical products, requires careful handling and disposal. Hospitals must invest in systems to reduce the generation of hazardous waste, such as adopting reusable instruments and reducing the use of harmful chemicals where possible. In some cases, hospitals may partner with specialized waste disposal companies to ensure that hazardous waste is incinerated or treated in an environmentally responsible manner.

6.1.4.3 Innovative disposal methods

Innovative disposal technologies, such as autoclaving (sterilizing) medical waste, can help reduce the environmental impact of healthcare waste. New technologies in waste-to-energy systems, where non-recyclable waste is converted into usable energy, are also becoming more widely adopted in hospitals looking to reduce waste sent to landfills.

7. Bridging digital and green goals in tertiary care

As healthcare systems around the world strive to meet the demands of a growing and aging population, the integration of digital technologies and sustainability practices has emerged as a critical solution. In tertiary care, which provides advanced and specialized medical services, bridging the goals of digital transformation and environmental sustainability presents unique opportunities and challenges. This chapter explores how the synergistic application of digital technologies, particularly Artificial Intelligence (AI) and Telemedicine, can contribute to reducing emissions and waste in tertiary care settings, as well as the challenges involved in achieving a balanced implementation of these technologies [89–95].

7.1 Synergizing digital technologies with sustainability efforts

The concept of “synergizing” digital technologies and sustainability in tertiary care means that the two objectives—technological advancement and environmental

responsibility—are not mutually exclusive but rather can be integrated to mutually enhance each other. Digital tools like AI, Big Data, and Telemedicine are revolutionizing how care is delivered, improving patient outcomes and operational efficiencies. At the same time, these same technologies have the potential to significantly reduce the environmental impact of healthcare facilities.

AI plays a pivotal role in this synergy. For example, AI-powered predictive analytics can optimize energy usage in hospitals by analyzing data on patient flows, equipment usage, and environmental factors to regulate heating, ventilation, and air conditioning (HVAC) systems more efficiently. AI can also support smart building technologies that automatically adjust lighting, heating, and cooling based on the real-time needs of a healthcare facility. This data-driven approach reduces energy consumption, lowers operational costs, and minimizes the carbon footprint of tertiary care centers.

Additionally, the use of AI in clinical care can reduce unnecessary resource consumption. For instance, AI can assist in diagnostic decision-making, helping to avoid the overuse of expensive and energy-intensive imaging modalities like CT scans or MRIs. By improving the accuracy of diagnoses and predicting patient needs more effectively, AI helps optimize resource allocation, ensuring that only necessary treatments and interventions are delivered, further reducing waste.

7.2 How telemedicine and AI contribute to reducing emissions and waste

Telemedicine and AI, when applied thoughtfully in tertiary care, can make a substantial contribution to both reducing emissions and minimizing waste.

7.2.1 Reducing emissions

Telemedicine, the delivery of healthcare services remotely through digital platforms, is one of the most impactful tools in reducing healthcare's environmental footprint. The environmental impact of healthcare is significantly influenced by patient travel, which leads to greenhouse gas emissions from transportation. By enabling patients to consult with specialists remotely, telemedicine reduces the need for long-distance travel, thereby cutting down on the carbon footprint associated with commuting to healthcare facilities.

In tertiary care, telemedicine is especially beneficial in situations where patients need to access highly specialized care that may not be available in their local communities. By allowing patients to receive consultations, follow-up appointments, and even diagnostic evaluations remotely, telemedicine minimizes travel and associated emissions. Moreover, virtual consultations can reduce the overcrowding of hospitals and clinics, leading to less strain on physical infrastructure and less energy consumption per patient visit.

Similarly, the use of AI in telemedicine platforms enhances the quality and efficiency of remote consultations. AI-powered chatbots, for example, can triage patient inquiries, provide initial assessments, and even offer therapeutic suggestions based on data. This reduces the need for in-person visits and minimizes resource consumption while maintaining high standards of care.

7.2.2 Reducing waste

AI also contributes significantly to reducing waste in tertiary care. Hospitals and healthcare systems are notorious for generating large amounts of waste, including

medical waste, single-use plastics, and packaging. AI, through its predictive capabilities, can help manage resources more efficiently, thereby reducing waste. For example, AI can optimize inventory management by predicting the demand for medical supplies and ensuring that they are ordered only when necessary, reducing the risk of overstocking and subsequent wastage.

Additionally, AI can be employed in the efficient use of medical equipment, helping to track usage patterns and maintain a balance between underuse and overuse. In surgery or diagnostic imaging, for instance, AI can analyze patient data to determine whether a particular procedure is truly necessary, reducing unnecessary tests, scans, and interventions that lead to the generation of waste.

Telemedicine also helps reduce waste by minimizing the need for physical appointments and in-hospital visits, reducing the consumption of resources like paper, plastics, and medical disposables that are often used during in-person visits. Furthermore, the shift toward digital records in telemedicine reduces the environmental burden of paper-based documentation, contributing to sustainability efforts by cutting down on paper waste.

7.2.3 Challenges in achieving balanced implementation

Despite the clear benefits, achieving a balanced implementation of digital technologies and green practices in tertiary care comes with several challenges.

7.2.3.1 Initial costs and infrastructure development

One of the main hurdles in integrating digital technologies and sustainability efforts is the initial financial investment required. The cost of upgrading hospital infrastructure to support AI systems, telemedicine platforms, and energy-efficient technologies can be prohibitively high. Many healthcare organizations, especially those in low- and middle-income countries, may struggle to allocate the necessary resources for such investments. Additionally, the integration of AI and telemedicine may require significant changes to existing workflows and staff training, which can incur further costs [95–111].

7.2.3.2 Data privacy and security concerns

The adoption of digital technologies, particularly AI and telemedicine, raises significant concerns regarding patient privacy and data security. The collection and sharing of sensitive health information through digital platforms require robust cybersecurity measures to protect against data breaches and unauthorized access. While the benefits of AI-driven insights and telemedicine consultations are clear, they must be balanced against the need to safeguard patient confidentiality. Ensuring compliance with regulations such as GDPR or HIPAA is crucial but can be challenging in the fast-evolving field of digital health.

7.2.3.3 Resistance to change

Another challenge is the resistance to change within healthcare systems. Healthcare providers, including physicians, nurses, and administrators, may be hesitant to adopt new technologies due to concerns about job security, loss of control, or a lack of familiarity with digital tools. Training healthcare workers to effectively use AI and telemedicine platforms is crucial, but it can be time-consuming and costly.

Overcoming this resistance and ensuring that healthcare workers embrace new technologies as tools to enhance their work rather than replace it is a significant challenge.

7.2.3.4 Technological and environmental constraints

The implementation of both digital and green technologies requires access to reliable infrastructure, such as high-speed internet for telemedicine and renewable energy sources for green practices. In some regions, particularly rural or underdeveloped areas, the lack of adequate technological infrastructure can limit the effectiveness of digital health interventions. Similarly, transitioning to green practices, such as using renewable energy or adopting sustainable procurement strategies, may be hindered by local regulatory frameworks or a lack of access to sustainable alternatives.

8. Future perspectives in the digital and green transformation of tertiary care

As the world moves toward a more sustainable and digitally empowered future, the role of tertiary care in driving innovation and achieving these goals is becoming more vital. The emergence of cutting-edge technologies such as smart hospitals, the Internet of Things (IoT), and the growing push for net-zero emissions are reshaping the healthcare landscape. Tertiary care facilities, given their complexity and responsibility for specialized care, are at the forefront of integrating these technologies and addressing global health and sustainability challenges. This section explores the future of tertiary care with a focus on these transformative technologies and their potential to harmonize digital and green transformations in healthcare systems.

8.1 Integrating digital and green strategies for infectious disease control

The synergy between digital and green transformation in tertiary care magnifies the ability to control infectious diseases. Digital technologies, such as AI and telemedicine, can significantly reduce the carbon footprint by minimizing the need for travel, optimizing hospital operations, and improving the efficiency of resource management. For instance, AI systems that optimize energy consumption in hospitals not only reduce costs but also contribute to sustainability goals while improving infection control measures. Additionally, the digitalization of healthcare processes, such as electronic health records, allows for faster identification and isolation of patients with infectious diseases, thus preventing outbreaks from spreading [65–78, 112–118].

8.2 Emerging technologies: Smart hospitals, IoT in healthcare, and net-zero emissions

8.2.1 Smart hospitals

A smart hospital is a healthcare facility that leverages digital technologies, including IoT devices, artificial intelligence (AI), and advanced data analytics, to improve patient care, streamline operations, and enhance sustainability. The concept of a smart hospital goes beyond simple automation—it involves the creation of a connected ecosystem where systems are fully integrated, and data flows seamlessly between

devices, healthcare providers, and administrative teams. For instance, smart hospitals utilize sensors and real-time data collection to monitor patients' health remotely, track vital signs, and predict potential health crises before they occur. This technology improves patient outcomes, reduces medical errors, and enhances patient satisfaction by enabling personalized care. On the operational side, smart hospitals use AI-driven algorithms to optimize resource management, ensuring that staff is allocated efficiently and that energy consumption is minimized. Furthermore, smart hospitals can contribute significantly to sustainability goals. Automated systems can adjust lighting, heating, and cooling based on real-time occupancy and usage, significantly reducing energy consumption. For example, during low-traffic hours, lighting and HVAC systems can automatically reduce their power usage, contributing to a hospital's green goals.

8.3 IoT in healthcare

The Internet of Things (IoT) in healthcare refers to a network of interconnected devices that collect, share, and analyze health data. In tertiary care, IoT devices can be used for remote patient monitoring, such as wearable devices that track a patient's heart rate, blood pressure, or oxygen levels. These devices not only allow for continuous monitoring of patients but also enable healthcare professionals to detect early warning signs of medical issues before they become critical, reducing hospital admissions and improving patient care. IoT is also vital for improving operational efficiency. By connecting medical equipment, patient records, and facility systems, IoT enables hospitals to streamline processes, reduce waste, and enhance real-time decision-making. For instance, automated inventory management systems connected through IoT sensors can notify hospital staff when supplies are running low, ensuring timely restocking and minimizing waste. Additionally, IoT-enabled environmental control systems can regulate energy use, reducing a hospital's carbon footprint.

The use of IoT in healthcare further supports sustainability efforts as it reduces the need for in-person visits and the associated travel emissions. Remote monitoring, telemedicine consultations, and virtual check-ups reduce the environmental impact of patient care while improving access, particularly for patients in rural or under-served areas.

8.4 Net-zero emissions in tertiary care

Net-zero emissions is the state in which the total amount of greenhouse gases emitted is balanced by the amount removed from the atmosphere. For healthcare institutions, achieving net-zero emissions involves a combination of energy efficiency improvements, the use of renewable energy sources, sustainable building designs, and waste reduction.

Tertiary care centers, with their significant energy needs, are particularly suited for the adoption of green technologies. Solar panels, wind energy, and energy-efficient HVAC systems can drastically reduce a hospital's reliance on non-renewable energy sources. Furthermore, hospitals can implement waste management systems that reduce medical and organic waste sent to landfills, recycle materials like plastics and metals, and use sustainable, biodegradable products. Hospitals can also contribute to achieving net-zero goals by incorporating green building practices. Certification programs such as LEED (Leadership in Energy and Environmental Design) have set standards for sustainable buildings, and many tertiary care centers are seeking such certifications to reduce their environmental footprint.

8.5 Tertiary care's leadership in advancing global health and sustainability goals

Tertiary care facilities, due to their specialized expertise and resources, are uniquely positioned to lead the way in advancing both global health and sustainability goals. The healthcare sector is one of the largest global contributors to carbon emissions and waste, yet it is also one of the most important sectors in achieving the United Nations Sustainable Development Goals (SDGs), particularly in areas like health (SDG 3) and climate action (SDG 13). Tertiary care centers, by adopting digital and green innovations, can directly contribute to these global objectives. **Global Health Goals:** By investing in advanced technologies like AI, telemedicine, and IoT, tertiary care centers can expand access to quality healthcare and reduce health disparities. For example, telemedicine allows specialists in developed regions to consult with patients in underserved areas, improving the reach of tertiary care. Furthermore, AI-driven diagnostics and treatment plans can lead to more accurate, faster medical interventions, improving patient outcomes. **Sustainability Goals:** Tertiary care facilities can play a crucial role in reducing healthcare's environmental impact. By adopting green technologies and strategies, hospitals can help mitigate climate change and reduce resource depletion. This includes efforts to reduce carbon emissions, minimize waste, and optimize resource use through digital tools. As leaders in health and sustainability, tertiary care centers must serve as models for other healthcare facilities. Their experiences in adopting smart technologies, implementing sustainable practices, and embracing digital tools can inform best practices and provide guidance for healthcare providers worldwide. Additionally, tertiary care hospitals can engage in research and development to advance new technologies that benefit both health outcomes and sustainability.

8.6 Vision for harmonized digital and green transformations

The future of healthcare lies in the successful harmonization of digital and green transformations. The convergence of these two domains will create a healthcare ecosystem that is not only efficient and patient-centered but also environmentally sustainable.

8.7 Integration of digital and green technologies

Digital tools, particularly those driven by AI and IoT, can be leveraged to optimize sustainability efforts in hospitals. For example, AI algorithms can predict energy usage patterns, allowing hospitals to reduce their energy consumption without sacrificing care quality. Similarly, digital platforms can help hospitals track their carbon footprints, monitor waste generation, and implement more efficient waste disposal practices.

8.8 Enhanced collaboration for global goals

Achieving a balance between digital and green goals requires collaboration across multiple stakeholders. Policymakers must provide incentives for healthcare facilities to adopt digital and sustainable practices, while technology companies must continue to innovate to provide solutions that address both healthcare needs and

environmental concerns. Hospitals, particularly those in tertiary care, must be proactive in leading these efforts, demonstrating the potential for sustainable healthcare that does not compromise on care quality or access.

8.9 A future of resilient and sustainable healthcare systems

As we look toward the future, the vision for healthcare is one of resilience, equity, and sustainability. Tertiary care institutions will continue to serve as the backbone of advanced medical care, while simultaneously embracing technologies that drive both patient outcomes and environmental sustainability. This vision includes a network of smart, energy-efficient, digitally connected hospitals that reduce emissions, minimize waste, and provide world-class care to all.

9. Conclusion

Tertiary care is undeniably at the heart of the evolving healthcare landscape, serving as both a beacon of advanced medical expertise and a critical force in driving digital and green transformations. As the world continues to grapple with the dual challenges of improving health outcomes and mitigating climate change, tertiary care facilities have the opportunity—and the responsibility—to lead the way in integrating cutting-edge digital technologies with sustainable practices. The integration of innovations such as smart hospitals, the Internet of Things (IoT), artificial intelligence (AI), and green energy solutions has already begun reshaping the tertiary care sector, enhancing patient outcomes while reducing operational inefficiencies and environmental impact. By leveraging these technologies, tertiary care centers can not only improve the quality of care but also play a pivotal role in achieving global health and sustainability goals. Through strategic adoption of these digital and green innovations, tertiary care providers have the potential to significantly reduce healthcare's carbon footprint, optimize resource usage, and deliver more equitable, accessible care to a broader population.

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Perspective Chapter: Telemedicine beyond the Pandemic: Innovations, Challenges, and the Future of Digital Healthcare

Masab A. Mansoor and Andrew F. Ibrahim

Abstract

The COVID-19 pandemic catalyzed unprecedented adoption of telemedicine, transforming it from an alternative care modality into a mainstream healthcare delivery mechanism. This chapter examines how telemedicine has evolved beyond its pandemic-driven expansion, exploring the innovations that have emerged, the persistent challenges that remain, and the trajectory of digital healthcare's future. Through analysis of technological advancements, regulatory adaptations, and changing patient and provider behaviors, this chapter identifies the key factors that will determine telemedicine's long-term integration into healthcare systems. Special attention is given to emerging care models, health equity considerations, and the evolving regulatory landscape that will shape how digital health technologies address unmet healthcare needs. By examining post-pandemic telemedicine implementation across diverse healthcare settings, this chapter provides insights into creating sustainable telemedicine ecosystems that enhance access, quality, and efficiency in healthcare delivery.

Keywords: telemedicine, digital health, virtual care, healthcare innovation, remote monitoring, health equity, regulatory policy, post-pandemic healthcare

1. Introduction

Telemedicine—the use of telecommunications technology to provide clinical healthcare at a distance—has evolved from a niche service to a fundamental component of modern healthcare delivery. While the concept of remote healthcare can be traced back to early radio consultations in the 1920s and NASA's space mission telemetry in support of astronauts in the early 1960s, its widespread adoption remained limited until the COVID-19 pandemic dramatically accelerated its implementation [1]. This chapter examines how telemedicine has evolved beyond its pandemic-driven expansion and explores the innovations, challenges, and future directions that will shape digital healthcare in the post-pandemic era.

1.1 Historical context of telemedicine prior to COVID-19

Prior to 2020, telemedicine adoption faced significant barriers despite decades of technological advancement. These barriers included restrictive reimbursement policies, provider hesitation, licensing complications, and patient unfamiliarity [2]. Telemedicine primarily served specific use cases: rural healthcare access, specialty care in underserved areas, and convenience-oriented direct-to-consumer virtual urgent care [3]. While some healthcare organizations had established robust telemedicine programs, they remained the exception rather than the norm, with virtual visits constituting less than 1% of outpatient encounters in the United States (U.S.) before the pandemic [4].

Early telemedicine initiatives demonstrated promise across various contexts. The U.S. Veterans Health Administration's telemedicine program, established in 2003, showed improved outcomes and reduced hospitalizations for chronic disease management [5]. Similarly, telestroke networks demonstrated significant improvements in door-to-treatment times and expanded access to life-saving interventions in regions lacking neurological specialists [6]. Despite these successes, the broader healthcare ecosystem maintained its traditional in-person care paradigm, with regulatory frameworks, payment models, and clinical workflows optimized for face-to-face encounters.

1.2 Pandemic-driven acceleration and adoption

The COVID-19 pandemic catalyzed an unprecedented surge in telemedicine utilization as healthcare systems worldwide rapidly pivoted to virtual care to maintain essential services while minimizing viral transmission. This transformation occurred with remarkable speed—organizations that had planned multi-year telemedicine implementation timelines compressed their efforts into weeks or even days [7]. In April 2020, telemedicine visits increased by more than 8000% compared to pre-pandemic levels in some health systems [8]. This explosive growth was enabled by rapid regulatory adaptations. In the U.S., the Centers for Medicare and Medicaid Services (CMS) expanded telemedicine reimbursement, waived geographic restrictions, permitted new patient telemedicine encounters, and allowed various technologies (including consumer platforms) for telemedicine delivery during the Public Health Emergency (PHE) [9]. Similar policy changes occurred globally, removing long-standing barriers to telemedicine adoption across different healthcare systems.

The pandemic not only accelerated telemedicine implementation but fundamentally shifted perceptions among providers and patients. Clinicians who had never conducted virtual visits quickly adapted their practice, while patients across demographic groups—including previously hesitant populations such as older adults—embraced remote care options [10]. This widespread exposure to telemedicine created new expectations for healthcare accessibility and convenience that persist beyond the acute crisis phase of the pandemic.

1.3 Transition from emergency response to sustainable integration

As healthcare systems emerged from crisis mode, attention shifted from rapid deployment to sustainable integration of telemedicine into care delivery.

This transition phase revealed both opportunities and challenges. While some pandemic-era policy changes have been extended or made permanent, others have reverted to pre-pandemic restrictions, creating uncertainty in the regulatory landscape [11]. Healthcare organizations face complex decisions about infrastructure investments, workflow redesign, and staffing models to support hybrid care delivery systems that effectively blend virtual and in-person services [12].

Patient utilization patterns have also evolved post-emergency. After peaking at 69% of all outpatient visits in April 2020, telemedicine utilization stabilized at approximately 15–20% of all encounters by mid-2022—significantly higher than pre-pandemic levels but reflecting a selective rather than universal application [13]. This stabilization suggests a maturation in understanding which clinical scenarios benefit most from virtual care modalities, moving beyond the pandemic’s “virtual by necessity” approach to a more nuanced “virtual by design” strategy.

1.4 Chapter objectives and scope

This chapter examines the evolving landscape of telemedicine beyond its pandemic-driven expansion, with several specific objectives:

1. Analyze technological innovations that have emerged or accelerated in response to expanded telemedicine adoption.
2. Identify sustainable care models that effectively integrate virtual and in-person services.
3. Explore the regulatory and policy frameworks needed to support telemedicine’s continued evolution.
4. Assess strategies for addressing health equity concerns in digital healthcare delivery.
5. Examine implementation challenges and potential solutions across diverse healthcare settings.
6. Project future developments that will shape telemedicine’s trajectory.

By examining these dimensions, this chapter aims to provide healthcare leaders, policy makers, technologists, and clinicians with a comprehensive understanding of how telemedicine can transition from an emergency response mechanism to a fundamental component of resilient, accessible healthcare systems.

2. Evolution of telemedicine technologies post-pandemic

The pandemic not only accelerated telemedicine adoption but also catalyzed rapid technological innovation across the digital health ecosystem. As telemedicine transitioned from an emergency solution to an established care modality, the focus shifted from basic connectivity to enhanced functionality, seamless integration, and improved user experience.

2.1 Advancements in virtual visit platforms

Early pandemic telemedicine often relied on standalone solutions that existed parallel to core clinical systems. Post-pandemic platforms increasingly feature bidirectional integration with electronic health records (EHRs), enabling seamless documentation, order entry, and access to patient data during virtual encounters [14]. Modern telemedicine platforms have expanded beyond basic audio-video connectivity to incorporate multimodal communication features, including multi-participant video, integrated text-based chat, screen sharing capabilities, and integrated language interpretation services [15].

A significant post-pandemic development is the integration of ambient clinical intelligence technologies into virtual visit platforms. These systems leverage artificial intelligence to automatically document encounters, extract clinical insights, and reduce administrative burden [16]. Natural language processing tools can generate draft clinical notes from virtual visit conversations, allowing clinicians to focus more on patient interaction than documentation. These capabilities are visible on **Table 1**.

2.2 Remote patient monitoring innovations

Remote patient monitoring (RPM) technologies have expanded from primarily chronic disease management applications to broader use cases across the care continuum. Pre-pandemic RPM typically focused on episodic measurements of basic physiological parameters. Post-pandemic innovations have enabled more continuous monitoring paradigms [17]. Advanced wearable sensors now provide continuous electrocardiography, respiratory monitoring, and other vital signs, generating richer datasets for clinical decision-making and early intervention.

The integration of consumer health devices into clinical RPM programs represents a notable trend. Consumer smartwatches, fitness trackers, and smartphone sensors have gained improved accuracy and expanded FDA clearances for monitoring capabilities [18]. This convergence between consumer and clinical-grade devices has expanded RPM accessibility and reduced implementation friction. Advanced analytics that transform raw physiological data into actionable clinical insights have enhanced the value of RPM data. Machine learning algorithms increasingly

Capability	Pre-pandemic system	Early pandemic adaptation	Current advanced systems
EHR Integration	Limited or manual	Basic unidirectional data flow	Deep bidirectional integration
Multi-participant Support	Rare	Basic templates	Seamless role-based participation
Documentation Support	Manual	Simplified for rapid adoption	AI-assisted ambient documentation
Technical Requirements	Often complex	Streamlined for crisis response	Optimized for diverse devices and bandwidth
Patient Experience	Complex scheduling and access	Streamlined for crisis response	Integrated into comprehensive digital front door

Table 1.
Evolution of virtual visit platform capabilities.

filter signal from noise, identify meaningful trends, predict decompensation, and prioritize patients requiring intervention [19]. These systems address alert fatigue by creating multi-parameter alerts rather than single-threshold notifications.

2.3 AI and predictive analytics integration

Artificial intelligence applications in telemedicine have matured from experimental projects to operational systems supporting clinical decision-making and resource allocation. Computer vision technologies have found numerous applications in telemedicine, including dermatological assessment through smartphone cameras, medication adherence verification, movement disorder evaluation, and wound assessment [20].

Natural language processing systems adapted for telemedicine contexts support applications such as automated documentation, sentiment analysis, symptom extraction, and risk factor identification from conversational data [21]. Predictive analytics increasingly guide resource allocation and intervention targeting in telemedicine programs, identifying patients who would benefit from proactive virtual outreach and determining optimal intervention timing [22].

2.4 Digital therapeutics and virtual reality applications

The boundaries of telemedicine have expanded to incorporate digital therapeutics—evidence-based interventions delivered through software applications—and immersive technologies. Prescription digital therapeutics with regulatory clearance have gained traction for conditions including substance use disorders, chronic insomnia, and attention deficit hyperactivity disorder [23]. These software-based interventions deliver evidence-based therapies through structured digital programs combining educational content, behavior modification techniques, and clinical monitoring.

Virtual reality applications have moved beyond experimental status to become established treatment options, particularly for behavioral health and rehabilitation. VR-based exposure therapy, pain management, physical rehabilitation, and cognitive training have demonstrated clinical efficacy comparable or superior to conventional interventions [24]. Augmented reality applications increasingly support remote clinical guidance, allowing specialists to virtually “see what the patient sees” and provide visual guidance through mobile devices [25].

The technological evolution of telemedicine demonstrates a trajectory from basic connectivity solutions toward sophisticated, purpose-built systems that extend clinical capabilities rather than merely replicating in-person interactions. This evolution reflects a fundamental shift from viewing telemedicine as a crisis-driven substitute to recognizing it as a distinct modality with unique advantages.

3. Emerging telemedicine care models

The integration of telemedicine technologies into healthcare delivery has catalyzed innovative care models that extend beyond simple replacement of in-person visits with virtual equivalents. These emerging models reimagine the entire care delivery process, leveraging digital capabilities to create new approaches to healthcare access, continuity, and specialization.

3.1 Hospital at home programs

Hospital at Home (HaH) programs represent one of the most significant care model innovations accelerated by the pandemic. These programs deliver acute care services—traditionally provided in inpatient settings—to patients in their homes through a combination of virtual connectivity, remote monitoring, in-person visits, and logistical support. Programs typically include initial patient selection, remote monitoring deployment, regular virtual physician rounds, scheduled in-home visits, medication delivery, emergency response protocols, and transition planning. The pandemic significantly accelerated HaH adoption through the CMS’s Acute Hospital Care at Home waiver program [26].

Research on HaH programs has demonstrated comparable or improved clinical outcomes compared to traditional hospitalization for selected conditions [27]. These programs have shown reduced rates of delirium, healthcare-associated infections, and functional decline—complications often associated with hospitalization among older adults. Economic analyses indicate cost savings of 15–30% compared to traditional inpatient care (Table 2) [28].

3.2 Hybrid care delivery systems

Hybrid care models—which strategically blend in-person and virtual interactions within care episodes—have emerged as a significant post-pandemic innovation. Unlike the pandemic-era approach of simply replacing in-person visits, hybrid models deliberately design care pathways that leverage the strengths of each modality. Advanced hybrid care systems employ decision support tools that recommend the optimal care modality based on clinical needs, patient preferences, resource availability, and interaction history [31]. Hybrid models increasingly focus on maintaining continuity of care relationships across modalities rather than treating virtual care as a separate service stream. Key innovations include unified scheduling systems, consistent provider assignment across modalities, and synchronized documentation systems [32].

An emerging subset of hybrid models employs a “virtual-first” approach, where the default initial interaction occurs through a digital channel, with appropriate escalation to in-person care based on specific triggers. Virtual-first designs have demonstrated significant efficiency gains while maintaining high patient satisfaction when implemented with appropriate escalation pathways [33].

Outcome measure	Traditional hospitalization	Hospital at home	Difference
30-day Readmission Rate	15.6%	11.8%	–3.8%
Delirium Incidence	15–25%	4–8%	–11% to –17%
Healthcare-Associated Infections	3–5%	<1%	–2% to –4%
Patient Satisfaction (0–10 scale)	7.2	8.5	+1.3
Average Cost per Episode	\$7500	\$5600	–25%

Table 2.
Comparison of Hospital at Home vs. Traditional Hospitalization Outcomes. Values based on aggregate data from multiple studies [27–30].

3.3 Specialty-specific telemedicine applications

Specialty telemedicine has evolved beyond simple video consultations to encompass comprehensive care models tailored to specific clinical domains. The behavioral health field has experienced perhaps the most complete transformation, with virtual care becoming the predominant delivery mode for many services. Advanced telepsychiatry models now include measurement-based care with integrated digital assessment tools, virtual intensive outpatient programs, and collaborative care models connecting behavioral health with primary care [34].

Telerehabilitation has evolved from simple video-guided exercises to sophisticated systems incorporating motion tracking through computer vision, remote monitoring of exercise adherence, and virtual reality environments for immersive rehabilitation [35]. Primary care has developed comprehensive virtual models that extend beyond episodic sick visits to encompass the full spectrum of primary care functions [36]. Innovative consultation models have emerged to extend specialist expertise beyond traditional geographic limitations, including eConsult systems and virtual collaborative care for chronic disease management [37].

3.4 Integration with retail health and pharmacy services

The integration of telemedicine with retail health and pharmacy services represents a significant care model innovation that leverages existing community infrastructure. Retail clinics have evolved beyond simple walk-in care to incorporate sophisticated hybrid models featuring virtual physician oversight of advanced practice providers, remote diagnostic capabilities, and specialist teleconsultation availability [38]. Pharmacies increasingly serve as access points for telemedicine services, particularly in rural and underserved communities, offering telemedicine kiosks, pharmacist-facilitated telemedicine visits, and remote monitoring hubs [3]. The integration of home delivery systems with telemedicine creates comprehensive care models that address medication, supply, and testing needs, including same-day medication delivery following telemedicine prescribing and home diagnostic testing with virtual result interpretation [17].

These emerging care models demonstrate how telemedicine has evolved from a standalone service to an integrated component of comprehensive care delivery systems. As these models mature, they increasingly blur the distinction between “virtual” and “in-person” care, focusing instead on creating seamless, modality-appropriate experiences that optimize outcomes, efficiency, and patient convenience.

4. Regulatory and policy landscape

The regulatory and policy environment for telemedicine has undergone significant transformation since the pandemic began. What started as emergency waivers and temporary flexibilities has evolved into a complex patchwork of permanent changes, extended temporary provisions, and reversion to pre-pandemic restrictions.

4.1 Post-PHE policy adaptations

The transition from pandemic emergency response to post-emergency telemedicine policy has followed different trajectories across regions and regulatory domains.

The U.S. federal government implemented unprecedented telemedicine flexibilities during the COVID-19 Public Health Emergency (PHE), including geographic restriction waivers, expansion of eligible provider types, and permission for audio-only telemedicine.

The transition from these emergency provisions has been incremental. The Consolidated Appropriations Act of 2023 extended key Medicare telemedicine flexibilities through December 31, 2024 [39]. However, other federal flexibilities have reverted to pre-pandemic restrictions, creating a complex regulatory environment. For example, prescribing controlled substances via telemedicine became subject to in-person examination requirements again, with limited exceptions [40].

State policies governing Medicaid programs and private insurance requirements have created significant geographic variation in telemedicine regulations. Post-pandemic state approaches fall into three general categories: (1) Comprehensive Permanence States that codified pandemic-era telemedicine flexibilities into permanent law; (2) Selective Permanence States that maintained selected flexibilities; and (3) Reversion States that allowed most flexibilities to expire [41].

Globally, countries have taken diverse approaches to post-pandemic telemedicine regulation. The European Union has worked toward greater standardization through the European Health Data Space initiative [42]. Australia transformed its temporary COVID-19 Medicare Benefits Schedule telemedicine items into permanent fixtures, though with modified eligibility requirements emphasizing established care relationships [43].

4.2 Reimbursement models and financial sustainability

Reimbursement remains the fundamental policy lever determining telemedicine sustainability. Fee-for-service telemedicine reimbursement has evolved along several dimensions. During the pandemic, many payers required payment parity between virtual and in-person services. Post-pandemic, approximately 22 U.S. states maintain some form of payment parity requirement, while others have allowed differential payment based on modality [44].

Telemedicine financial models are increasingly integrated into value-based care arrangements rather than treated as standalone services. Organizations operating under capitated arrangements have greater flexibility to deploy telemedicine strategically without direct reimbursement constraints. The Center for Medicare and Medicaid Innovation has incorporated telemedicine flexibilities into various alternative payment models, providing financial pathways for telemedicine adoption outside traditional fee-for-service constraints [45].

Direct-to-consumer telemedicine services have evolved distinct financial models, including subscription-based access, episode-based pricing, employer-sponsored benefits, and retail integration. These consumer-oriented financial models operate partially outside traditional reimbursement frameworks, creating alternative sustainability mechanisms when insurance coverage remains uncertain [46].

4.3 Licensure and practice across borders

Professional licensure requirements represent one of the most significant regulatory challenges for telemedicine expansion. Licensure compacts—agreements between states allowing expedited licensing across state lines—have gained momentum as mechanisms to facilitate interstate telemedicine practice. The Interstate

Medical Licensure Compact has expanded to 37 participating states, creating expedited pathways for physician licensure across state lines [47].

Some states have implemented permanent exceptions to standard licensure requirements specifically for telemedicine, including consultation exceptions, patient relationship exceptions, and border state exceptions. These create narrowly defined pathways for interstate practice while maintaining state regulatory authority [48]. Cross-border telemedicine practice internationally faces even greater regulatory complexity. Certain regions have developed cross-national frameworks, such as the European Union's mutual recognition provisions for medical qualifications. The lack of international standards for telemedicine practice remains a significant barrier to global telemedicine expansion [49].

4.4 Data privacy and security frameworks

Data privacy and security regulations for telemedicine have evolved significantly post-pandemic. The U.S. Department of Health and Human Services Office for Civil Rights exercised enforcement discretion regarding telemedicine platforms during the pandemic, allowing use of consumer communication applications that would not typically meet HIPAA requirements. This enforcement discretion has been phased out, requiring telemedicine services to return to full HIPAA compliance [50].

Informed consent requirements for telemedicine have become more standardized, with many states codifying specific telemedicine consent provisions into permanent law. These typically include disclosure of telemedicine limitations and risks, information about privacy practices, alternative care options, and technical failure contingency plans [51]. Cross-border telemedicine faces complex data protection challenges, particularly with frameworks like the European General Data Protection Regulation (GDPR). Key considerations include data localization requirements, restrictions on cross-border data transfers, varying definitions of protected health information, and diverse breach notification requirements [52].

The post-pandemic regulatory landscape reveals a field in transition—moving from emergency response toward sustainable integration, but with significant policy gaps and inconsistencies remaining. The patchwork nature of current regulations creates both challenges and opportunities for policy innovation and evidence development to inform more coherent long-term frameworks.

5. Addressing health equity through digital care

While telemedicine expanded rapidly during the pandemic, its benefits were not equally distributed across all populations. The digital transformation of healthcare has simultaneously created new opportunities for addressing longstanding healthcare disparities and risks exacerbating existing inequities.

5.1 Bridging the digital divide

The digital divide—disparities in access to technology, connectivity, and digital literacy—represents the most fundamental barrier to equitable telemedicine implementation. Research during the pandemic revealed significant disparities in telemedicine utilization along socioeconomic, racial/ethnic, geographic, and age-related lines [53].

Approximately 15% of U.S. adults do not own a smartphone, with lower ownership rates among older adults, rural residents, and those with lower incomes [54]. Computer ownership shows even greater disparities, with 41% of households earning less than \$30,000 lacking a desktop or laptop computer. Approximately 19 million Americans lack access to broadband internet infrastructure, with rural communities disproportionately affected [55].

Beyond physical access, effective telemedicine participation requires digital skills and confidence. Approximately 16% of U.S. adults are not digitally literate, with higher rates among older adults, those with lower educational attainment, and non-English speakers [56]. These literacy and confidence factors often receive less attention than hardware and connectivity issues but represent equally significant barriers to equitable telemedicine access.

Addressing the digital divide requires coordinated interventions across multiple levels, including policy interventions (broadband expansion initiatives), healthcare system approaches (technology lending programs), community-based strategies (digital literacy training), and design solutions (low-bandwidth options). Effective digital divide interventions increasingly employ comprehensive approaches rather than focusing on single factors in isolation [57].

5.2 Cultural competence in virtual care

Cultural competence takes on new dimensions in virtual environments. Language barriers present particular challenges, as interpreter integration in telemedicine platforms varies widely in quality and accessibility, and non-verbal communication cues may be less visible in virtual formats. Effective language access requires both technological solutions and process adaptations [53].

Different cultural groups may experience virtual care differently based on cultural norms regarding technology use, privacy expectations, communication preferences, and health beliefs. Culturally adapted telemedicine implementations acknowledge these differences through provider training, customized workflows, and engagement approaches tailored to community preferences [58].

Advancing cultural competence in telemedicine increasingly involves community participation in design and implementation through advisory boards, co-design methodologies, and community health workers serving as cultural brokers between healthcare systems and communities. These participatory approaches ensure that telemedicine implementations reflect community priorities and needs [59].

5.3 Accessibility considerations

Telemedicine presents both opportunities and challenges for individuals with disabilities. Telemedicine platforms must address varied accessibility requirements for visual disabilities (screen reader compatibility), hearing impairments (closed captioning), motor limitations (voice control options), and cognitive disabilities (plain language information). The varied nature of disability requires flexible, multi-modal approaches [60].

Telemedicine accessibility exists within established legal and ethical frameworks including the Americans with Disabilities Act and Web Content Accessibility Guidelines (WCAG). Growing case law establishes healthcare organizations' responsibility for digital accessibility [61].

Universal design principles—creating environments and tools usable by all people without adaptation—provide a framework for accessible telemedicine development. These include designing for flexibility, incorporating multiple communication modalities, minimizing unnecessary complexity, and creating tolerance for error. Universal design approaches benefit all users while ensuring accessibility for those with specific needs [62].

5.4 Community-based telemedicine models

Community-based telemedicine models represent a promising approach for addressing equity challenges by embedding digital health technologies within trusted community contexts. Facilitated telemedicine models employ in-person facilitators to support virtual connections with providers, including community health workers assisting with technology navigation, school-based telemedicine programs, pharmacy-supported telemedicine kiosks, and mobile health units [63].

Physical locations providing telemedicine access infrastructure have emerged as a strategy for addressing connectivity barriers, including library-based telemedicine rooms, community center telemedicine stations, and Federally Qualified Health Center satellite locations with telemedicine capabilities [51].

Innovative programs have expanded community health worker roles to include digital health support functions, including telemedicine navigation, digital health education, and cultural and linguistic bridge functions. These models leverage established community health worker frameworks while adding digital competencies [64].

While these community-based models demonstrate promising outcomes for engaging underserved populations, they face sustainability challenges related to implementation costs, reimbursement pathways, and workforce considerations. Advancing these models requires continued evaluation, policy support, and sustainable financing mechanisms [65].

Addressing health equity in telemedicine requires moving beyond viewing digital health as inherently either barrier or solution. Instead, deliberate design choices, implementation approaches, and policy frameworks determine whether telemedicine advances or hinders equitable healthcare access and outcomes.

6. Implementation challenges and solutions

As telemedicine transitions from emergency deployment to sustainable integration, healthcare organizations face complex implementation challenges that extend beyond technology selection. Successful implementation requires addressing workforce adaptation, systems integration, quality measurement, and patient engagement dimensions simultaneously.

6.1 Workforce training and adaptation

The healthcare workforce represents both the greatest asset and potential bottleneck in telemedicine implementation. Effective telemedicine delivery requires a multidimensional skill set including “webside manner” (adapting clinical communication to virtual environments), digital assessment skills, technical troubleshooting abilities, documentation efficiency, and digital patient education techniques.

Healthcare organizations increasingly recognize that these skills require structured training rather than assuming providers will develop them through experience [66].

Telemedicine implementation often requires workforce role adaptation and team model evolution. Successful implementation typically involves defining and developing specialized roles such as virtual care coordinators, digital patient navigators, hybrid medical assistants, telemedicine specialists, and remote monitoring analysts [32].

Training approaches for telemedicine competencies have evolved to include simulation-based training, observation and coaching, specialty-specific protocols, continuous micro-learning, and patient feedback integration. These methodologies reflect recognition that telemedicine delivery requires deliberate skill development rather than representing a simple location change for existing clinical activities [67].

6.2 Technology integration with existing systems

Telemedicine technologies must function within complex technology ecosystems rather than as standalone solutions. The relationship between telemedicine platforms and electronic health records presents particular challenges, including bidirectional data flow, workflow integration, schedule management, and billing integration. The degree of EHR integration significantly impacts telemedicine efficiency [19].

Patients increasingly interact with multiple digital health tools, creating challenges related to digital front door consolidation, authentication harmonization, consistent user experience, and data synchronization. These patient-facing integration challenges significantly impact adoption and engagement [68].

Remote patient monitoring presents particular integration complexities, including device integration, alert integration, data normalization, and visualization integration. The proliferation of monitoring devices and platforms has created significant integration challenges requiring standards-based approaches [69].

Healthcare organizations increasingly employ structured approaches to telemedicine integration, including API-driven architectures, integration platforms, FHIR implementation for consistent data exchange, and vendor partnership models. These architectural approaches reflect the maturation of telemedicine implementation from tactical emergency response to strategic integration [14].

6.3 Quality measurement in virtual care

Measuring and ensuring quality in telemedicine delivery presents unique challenges. Comprehensive telemedicine quality frameworks address domains unique to virtual care, including technical quality (reliability, connectivity), digital clinical quality (appropriateness of virtual care selection), interpersonal quality in virtual contexts (communication effectiveness), digital access and equity (disparities in utilization), and care coordination in hybrid models (continuity between virtual and in-person care) [70].

Telemedicine quality measurement employs diverse methodologies including technical metadata analysis, virtual visit recording review, specialized patient experience measurement, virtual clinical assessment, and digital equity analytics. These varied approaches reflect the multidimensional nature of telemedicine quality [71].

Telemedicine quality improvement has evolved to include telemedicine-specific failure mode and effects analysis, virtual plan-do-study-act cycles, digital experience mapping, technology-enabled feedback loops, and cross-organization learning

collaboratives. These approaches address telemedicine as a distinct care modality requiring specialized quality methods [72].

6.4 Patient engagement and digital literacy

Patient engagement represents a critical success factor in telemedicine implementation. Effective telemedicine implementation includes structured digital onboarding rather than assuming patient readiness, including pre-visit technical preparation, digital readiness assessment, graduated engagement approaches, family and caregiver engagement, and multi-channel instruction [73]. Beyond initial onboarding, sustainable telemedicine implementation requires ongoing digital literacy support through telemedicine navigators, virtual waiting rooms with technical support, peer support programs, and targeted micro-learning interventions. These support models recognize digital literacy as a clinical care requirement with direct implications for healthcare access [74].

Comprehensive telemedicine implementation addresses engagement beyond single virtual visits through asynchronous engagement between visits, remote monitoring engagement strategies, digital therapeutic adherence support, and digital navigation across hybrid experiences. These longitudinal engagement approaches reflect the evolution of telemedicine from episodic interactions to continuous care relationships [75]. User experience design increasingly focuses on engagement and accessibility as core implementation requirements, including simplified user interfaces, adaptive interfaces adjusting to user capabilities, engagement-focused design applying behavioral principles, and inclusive design methodologies. This emphasis represents a shift from technical functionality focus to user-centered approaches [76].

The most successful telemedicine implementations address these multidimensional challenges holistically rather than focusing solely on technical deployment. By attending to workforce development, systems integration, quality measurement, and patient engagement simultaneously, healthcare organizations can create sustainable telemedicine programs that deliver value beyond the pandemic emergency response.

7. Future trajectory of digital healthcare

As telemedicine evolves from pandemic response to sustainable infrastructure, several emerging trends and technologies promise to further transform digital healthcare delivery.

7.1 Emerging technologies poised to transform telemedicine

Remote diagnostic capabilities represent a critical frontier in telemedicine advancement, with several promising technologies emerging, including AI-enhanced smartphone diagnostics for various conditions through advanced image processing and sound analysis [77], home diagnostic platforms combining multiple testing capabilities, digital stethoscopes with enhanced signal processing, handheld ultrasound devices with AI guidance, and minimally invasive sensors for continuous monitoring. These diagnostic advances potentially address a fundamental limitation of current telemedicine—restricted physical examination capabilities [78].

Ambient clinical intelligence technologies promise to transform the telemedicine experience through voice-first interfaces, automated clinical documentation systems, ambient symptom detection analyzing speech patterns and facial expressions, and intelligent care gap identification systems. These technologies address significant workflow and documentation burdens that currently limit telemedicine scalability [7].

Extended reality technologies—spanning virtual, augmented, and mixed reality—offer new possibilities for immersive healthcare delivery, including immersive treatment experiences, augmented reality overlays allowing specialists to guide procedures remotely, shared visualization of medical imaging during consultations, and AI-driven movement tracking for home-based rehabilitation [79].

Robotic and haptic systems increasingly bridge the physical separation inherent in telemedicine, including advanced telepresence platforms, haptic examination gloves allowing providers to “feel” patients remotely through force feedback, and devices enabling standardized physical assessment through robotic proxies. While some of these technologies remain in developmental stages, they represent significant potential for expanding telemedicine into clinical domains currently requiring physical presence [80].

7.2 Global perspectives and international collaboration

The future of telemedicine will be increasingly global, with cross-border collaboration shaping its evolution across different healthcare systems and economic contexts. Telemedicine innovation increasingly emerges from low and middle-income countries, where necessity drives creative approaches including reverse innovation models, leapfrog implementations bypassing traditional infrastructure, and adaptations for limited connectivity environments [49].

Various models for international telemedicine delivery continue to evolve despite regulatory complexity, including centers of excellence networks providing virtual consultations globally, humanitarian telemedicine initiatives connecting volunteer specialists with underserved regions, and diaspora clinician networks connecting emigrated healthcare providers with their countries of origin [81].

International standards development increasingly shapes telemedicine’s global future through technical interoperability standards, international consensus on clinical practice standards, standardized approaches to quality assessment, and shared ethical principles for responsible implementation across contexts [82].

7.3 Research priorities and evidence development

Telemedicine research is increasingly shifting from feasibility questions to comparative effectiveness, including studies comparing outcomes between different telemedicine delivery approaches, examining optimal combinations of virtual and in-person care, researching comprehensive digital care journeys, identifying which patients benefit most from different telemedicine approaches, and examining telemedicine effects beyond immediate utilization metrics. This research evolution reflects telemedicine’s maturation from novel intervention to established care modality [83].

Implementation research increasingly addresses how context influences telemedicine outcomes through contextual factor analysis, adaptation frameworks for different settings and populations, de-implementation research examining when to

reduce low-value telemedicine applications, and hybrid effectiveness-implementation designs addressing both clinical and implementation outcomes simultaneously [84].

Patient priorities increasingly drive telemedicine research questions and methods through systematic assessment of outcomes meaningful to patients, research approaches directly involving patients in telemedicine design and evaluation, studies examining how to align telemedicine delivery with individual preferences, and equity-focused research designs specifically addressing telemedicine's impact on healthcare disparities [85].

7.4 Vision for integrated care ecosystems

The future of telemedicine likely involves evolution beyond standalone services toward integrated digital ecosystems seamlessly connecting various care modalities and services. Healthcare platform ecosystems increasingly integrate multiple services through unified technical infrastructure, including integrated platforms combining telemedicine, pharmacy, insurance, and wellness functions, systems with API-driven architectures enabling third-party innovation, and cross-continuum platforms spanning prevention, acute care, recovery, and ongoing management [86].

Hospital-at-home models continue to evolve toward comprehensive acute care alternatives through advanced remote nursing capabilities, AI-driven systems continuously evaluating patient status, technologies supporting complex medication regimens in home settings, and hybrid specialist consultation models combining remote expertise with in-home generalist presence [87].

Future care models increasingly emphasize continuity between physical and virtual touchpoints through comprehensive documentation systems capturing both virtual and in-person interactions, AI-driven guidance directing patients to appropriate care modalities based on need, and care approaches maintaining provider continuity regardless of interaction modality [88].

Future telemedicine increasingly shifts from reactive to proactive and predictive approaches through AI-driven systems identifying early intervention opportunities, real-time assessment of patient status informing virtual check-in frequency, personalized predictive models guiding individualized care recommendations, and smart home technology integration with healthcare monitoring [89].

The future trajectory of telemedicine suggests evolution beyond replicating traditional care virtually toward fundamentally reimaged care models leveraging digital capabilities to deliver experiences impossible in traditional settings. This transformation will likely occur unevenly across different healthcare contexts and clinical domains, with regulatory frameworks, payment models, and evidence development influencing adoption patterns. However, the direction appears clear—toward more integrated, proactive, and personalized digital health experiences that blur traditional boundaries between virtual and physical care.

8. Conclusion

The evolution of telemedicine beyond the pandemic represents a pivotal transition in healthcare delivery—from emergency adaptation to strategic transformation. This chapter has examined multiple dimensions of this evolution, from technological advancements and care model innovations to regulatory developments, equity considerations, implementation challenges, and future directions.

8.1 Summary of key insights

The post-pandemic telemedicine landscape reveals several foundational insights: *From substitution to transformation:* Telemedicine and telemedicine have evolved from simply replicating in-person care virtually to creating new care models that leverage digital capabilities for experiences impossible in traditional settings. The most successful implementations have moved beyond viewing telemedicine as a substitute toward recognizing it as a distinct modality with unique advantages.

Integration rather than separation: The artificial boundary between “virtual” and “traditional” care is increasingly dissolving as healthcare systems develop hybrid approaches that blend modalities based on clinical needs, patient preferences, and resource considerations. The future lies in integrated approaches that create seamless experiences across physical and virtual touchpoints.

Beyond technology to implementation: While technological capabilities continue to advance rapidly, the primary challenges in telemedicine implementation increasingly involve human factors, workflow integration, and organizational adaptation rather than technical limitations. Successful telemedicine programs focus as much on change management, training, and process redesign as on technology selection.

Equity as design principle: The pandemic exposed significant disparities in telemedicine access and utilization, highlighting the importance of designing for equity from the outset rather than as an afterthought. Addressing the digital divide requires multi-level interventions spanning policy, community engagement, technology design, and care delivery approaches.

Policy-practice gap: A significant disconnect persists between telemedicine’s practical evolution and the regulatory frameworks governing its use. While telemedicine implementation has advanced rapidly, policies regarding reimbursement, licensure, and data exchange have evolved more incrementally, creating uncertainty that affects long-term planning and investment.

Evidence evolution: The evidence base for telemedicine continues to mature, with research questions evolving from basic feasibility and satisfaction to more nuanced investigations of comparative effectiveness, implementation factors, and context-specific outcomes. This evidence evolution will increasingly guide more targeted and appropriate telemedicine application.

8.2 Recommendations for stakeholders

Based on the analysis presented throughout this chapter, several recommendations emerge for different stakeholder groups involved in telemedicine implementation and policy.

Healthcare Organizations should develop comprehensive digital strategy rather than treating telemedicine as a separate service line, invest in workforce development beyond basic technology training, implement structured approaches to digital equity, design quality measurement systems that address telemedicine-specific domains, and balance standardization with customization to allow specialty-specific adaptation.

Policy Makers should transition from temporary flexibilities to permanent, evidence-based regulatory frameworks, address licensure barriers through interstate compacts and long-term solutions for cross-state practice, develop reimbursement approaches that incentivize appropriate telemedicine utilization, invest in digital infrastructure as healthcare infrastructure, and support telemedicine research and evidence development.

Technology Developers should prioritize user experience and accessibility across diverse populations from initial design stages, focus on integration capabilities rather than standalone functionality, develop solutions for remote diagnostic capabilities, create tiered functionality supporting various connectivity environments, and incorporate implementation support tools.

Healthcare professionals should embrace telemedicine competency development as a core clinical skill set, participate actively in telemedicine program design, advocate for telemedicine implementations that advance health equity, contribute to developing specialty-specific best practices, and maintain critical perspective on appropriate telemedicine application.

Patients and Communities can engage in digital literacy development, advocate for telemedicine designs and policies that address diverse needs and preferences, participate in research and feedback mechanisms, communicate preferences regarding care modality, and collaborate through community organizations to create supportive infrastructure for telemedicine access.

8.3 Future research directions

Several critical research areas require further development to guide telemedicine's continued evolution, including:

Longitudinal impact studies: Research examining telemedicine's long-term effects on care patterns, outcomes, and costs beyond immediate pandemic-driven implementation

- *Implementation context analysis:* Studies identifying which organizational factors, implementation approaches, and contextual elements influence telemedicine success
- *Modality optimization research:* Investigations determining which telemedicine modalities are most effective for specific clinical scenarios and patient populations
- *Digital equity interventions:* Evaluations of strategies for addressing telemedicine access disparities across different dimensions of the digital divide
- *Workforce impact assessment:* Research examining how telemedicine implementation affects provider experience, burnout, and workforce sustainability
- *Hybrid care model development:* Studies identifying optimal approaches for blending virtual and in-person care across different specialties and conditions
- *Regulatory impact analysis:* Examinations of how different policy approaches affect telemedicine implementation, utilization, and outcomes

The future of telemedicine lies not in whether it will remain a significant component of healthcare delivery—the pandemic permanently established its role—but in how it will be integrated, optimized, and evolved to fulfill its potential in improving healthcare access, quality, efficiency, and experience. The pandemic catalyzed unprecedented adoption and adaptation, but the true transformation of healthcare through

digital modalities remains an ongoing journey requiring continued innovation, evidence development, and thoughtful implementation. By addressing the challenges outlined in this chapter while building on emerging opportunities, telemedicine can transition from crisis response to fundamental infrastructure supporting more accessible, equitable, and patient-centered healthcare systems.

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Bridging the Digital Health Divide: AI-Powered Telemedicine, Policy Barriers, and Equity Solutions for Underserved Communities

Mthabisi Talent George Moyo

Abstract

The rapid expansion of telemedicine, driven by the COVID-19 pandemic, has highlighted persistent inequities in access, particularly among underserved populations. This chapter explores the digital health divide and how artificial intelligence (AI)-driven telemedicine, combined with policy reforms, can help bridge these gaps. The telemedicine equity framework (TEF) is introduced as a practical tool for policymakers, researchers, and healthcare system designers to assess and address digital health disparities. The TEF focuses on four core areas: technology readiness, infrastructure access, policy environment, and community capacity. It aims to provide a comprehensive approach to ensuring equitable access to telemedicine services. The chapter examines key barriers, including broadband gaps, digital literacy, and healthcare workforce shortages, and the ethical considerations surrounding AI applications in telemedicine. It highlights case studies such as AI-powered maternal health triage in rural Africa and mHealth solutions for tuberculosis adherence in India, which demonstrate the potential of digital health to reach underserved populations. Additionally, the chapter explores the role of blockchain in enabling secure, decentralized health records and discusses the policy challenges that arise from cross-jurisdictional telemedicine, such as licensing restrictions and data sovereignty. Policy recommendations emphasize aligning regulation with equity goals, supporting digital literacy initiatives, and fostering community engagement in digital health solutions. Through global case studies, the chapter illustrates the importance of inclusivity in designing and implementing telemedicine systems, ultimately contributing to universal health coverage and sustainable digital health futures.

Keywords: digital health, telemedicine, AI-driven healthcare, policy reform, health equity

1. Introduction

The COVID-19 pandemic rapidly transformed telemedicine from a niche service to a core component of healthcare delivery [1]. Governments, health systems, and

private innovators deployed virtual platforms to sustain care, reduce infection risks, and expand remote monitoring, while artificial intelligence (AI) tools, chatbots, and mobile health (mHealth) apps gained global traction [2]. Yet this digital shift revealed a troubling paradox: those most in need of care were often least able to access it [1, 3]. Despite progress, telemedicine remains inaccessible in many low-resource communities due to broadband deserts, limited devices, language and literacy barriers, and workforce shortages [4]. Globally, 2.6 billion people lack Internet access and 3.4 billion lack reliable connectivity, challenges that disproportionately affect rural, remote, Indigenous, and marginalized urban populations [5]. These divides reflect not only technical gaps but deeper systemic inequities rooted in historical neglect and policy inertia [5].

To avoid worsening disparities, digital health must be intentionally designed to advance equity. The telemedicine equity framework (TEF), a novel, interdisciplinary tool, offers a practical approach for assessing and implementing equitable strategies across four domains: technological maturity, infrastructural access, policy environment, and community capacity.

This chapter reimagines digital health through an equity-centered lens, exploring how technologies like AI, blockchain, and mHealth can close not widen existing gaps. It examines barriers to access and highlights inclusive innovations, offering not just an analysis of inequality but a blueprint for change. By uniting innovation, policy, and lived experience, it envisions a digital health future where no one is left offline, unseen, or unheard.

2. Understanding the digital health divide

Despite the surge in telemedicine usage during and after the COVID-19 pandemic, millions remain excluded from its benefits [3]. The “digital health divide” represents more than a technological gap, and it encapsulates deep-rooted disparities shaped by socioeconomic status, geography, education, culture, and identity [6]. To bridge this divide, we must understand the layered nature of exclusion that limits healthcare access in underserved populations. Technological barriers, cultural mismatches, and intersectional inequalities all contribute to the persistence of inequity, highlighting the need for digital health systems designed with equity at their core.

2.1 Socioeconomic and infrastructural barriers

In underserved communities, rural, remote, and low-income urban alike the absence of reliable broadband remains a primary barrier [7]. In sub-Saharan Africa, for instance, less than 30% of the population has consistent access to the Internet, and in rural areas of the United States (U.S.), 22% of adults report not using the Internet at all [8, 9]. However, Internet connectivity represents only one facet of the broader digital divide. This divide also encompasses limited access to essential digital devices such as smartphones, tablets, and computers; inconsistent or unreliable electricity supply; and financial barriers that prevent individuals from affording data plans or necessary hardware upgrades [6]. **Table 1** illustrates a comparative matrix of how digital health barriers are distributed across rural, urban poor, and Indigenous communities. This highlights the overlapping nature of infrastructural and socioeconomic challenges that constrain equitable telemedicine access.

Digital health barrier	Rural communities	Urban poor	Indigenous communities
Broadband Internet Access	Severely Limited	Moderate Access	Severely Limited
Availability	Moderate Access	Low Availability	Limited
Reliable Electricity Supply	Unstable Supply	Moderate Supply	Unstable Supply
Basic Digital Literacy	Low Literacy Levels	Basic to Moderate	Low Literacy Levels
Language and Communication Accessibility	Partial Accessibility	High Need for Translation	Culturally Inaccessible
Trust in Health Technology Platforms	Low Trust	Cautious Trust	Historical

Table 1.
Comparative matrix of digital health barriers across underserved communities.

Technological innovation often assumes an “always-connected” end user, yet the reality is far more dispersed [10]. For many individuals, even the regular charging of devices presents a logistical challenge. These infrastructural limitations significantly influence the accessibility and feasibility of telemedicine services, determining which services are practically deployable and accessible to specific populations. The “last mile” of digital infrastructure is not merely a technical issue; it represents a critical equity concern, disproportionately impacting already singled out groups [11].

2.2 Cultural and educational gaps

Despite the availability of infrastructure, digital health tools continue to be underutilized due to significant barriers to language, literacy, and trust [12]. A large portion of the population faces challenges in acquiring the digital skills necessary to effectively navigate apps, patient portals, and virtual consultations [13].

In multilingual countries, many telemedicine platforms operate in dominant languages, inadvertently excluding speakers of Indigenous and Indigenous languages [14]. Additionally, there is a pervasive mistrust of digital technologies, especially within those affected by surveillance, and medical supervision [15]. If patients are concerned about potential misuse of their data or fear being misunderstood, they are less likely to engage with these platforms [16]. To promote meaningful engagement, it is crucial to develop digital systems that are culturally responsive, linguistically inclusive, and user-friendly [17].

2.3 The role of intersectionality in compounding exclusion

The digital health divide is characterized by disproportionate impacts across various demographic groups, with women, individuals with disabilities, racial and ethnic minorities, the elderly, and LGBTQ+ populations encountering intersecting barriers that exacerbate exclusion [18, 19]. For instance, Indigenous women in remote regions of Canada may experience compounded challenges, including geographic isolation, cultural mistrust of the healthcare system, and gendered expectations that restrict their autonomy or availability for seeking healthcare services [20].

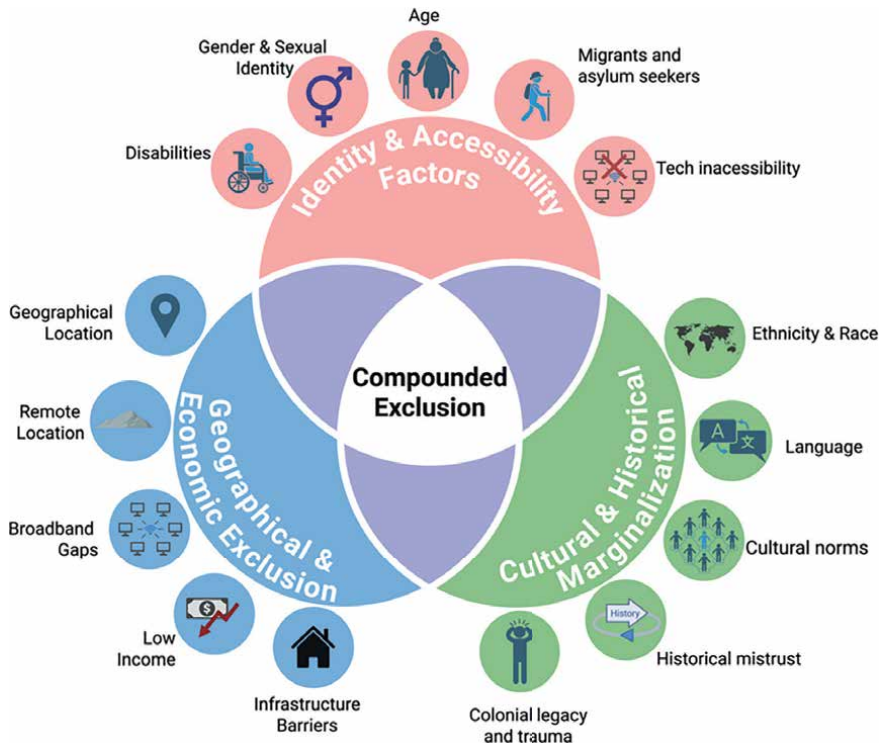


Figure 1.
Intersectional factors affecting digital health exclusion.

Figure 1 below presents a visual model of how these intersectional factors—structural, cultural, and identity-based—overlap to intensify digital health exclusion. The diagram serves as a conceptual tool to recognize the compounding nature of disadvantage that must be addressed in any equitable telemedicine design.

Recognizing intersectionality is key to designing inclusive telemedicine solutions. Programs must move beyond a one-size-fits-all model to account for the layered vulnerabilities that shape digital health access. Without this lens, well-intentioned innovations risk reinforcing existing disparities rather than dismantling them.

3. AI-driven telemedicine: Opportunities and ethical imperatives

The integration of AI into telemedicine has revolutionized the landscape of remote health care, characterized by enhanced efficiency, scalability, and complexity [21]. AI-driven technologies, ranging from predictive analytics and diagnostic support to virtual counseling and remote patient monitoring, are fundamentally transforming the methods through which health care is accessed, delivered, and assessed. In resource-constrained environments, AI has the potential to amplify service reach, alleviate clinician workload, and enhance the precision of clinical decision-making [22].

However, despite the undeniable promise of AI in digital health, its implementation poses significant risks [23]. Inadequate system design, biased datasets, and insufficient regulatory safeguards may exacerbate the healthcare disparities AI seeks

to address [24]. The analysis focuses on the dual nature of AI in telemedicine, its capacity to revolutionize care delivery, and the ethical dilemmas it introduces, while evaluating the current regulatory landscape that governs its integration.

3.1 Machine learning in diagnostics, triage, and personalized care

Machine learning (ML) models have transformed remote diagnostics and triage by enabling systems to “learn” from vast datasets of symptoms, images, and outcomes [25]. AI can rapidly analyze patient-reported data such as cough patterns, skin lesions, or risk factors and generate probability-based assessments [26]. For instance, in dermatology, ML models have achieved near-dermatologist accuracy in identifying skin cancers digital images [27–29]. In triage, AI can prioritize patients based on severity, flag high-risk cases for follow-up, and reduce time-to-treatment, especially in crisis contexts [22]. Furthermore, predictive modeling facilitates personalized care pathways. Algorithms trained on longitudinal health data can predict complications (e.g., diabetes-related vision loss) and suggest preventive interventions, potentially improving outcomes and reducing costs [22]. These functions are particularly valuable in resource-constrained settings, where clinical staff shortages and logistical barriers delay diagnoses [22, 30]. AI becomes not just an aid but a multiplier of health system capacity [30].

3.2 AI Chatbots and virtual agents in low-resource settings

Conversational AI via chatbots, short message service (SMS) agents, or voice assistants has found a niche in global health as a scalable, always-available support system [31]. These tools deliver mental health check-ins, maternal health guidance, medication adherence reminders, and even chronic disease management in multiple languages [22]. For example, in parts of Southeast Asia, WhatsApp-based chatbots guide TB patients through treatment regimens [32]. In refugee camps, AI-powered mental health tools offer anonymous emotional support, navigating stigma and language barriers [32]. Virtual agents require minimal infrastructure only a mobile device and intermittent connectivity making them ideal for low-income and rural settings. When integrated with national health systems, they can streamline referrals and feedback loops, improving service delivery at scale [33].

3.3 Ethical imperatives: Bias, transparency, and data privacy

AI in health care offers significant benefits but raises ethical challenges, notably algorithmic bias from training data over representing white, urban, or male populations, leading to inaccurate outcomes for other groups—such as pulse oximeters misreading darker skin tones [34–40]. Lack of explainability in deep learning models reduces trust in high-stakes decisions [34, 41], while data privacy risks persist, especially in regions without strong legal protections, risking misuse of sensitive health data [34, 42]. In response, global bodies provide guidelines: the World Health Organization (WHO) promotes transparency, inclusivity, and accountability [43, 44]; the European Union’s (EU) General Data Protection Regulation (GDPR) enforces data minimization and informed consent [45]; and the United Nations Educational, Scientific and Cultural Organization (UNESCO) and the Organization for Economic Co-operation and Development (OECD) advocate human-centered, rights-based AI ethics [46, 47]. Together, these frameworks help ensure AI protects patients, advances equity, and builds trust worldwide. **Table 2** highlights AI telemedicine applications alongside their ethical and operational risks.

Ai opportunity	Illustrative application	Ethical/Operational risk	Real-world or hypothetical example
Enhanced Diagnostic Precision	AI-enabled image analysis for early detection of diseases (e.g., cancer and retinopathy)	Diagnostic errors due to biased or non-representative training data	Retinal scan misclassification in patients from underrepresented ethnic groups
Efficient Triage and Workflow Optimization	Natural language processing (NLP) tools for prioritizing emergency cases	Algorithmic opacity and lack of explainability	Clinicians may not trust or understand AI's rationale in critical decisions
Remote Monitoring and Proactive Care	Wearables and smart sensors transmitting real-time vitals to clinicians	Data security and unauthorized third-party access	Breach of patient data from unsecured wearable devices
Expanded Access to Care	AI-driven chatbots delivering primary care guidance in underserved areas	Risk of mismanagement or misdiagnosis without oversight	Rural patients relying solely on AI for conditions requiring in-person evaluation
Reduction in Provider Burnout	Automation of administrative tasks, e.g., clinical documentation	Deskilling and reduced clinical intuition	Clinicians becoming overly reliant on AI-generated assessments
Cost Efficiency and Resource Allocation	AI tools streamlining appointment scheduling and resource deployment	Digital divide and unequal access to AI-enabled services	Advanced AI services concentrated in urban or private healthcare settings
Personalized Treatment Strategies	AI integration of genomics and electronic health record (EHR) data for tailored care	Ethical concerns over informed consent and data ownership	Use of patient genomic data in algorithm development without explicit permission

Table 2.
Opportunities and risks of AI in telemedicine — with illustrative examples.

4. Blockchain and digital infrastructure for secure, decentralized health records

As health systems digitize post-COVID-19, secure, interoperable infrastructure is essential for equitable care. Yet for billions, especially in underserved or displaced communities, telemedicine is limited without trusted, portable, and patient-controlled data. Health records often remain siloed or inaccessible [48]. Beyond cryptocurrency, blockchain offers a decentralized framework for health data governance, with potential to empower patients, enhance transparency, and rebuild trust [48, 49]. However, its impact depends on ethical use, equitable access, and contextual relevance. This section examines both the potential and limitations of blockchain in advancing digital health equity [50].

4.1 Blockchain for patient-controlled, portable, and verifiable health records

At its core, blockchain enables decentralized data stewardship, where individuals not institutions can securely manage access to their health records. Each medical transaction or update is cryptographically recorded across a distributed ledger, creating an immutable and verifiable history of care. For patients in low-resource settings, humanitarian crises, or mobile populations, this offers a pathway to consistent and portable health documentation—without dependence on a single facility or nation-state [51].

4.2 Smart contracts: Automating trust and consent across jurisdictions

In global telemedicine, legal ambiguities and data-sharing inconsistencies often undermine care continuity [44]. Smart contracts self-executing blockchain-based code can bridge this gap by encoding rules around informed consent, data access, or provider obligations. For example, a refugee patient could grant time-limited, read-only access to mental health records for a virtual consultation across borders, with consent revocable at any time [48]. This approach ensures granular, enforceable control over how health data is used and by whom particularly critical in regions with limited legal protections or digital literacy. Moreover, smart contracts can streamline billing, prescription validation, and referral workflows, reducing administrative friction and improving care coordination [49].

4.3 Challenges: Energy, equity, and infrastructure realities

Blockchain holds transformative potential for digital health but faces significant implementation challenges, especially in underserved regions with poor infrastructure and digital inequities [52]. High energy demands, particularly

Opportunity	Description / Example	Limitation	Description / Example
Data Integrity and Security	Immutable, time-stamped records ensure tamper-resistance, reducing risks of fraud and unauthorized access	Scalability constraints	Blockchain networks struggle with large volumes of health data, e.g., imaging or genomics
Interoperable Health Records	Decentralized access enables seamless sharing of patient data across providers and borders	Lack of standardization	Inconsistent data formats and blockchain protocols limit integration across systems
Patient-Centric Consent Management	Smart contracts allow patients to control access to their health data in real time	Usability and digital literacy gaps	Many patients may lack the skills or tools to manage blockchain-based permissions
Transparent Clinical Trials and Research Audits	Blockchain can log trial phases, data changes, and consent events, increasing trust and traceability	Regulatory ambiguity	Few jurisdictions have clear guidelines on blockchain use in biomedical research
Secure Pharmaceutical Supply Chains	Tracks provenance of medications, reducing counterfeiting and ensuring cold chain compliance	Cost of infrastructure integration	Linking blockchain to physical supply chains requires major upgrades in logistics systems
Fraud Prevention in Billing and Claims	Smart contracts and verifiable transactions reduce insurance fraud and billing errors	Institutional resistance	Insurers and intermediaries may resist systems that reduce their administrative control
Cross-Border Data Portability	Patients can carry their decentralized health records across countries, supporting care continuity	Legal conflicts with data protection laws	Blockchain's immutability can clash with privacy mandates like the GDPR "right to be forgotten"

Table 3.
Advantages and limitations of blockchain in digital health.

from proof-of-work models like Bitcoin, make it unsuitable in areas with unstable power, while more efficient alternatives like proof-of-stake remain impractical due to environmental and financial constraints [53]. Adoption is further limited by high costs, technical expertise requirements, and maintenance needs, which strain regions with limited infrastructure and health budgets. Without local capacity-building, blockchain risks perpetuating global inequities; sustainable success requires developing local skills and equitable partnerships [54]. Connectivity and digital literacy gaps also hinder use, as blockchain depends on Internet access, digital tools, and user competency—often lacking due to literacy, language barriers, or distrust [55]. Additionally, lack of global standards raises interoperability issues, risking new data silos within fragmented health systems and impeding data exchange [56]. Therefore, blockchain should be seen as a supportive technology integrated into broader digital health strategies emphasizing sustainability, inclusivity, and standardization. **Table 3** summarizes its benefits and limitations.

5. mHealth and community-based digital models

mHealth solutions are transforming healthcare delivery in underserved communities by leveraging the widespread presence of mobile phones to improve patient education, treatment adherence, and real-time monitoring [57]. In areas with limited Internet and infrastructure, SMS-based mHealth tools offer a low-cost, scalable method for sending health messages and reminders. These have proven effective in boosting adherence for chronic conditions such as hypertension, diabetes, and tuberculosis [58]. Mobile apps provide more advanced capabilities—tracking health data, delivering personalized advice, and enabling direct communication with healthcare providers. When combined with real-time data and predictive analytics, they support proactive management of chronic diseases [59, 60]. However, mHealth's success depends not just on technology, but on people. Community health workers (CHWs), trusted for their local knowledge and cultural fluency, are essential in integrating these tools into care systems. They educate patients, enhance digital literacy, and ensure the solutions are culturally relevant and accessible [61].

5.1 Case studies

In India, where tuberculosis (TB) remains a significant public health challenge, mobile health (mHealth) solutions have markedly improved treatment adherence and reduced default rates. Daily SMS reminders to TB patients have significantly increased adherence and lowered the default rate by up to 40%, enabling real-time support that helps prevent TB spread and drug resistance [62]. Similarly, in Canadian Indigenous communities with historically poor maternal and infant health outcomes, mHealth has been employed to monitor pregnancies and enhance access to maternal health care. These tools provide culturally tailored educational content, vital check-ins, and remote consultations, reducing preventable childbirth complications, ensuring regular prenatal visits, and improving maternal health literacy. The integration of culturally relevant interventions has also boosted patient engagement and trust, highlighting the importance of cultural sensitivity in digital health [63].

5.2 Path forward

While mHealth presents a powerful tool for improving healthcare access and outcomes, significant challenges remain. The *digital divide* is still a major barrier in many parts of the world, with millions lacking access to reliable smartphones, Internet connectivity, or even basic digital literacy. To address these gaps, there must be a concerted effort to *expand digital infrastructure*, such as affordable internet access, low-cost smartphones, and widespread digital literacy programs [64]. In parallel, healthcare systems must *build local capacity* to support these digital tools, especially by training and empowering CHW who can bridge the gap between technology and patients. *Culturally tailored mHealth solutions* are critical for ensuring that the messages, content, and interventions resonate with diverse populations, and that they are adapted to local languages, customs, and practices [61]. Finally, it is essential to ensure the *sustainability* of mHealth programs. Many mHealth interventions are introduced as short-term solutions or pilots, but for long-term success, these programs must be embedded within existing health systems and supported through ongoing funding and policy commitment [61].

6. Policy barriers and cross-jurisdictional challenges

As AI-powered digital health technologies advance, the main barriers to equitable care have shifted from technology to regulation. Outdated, fragmented, and jurisdiction-bound policies have become new social determinants of health, restricting AI-driven telemedicine's potential to overcome geographic and socioeconomic disparities. Healthcare providers remain constrained by licensing systems tied to geography rather than capability; for example, physicians licensed in one U.S. state cannot legally consult patients in another without costly, burdensome re-licensing—a challenge mirrored in federal countries like Canada and Australia. Reimbursement policies often fail to cover telemedicine services equally, especially AI-assisted, or asynchronous care, disproportionately impacting rural and low-income populations who may have Internet but lack local specialists. Cross-border telemedicine faces additional hurdles including conflicting data privacy laws such as the European Union's GDPR versus the U.S. Health Insurance Portability and Accountability Act of 1996 (HIPAA), creating legal ambiguity around data storage, patient consent, and jurisdiction. This is compounded by unclear malpractice liability and patient redress frameworks, discouraging providers from expanding care across borders and further marginalizing vulnerable groups. These challenges—spanning licensure fragmentation, data sovereignty, reimbursement gaps, and inconsistent privacy enforcement—are global in scope. **Table 4** summarizes key telemedicine policy barriers alongside promising regional strategies to address them.

6.1 Rollback of temporary COVID-Era flexibilities and aligning regulation with innovation

The COVID-19 pandemic temporarily transformed telemedicine through emergency waivers that enabled cross-state licensing, expanded reimbursement, and encouraged remote care, significantly improving access especially for public populations such as rural communities, people with disabilities, low-income patients, and communities of color. However, the rollback of these flexibilities now threatens to reverse these gains, underscoring the urgent need to embed adaptability into policy frameworks beyond

Region	Policy & regulatory barriers	Cross-jurisdictional challenges	Proposed solutions
United States	- Fragmented state regulations - Inconsistent telemedicine reimbursement - Complex HIPAA compliance	- State licensure limits interstate telemedicine - Varied definitions of telemedicine services	- Expand interstate licensure compacts (e.g., Interstate Medical Licensure Compact (IMLC)) - Standardize reimbursement codes (Medicare/Medicaid) - Promote federal-level regulatory harmonization
European Union (EU)	- No unified EU digital health strategy - Uneven GDPR enforcement - Varying digital maturity across member states	- Incompatible EHR systems across borders - Language/legal barriers in cross-border consultations	- Establish interoperable EU-wide eHealth systems - Strengthen digital health single market directives - Promote multilingual, cross-border telemedicine platforms
Sub-Saharan Africa	- Absent national eHealth policies - Unregulated digital health providers - Outdated information computer technology infrastructure laws	- No clear rules on cross-border data flows - Legal inconsistencies across borders	- Develop African Union-led regional digital health frameworks - Implement data governance aligned with GDPR/WHO - Facilitate PPPs to fund legal infrastructure
Latin America	- Ambiguity in national telemedicine legislation - Limited integration into public health systems - Weak digital rights protection	- Minimal cross-border recognition of teleconsultation - Lack of portable insurance coverage	- Promote regional telemedicine pacts (e.g., MERCOSUR) - Harmonize patient data protection laws - Launch national certification for telemedicine providers
South & Southeast Asia	- Outdated health laws - Exclusion from insurance schemes - Weak cybersecurity enforcement	- Limited cross-national strategy for migrant access - Language fragmentation in platforms	- Update national laws to include digital health - Coordinate Association of Southeast Asian Nations (ASEAN)-wide telemedicine standards - Scale inclusive, multilingual digital health tools
Middle East & North Africa (MENA)	- Fragmented regulation across nations - Restriction on cross-border care - Conservative privacy laws	- Lack of digital ID systems - Instability hinders regional frameworks	- Align regulations with WHO digital health guidelines - Develop regional digital health alliances - Improve refugee access to cross-border telemedicine

Table 4.
Telemedicine policy barriers and proposed solutions by region.

times of crisis [61–64]. To ensure equitable outcomes, regulatory systems must evolve in tandem with technological innovation. Encouragingly, several jurisdictions are already implementing agile approaches: the U.S. Interstate Medical Licensure Compact facilitates cross-state physician practice, the United Kingdom’s regulatory sandbox model supports

policy-aligned innovation, Australia's National Digital Health Strategy standardizes telemedicine reimbursement across states, and India's eSanjeevani platform have streamlined remote consultations through national data and credentialing standards. These examples show that flexible, inclusive policymaking [61–64].

7. The telemedicine equity framework

The TEF is a structured, multi-dimensional tool designed to address and reduce digital health disparities that persist despite rapid advancements in AI-driven telemedicine [65–67]. While technological innovation has progressed swiftly, access and health outcomes remain uneven—particularly in underserved communities. Unlike vague calls for equity, the TEF offers a unified model that breaks digital readiness into four measurable pillars: *technology readiness*, *infrastructure access*, *policy environment*, and *community capacity* [61–67].

These pillars collectively assess the technological maturity, accessibility, regulatory support, and community-centered elements necessary for equitable digital health care. The framework produces an *equity readiness score (ERS)*, allowing policymakers, providers, and technologists to pinpoint gaps and prioritize interventions. Case studies—such as a low-income urban clinic in the United States and a rural telemedicine initiative in Latin America demonstrate the TEF's ability to uncover context-specific strengths and challenges, from digital literacy and device access to infrastructural and regulatory barriers. By offering a scalable, equity-centered assessment model, the TEF equips stakeholders with actionable insights to implement inclusive, effective telemedicine solutions ensuring digital transformation advances health equity rather than deepening existing inequalities [61–67].

8. Policy and practice recommendations

As shown in **Table 4** AI-driven telemedicine has the potential to transform health-care delivery in underserved communities, but without deliberate policy interventions and a strong commitment to equity, the digital divide will continue to widen [67]. Equitable access depends on policies that fund rural broadband expansion and support multilingual platforms to ensure connectivity and culturally competent care for non-English-speaking populations [68]. Building trust within regional communities is also essential; this requires digital literacy initiatives to address concerns about privacy, bias, and relevance, as well as co-developing telemedicine solutions that reflect community needs [42–44]. Ensuring transparency and accountability in AI systems—through clear data governance, explainable algorithms, and ongoing audits—can further mitigate bias and strengthen public confidence [44]. Finally, cross-sector collaboration among governments, tech companies, NGOs, and academic institutions is vital for developing sustainable and inclusive digital health systems by leveraging shared expertise, resources, and evidence-based practices [45–47].

9. Conclusion

AI-driven telemedicine holds immense potential to transform health care, but this must be guided by equity, inclusion, and justice. Innovation alone is not enough;

digital health must be rooted in a rights-based approach that ensures universal access and addresses structural barriers like the digital divide, affordability, and low health literacy. To achieve global health equity goals such as Universal Health Coverage (UHC) and Sustainable Development Goal 3 (SDG 3), AI solutions must be community-centered designed with, not just for, underserved populations and tailored to cultural and regional contexts. Collaboration across governments, tech developers, healthcare providers, NGOs, and academia is essential to build sustainable, inclusive systems. Ultimately, bridging the digital divide requires integrating innovation with lived experience, so AI-powered telemedicine becomes not just a tool of progress, but a foundation for health equity worldwide.

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Perspective Chapter: Pre-Acceptability in Digital Health Technology

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Abstract

Respiratory illnesses impose a significant burden on global and Irish healthcare systems. A promising strategy to address this involves implementing remote patient monitoring and telemedicine, enabling patients to receive medical follow-up care from home. Such initiatives can enhance treatment quality, promote better self-management, increase adherence to therapies, reduce healthcare costs, and improve overall patient well-being. However, a marked gap exists in understanding the service user's perspective and whether end-users will accept this change to meet their complex needs. This perspective review explored literature to identify factors contributing to the acceptability of digital health technology (DHT) among respiratory patients. An examination of published DHTs over the past decade was conducted. As technology in healthcare remains in its infancy, supporting evidence is broad and non-specific, primarily focusing on acceptability after a solution's deployment. Common themes associated with DHT acceptability include perceived usability, the quality of healthcare professional interaction, and self-management supported by data feedback. The review underscores a critical lack of focus on pre-implementation acceptability, long-term sustainability, risk management, and standardisation of DHTs. The identified gaps in knowledge are substantial, with the most urgent being pre-acceptability, risk, and standardisation. Consequently, there is a commensurate need to engage end-users in the co-design and policy-making process to ensure a sustainable and effective shift within healthcare towards remote monitoring and digital platforms.

Keywords: respiratory diseases, lung diseases, digital health technology, remote monitoring; health technology, acceptability, views or perspectives

1. Introduction

The COVID-19 pandemic forced various industries to rapidly incorporate digital technologies, disrupting traditional workflows. In healthcare delivery, the pandemic forced clinicians to consider new ways of working, to be more flexible and innovative in the mode of delivery of care to service users. In advance of the pandemic, generally

speaking, digital health technology was not considered an essential component of most healthcare professionals' workflows, but the pandemic rapidly accelerated the need for new ways to review service users. Digital health technology (DHT) will be the key to reducing the burden on healthcare systems, increasing access to specialist intervention, and to the reduction of lengthy waiting lists. DHT comes in many forms, such as wearable devices, online platforms, mobile health, telehealth, and telemedicine. Ultimately, digital health refers to the use of communications and health technologies to manage illness and provide information to service user [1]. In theory, the use of DHT is positive; however, many factors contribute to its success. These include the foresight and readiness of healthcare institutions, governments, infrastructure, and service users.

There are many variables to be considered when objectively reviewing "readiness" for digital health technology. Taking the service user for example, Müller et al. [2]. support the theory that digital health requires service users to be literate, health literate and Information Technology (IT) literate to enable them to engage and benefit from this improved technology. National Adult Learning Authority (NALA) published an audit in 2013 estimating that in Ireland, 17.9% or 1 in 6 of the population have low basic reading and writing levels. This includes the inability to read, search for information, and or have the ability to understand health information. This is a very relevant consideration when introducing health technology as a means of service delivery. Healthcare professionals must be cautious to ensure that the more vulnerable are not excluded.

There is a strong onus on the Irish Government to ensure that the nation of Ireland is prepared for this era of digital health transformation. There is a commensurate need for a bottom-up, top-down collaboration in the form of frameworks, policies, and procedures to ensure that Ireland plays a pivotal role in leading this new digital decade within Europe. The Irish government has shown commitment to this change in the form of a published document in 2021, entitled *The Embracing Digital Transformation*. The Digital Ireland Framework outlines key objectives across various sectors, including infrastructure, with the goal of providing nationwide Gigabit network coverage for households and businesses by 2028 and ensuring 5G access in all populated areas by 2030. Efforts are underway to expand high-speed connectivity, both domestically and internationally, while also tackling energy efficiency and sustainability challenges linked to digital advancements. Additionally, the framework emphasises strengthening Ireland's cybersecurity capabilities, expertise, and infrastructure to safeguard digital progress. *Harnessing Digital (2021) - The Digital Ireland Framework* aims to see the digitalisation of public services with a target of 90% of applicable services consumed online by 2030, and 80% of eligible citizens using MyGov ID by 2030, with a significant drive for further digitalisation of public services with a focus on the health system. The Health Service Executive National Service Plan identified 2022 eHealth investment priorities, focusing on establishing essential digital infrastructure and cybersecurity, sustaining critical national health systems, and advancing eHealth and ICT solutions to support the ongoing reform and modernisation of Ireland's healthcare system. While in theory, the targets identified and committed to by the Irish government are rather attractive, pessimists could be forgiven for alluding to the fact that, concerning healthcare, it may all be futile if an understanding of the needs and wants of the service user is not understood.

A review of the literature presents a very clear picture of the need for focused research to address this knowledge gap for various key stakeholders, in particular, that

considers the inputs of end-users. While research exists on the use of technologies by specific cohorts of service users, it is more often the case that these technologies were developed and then tested on service users with no prior input from the service users in terms of acceptability or utility from their perspective. Standardisation of DHT and risk are two gaps for which the literature yielded limited evidence of progress. Nationally and internationally, there is much work to be conducted, starting at the government level and involving those involved in policy making to address these areas. If DHT is not regulated or standardised, it poses an increased risk to the user. If industry and technology developers do not have to meet a minimum standard, there is a lack of clarity about whether the technology has the capabilities to meet the assumed intentions. The development of policy with pre-defined requirements and a robust quality control process is required.

A key area that has emerged in terms of the knowledge gap is concerning the pre-acceptability of DHT. Pre-acceptability is considered a person's intention to use a piece of technology, formally known as pre-adoption [3]. To date, the primary focus of research is specific to the users' perspective on health technology after a period of use. In this instance, time and money have been invested in technology development with no input from the intended user.

The key to successful uptake of any technology is user acceptance; however, this is impacted by multiple factors [4]. It is clear from the scoping review that multiple gaps in the literature exist when searching for concise evidence on DHT updates. The literature to date is broad, and indeed, the results make it difficult to quantify. A large proportion of the studies were classified as feasibility studies. It is clear that various types of technology are acceptable to cohorts of patients but lack clarity on if implemented long term if they are sustainable. As previously mentioned, acceptability can be explored in three different subtypes, and this has not been reflected in this review. Therefore, the pre-acceptability of DHT is a significant gap in knowledge within the literature.

2. Factors that impact the pre-acceptability of DHT

An extensive search of Cinahl, Pubmed, Scopus, ACM digital library, Sage, ProQuest, and Science Direct was carried out for this review over a three-month period. The author used multiple keywords, including Respiratory diseases, lung diseases, DHT, remote monitoring or health technology, acceptability, views or perspectives. Papers included in this review were those that were specific to the following criteria: (1) area of respiratory disease; (2) the population was adults; and (3) the primary or secondary outcomes included the acceptability of digital health technology. Papers whose focus was adolescents, paediatrics, or alternated medical conditions were excluded. There were multiple themes and patterns identified from this perspective review, however for the purpose of discussion for this paper, the common themes among all included studies were selected.

3. Pre acceptability

Pre-acceptability is considered a person's intention to use a piece of technology [3]. From this broad search of the literature, it is very apparent that technology has been developed, and then data was collected post a specific timeframe. There is no clear evidence that the intended service user was included in the design phase of any of the

technologies mentioned. Perceived usefulness and perceived ease of use are two key themes identified in the literature, which are also highlighted as being important in ensuring acceptability; however, designers have stressed the difficulty of addressing these factors in the early stages of technology design.

4. Utility and patient understanding/perceived usefulness and awareness of DHT

One of the most common themes in the literature is perceived usefulness. An individual's perception of how DHT will affect them commonly results in either engagement or disengagement.

In many studies, participants stated that they had an element of reassurance when using DHT. Kelly et al. [5] explored the experiences of COPD patients, where participants describe the feeling of being observed as providing peace of mind. It was reassuring to them that healthcare professionals were observing the data remotely and, if a problem arose, it would be dealt with promptly. Similarly, Nissan and Lindhardt [6] explain that individuals found it extremely beneficial that they had increased access to healthcare professionals and that they could receive counselling and guidance whenever they needed it. Due to the frequent interactions with healthcare professionals, there was less of a need for individuals to attend outpatient appointments, and also less waiting time for outpatient appointments, which could often be up to 6 months, therefore individuals reported this to be very beneficial [6].

Interestingly, Korpershoek et al. [7] discussed experiences to the contrary. Individuals in the Netherlands argue that one of the main reasons they would not engage with DHT is the fear of reduced face-to-face contact with healthcare professionals. This cohort of individuals preferred in-person contact and lacked trust in how DHT could benefit them in the management of their chronic disease. This view was mirrored by individuals in the United Kingdom (UK) who placed more value on in-person care [6].

Many studies explored the theme of perceived usefulness with the subheading of chronic disease self-management. Slevin et al. [8] and Vatnøy et al. [9] reported from their qualitative studies that participants view DHT as extremely useful in helping them to independently manage their chronic disease. Both studies utilised qualitative semi-structured interviews with convenience sample sizes of 30 and 10, respectively. Participants reported that having to engage with DHT ultimately forced them to become more aware of their disease and the frequency of symptoms. This was an unforeseen positive as by doing so, they then began to recognise symptoms of exacerbations sooner, which triggered engagement with healthcare professionals and in some cases, reduced the need for a hospital admission [5].

A conflicting argument was made by Loeckx et al. [10], who stated that individuals' perceptions were that technology could not help them manage an acute exacerbation of their chronic disease; therefore, it was perceived not to be a useful aid in the management of their illness. Overall, it seems that better self-management, a higher reported quality of life, and better continuity of treatment from medical experts were the outcomes of their enhanced knowledge and awareness of their illness [9]. Unfortunately, not all studies saw this as a facilitator to the adoption of DHT. The belief that using DHT threatens a person's identity, autonomy, and capacity for self-care is supported by a qualitative study carried out in the UK by Sanders et al. [11]. It was thought that using DHT would lead to a lifestyle that overemphasises illness

and promotes a high level of technological dependence. In order to avoid negative preconceptions about ageing and poor health, people were likewise eager to avoid technology.

A counterargument was presented by Slevin et al. [12], who suggested that using DHT was perceived to lessen an individual's perception of anxiety. For some people, enhanced access to health data and a focus on symptom awareness were perceived as contributing causes to anxiety [11]. In the end, it can be said that a person's opinion of perceived utility is an important factor that should be taken into account as both a facilitator and a barrier to the adoption of DHT.

5. Digital literacy

Digital literacy is defined as a person's ability to locate, evaluate, and disseminate information via a technological device. Digital health literacy, otherwise known as e-Health literacy, is the ability of a person to find, apprehend, and evaluate health information from electronic sources and apply the knowledge gained to address or solve health problems [13]. It's interesting to note that digital health literacy has been found in the research to both influence and potentially significantly hinder the adoption of DHT.

Slevin et al. [14] explored digital health literacy within their study, where findings suggest that individuals with previous experience with technology perceived that these skills enhanced their digital literacy abilities, therefore empowering them to engage with DHT. In the same study, digital literacy was reported to be a significant adoption barrier to digital health technology. The findings of the semi-structured interviews with a convenient sample size of 30 participants suggest that often individuals did not possess any digital literacy skills, resulting in an inability to interpret and act upon the readings of the device, therefore rendering the use of the device futile. Similarly, Sanders et al. [11] explained that a high volume of potential participants for a clinical trial declined an invitation based solely on the fear that they would have difficulty engaging with the technology requirements. This was based on previous experiences with general technology, and ultimately because of feeling alienated from evolving modern technologies. The researcher did not explore the main reasons for the feelings of alienation.

Digital literacy is a common theme within the literature when discussing the facilitators and barriers to digital health technology. There is potential for DHT to make a significant impact with evidence of positive patient outcomes; however, it solely depends on individuals possessing a unique skillset of digital literacy skills [13]. The impact of digital literacy on the overall adoption of digital health technology is identified by Slevin et al. [8] to be an under-researched topic, and is noted as an area for future research.

6. Education

The research also discusses education, particularly information technology (IT) education, as a factor that can help or hinder the adoption of DHT. Similarly, Sönnnerfors et al. [14] also identified that specific IT education was a facilitator of the adoption of digital health technology. Those who had some knowledge of IT were more willing to engage in comparison to those with no knowledge. It is not, however,

very well documented what the level of education of the participants was. None of the studies referred to this. It could be argued that those with some formal IT education could be educated to a higher degree, as this would be a requirement of most individuals who attended third-level education. A counterargument, however, could be made to suggest that given the diversity of the age profile of these studies (50–79 mean), this is an unfair assumption. Education and the level of education of participants is a significantly under-researched area, and most definitely is an area that should be considered for future evaluation.

7. Access to and reliability of technology

To many, the lack of access and fear of reliability was a significant barrier to the adoption of DHT. It would appear that some individuals have a lack of trust in technology and, therefore, are unwilling to engage with it. Korpershoek et al. [7] suggested that individuals do not feel that DHT can be trusted. Similarly, Disler et al. [15] discussed how individuals had concerns about the reliability, accuracy, and variability of some of the online information. It was also a big concern that people could not find and interpret the relevant information about their disease. An American e-Health literacy survey of 1270 patients reported that 70% of patients with chronic obstructive pulmonary disease felt confident that they could source the information, but were less confident in their capabilities of identifying quality information [16]. It should be noted that studies in this literature review investigated different areas of digital health technology, and indeed different types of technology also, however, the theme of reliability of the technology was common among most of the studies reviewed.

Another frequent element in this literature analysis was access to technology and the internet.

None of the studies in this review made specific reference to access to the internet and the reasons why this was an issue. It is unclear if the participants in these studies, which vary across multiple international countries such as the UK, Australia, Denmark, Norway, to name a few, were from an urban or rural geographical location. However, one study by Sönnerrfors et al. [14] in Sweden did note that data were gathered in both rural and urban locations, but the conclusions were not discussed differently.

This would suggest that successful adoption of DHT would require commitment and support from local government to invest in both rural and urban infrastructure and internet access. It would be safe to assume that rural Ireland would lack similar resources and most definitely require investment.

8. Data privacy and security

Data privacy is commonly discussed and is an area that internationally raises concerns. Policy makers follow stringent General Data Protection Regulation (GDPR) and data sharing guidelines when developing national frameworks for DHT. The Data Governance Board was founded by the Irish government in 2021 and has commenced work. This board is tasked to direct, oversee and drive data governance across the public sector (The Digital Ireland Framework, The purpose of the Data Protection Acts of 1988–2018 was to safeguard individuals' privacy. The law imposes obligations on those who hold and process personal information as well as rights on individuals about the privacy of that information. Although it is believed that people may have

strong feelings about their health data and its potential uses, it would be helpful to clarify that this is merely an assumption.

It would appear that some individuals have a lack of trust in technology and, therefore, are unwilling to engage with it. Korpershoek et al. [7] suggest that people do not think digital health technology is reliable. Similarly, Disler et al. [15] discussed how individuals had concerns about the reliability, accuracy, and variability of some of the online information. This is an extremely important aspect of this area, and one that requires insight and understanding. If service users are wary of using DHT due to security concerns, then it must be considered as an impacting factor on the pre-acceptability of DHT.

9. Engagement with healthcare professionals

Increased accessibility to healthcare professionals (HCPs) was identified as an impact factor on the acceptability of DHT. Chau et al. [16] attributed this to improved satisfaction with telemedicine, as service users had access to HCPs who could provide a timely assessment and assist in decision making on actions required. This introduced a sense of security and encouraged closer self-monitoring of symptoms; however, it is noted that some service users identified increased monitoring with negative outcomes, such as an increase in experience of anxiety. Similarly, Jácome et al. [17] report an increased value in the sharing of health data with HCPs, which also resulted in a positive effect on medication adherence and symptom awareness. It is somewhat of a culture change for many generations to engage with HCPs remotely, and indeed, arguably was forced upon most because of the COVID-19 pandemic. Unfortunately, this will be a challenge for the success of DHT, and many service users have an increased value in face-to-face appointments and or voice calls; ultimately, they lack trust in DHT [18, 19].

10. Self-management/data feedback

Self-management of chronic respiratory diseases is widely discussed in the literature and is strongly advocated for within appropriate guidelines [20]. There is evidence to suggest that DHT increase patients' awareness of their condition, reduce hospital admissions, and improve communication with healthcare professionals [21]; therefore, it could be suggested that DHT provides a concrete foundation towards successful self-management. Jácome et al. [17] share evidence that service users are more compliant with technology when there is adequate health data feedback. Users of the technology welcome the gentle reminder about medication adherence and increased symptom awareness helped change their perception of asthma control. Considering the national and international data on asthma alone, this has a significant influence. Asthma affects up to 334 million people worldwide, and Ireland has one of the highest rates in the world. The prevalence of asthma in the country is unclear. According to current statistics, 7–9.4% of adults and 21.5% of children in Ireland have a doctor-diagnosed case of asthma. 7283 acute, publicly funded hospitalisations (day cases and inpatients) were related to asthma in 2016. 1630 inpatient bed days were occupied by 4394 (60%) of these patients, accounting for 0.3% of all inpatient bed days and 2% of all respiratory inpatient bed days. Emergency admissions accounted for more than 97% (4252) of these inpatient hospitalisations [22].

There are significant grounds to suggest that the utilisation of DHT to enhance self-management could have a positive impact on both the service user and a positive financial impact for healthcare institutions. It is unclear, however, if the use of DHT would be feasible across multiple different respiratory disease types. Houchen-Wolloff et al. [23] explored the feasibility of using a web-based self-management program for chronic obstructive pulmonary disease patients and concluded due to the difficulty of recruiting, retaining, and engaging people that it would most deficiently not be feasible. This does highlight the need for technology development driven by data specific to the intended cohort.

11. Sustainability

One concerning outcome arising from this review is that only one study addressed the topic of sustainability. Indeed, most of the technologies introduced throughout the various cohorts of respiratory patients were considered acceptable; however, it is unclear if this enormous investment of time and money is of any value if the technology is sustainable long term. Shinoda et al. [24] show the variability in sustainability using DHT. This study reported that 90% of the 84 participants of people complied with using the technology at the initiation of the study; however, this figure dropped to 40% by the 12th week. Other factors to note are poor compliance in completing rates, which are similar to other telemedicine studies. The suggestion to improve sustainability is by frequent coaching of the user to continue to engage with the DHT.

The use of DHT within healthcare is becoming more popular. It is being used to assist chronic disease management, reduce the need for hospital admission and essentially reduce the burden on our healthcare system. An intriguing and welcome innovation that is presently being investigated globally is the introduction and integration of technology in the form of digital solutions into the delivery of healthcare. Because the objectives of digital solutions are so varied, stakeholders with a special interest in digital solutions must be included [25]. Success requires teamwork, as seen by **Figure 1**’s Quadruple Helix Hub architecture.

The success of any technology is dependent on the acceptance of the user. Perceived usefulness and awareness of DHT, support of self-management of

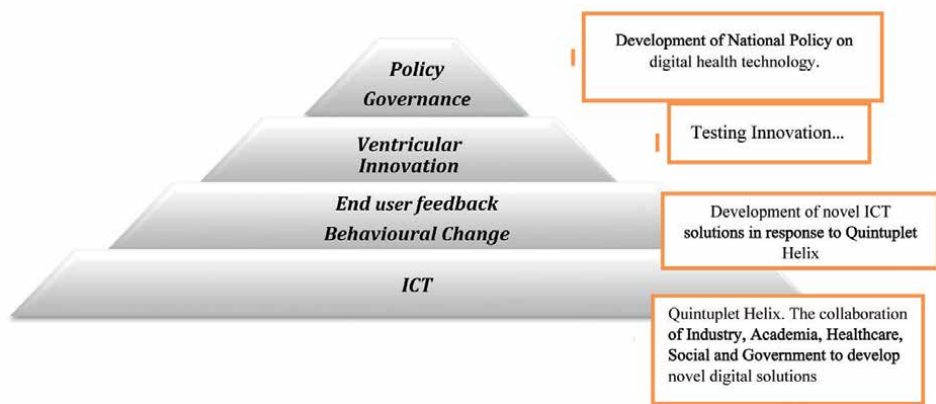


Figure 1. Addressing the interface between top-down digital health policies and service end-user needs, such as through a Quadruple Helix Hub Framework [26].

respiratory disease, engagement with healthcare professionals and design and ability of the technology to provide health data feedback are the key factors that influence the pre-acceptability of DHT. These factors must be considered in the early design phase; however caution is urged, as there may be different perspectives between those from an urban and rural geographical location. It would be foolish not to consider these differences. Sustainability within healthcare could be positively impacted by DHT if the factors contributing to the pre-acceptability were acknowledged and respected.

Acknowledgements

Tara Byrne acknowledges funding support from Technical University of the Shannon and Ireland's Health Service Executive for this Doctorate study.

Conflict of interest

The authors declare no conflict of interest.

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Perspective Chapter: Enhancing Elderly Care through AI Approach

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Abstract

As global populations age, ensuring the safety and well-being of elderly individuals—particularly through reliable fall detection—has become a pressing public health concern. This chapter explores the intersection of electronic engineering, artificial intelligence (AI), and healthcare technologies to address the challenge of real-time fall detection. We provide a comprehensive overview of the evolution from conventional sensor-based systems to modern AI-driven solutions, including vision-based detection, pose estimation models such as MediaPipe and YOLO, and edge computing platforms for real-time processing. A robust fall detection algorithm is proposed, leveraging ensemble classifiers and temporal pose data, and is evaluated against public datasets. Extensive comparisons with existing approaches demonstrate the proposed model's reliability, responsiveness, and computational efficiency. Through detailed discussion of system design, implementation, and deployment constraints, this chapter highlights the promise of AI in enhancing elderly care and enabling intelligent, decentralized health monitoring systems.

Keywords: image processing, machine learning, human action recognition, AI healthcare, elderly care

1. Introduction

The rapid aging of the global population has made elderly care a critical societal challenge. In 2022, there were over 770 million people aged 65 and above worldwide (about 10% of the global population), and this figure is projected to more than double to around 1.6 billion by 2050 [1, 2]. As people live longer, age-related declines in motor and cognitive function increase the risk of falls and related injuries. Falls have become the second leading cause of unintentional injury deaths globally [3]. Each year, tens of millions of older adults suffer falls; the World Health Organization estimates that about 37.3 million falls annually are severe enough to require medical attention, and roughly 684,000 of these are fatal [1, 4]. In addition to the human toll, such incidents place a substantial burden on healthcare systems. Studies have found that prompt medical intervention after a fall can significantly improve outcomes. For example, implementing a fall prevention plan in primary care settings that includes timely assessment and intervention has been shown to reduce the risk of fall-related

hospitalization by approximately 40% in older adults [5]. This underscores the urgent need for reliable fall detection systems that can automatically recognize falls in real time and rapidly alert caregivers or emergency services.

Early efforts in fall detection and prevention emerged from the fields of electronic and computer engineering, producing hardware devices such as personal emergency response systems and wearable fall alarms. Over time, technological advancements have expanded the toolkit for elderly care from simple electronics to sophisticated smart health solutions. In particular, the advent of the Internet of Things (IoT) and pervasive sensing has enabled continuous monitoring of seniors' environments and wellbeing. Wearable sensors, ambient environmental sensors, and smart home devices can now collect rich data on an individual's movements, activities and vital signs, all of which can be leveraged to detect falls or predict health deteriorations [6, 7]. High-speed wireless connectivity (e.g. 5G networks) further facilitates real-time transmission and processing of such data with minimal latency [8]. These developments have laid the foundation for intelligent fall detection solutions that operate seamlessly and unobtrusively as part of the living environment. For instance, modern fall detection systems may integrate accelerometers in smartwatches, depth cameras in homes, and pressure sensors in flooring, creating an electronic safety net around older individuals.

In parallel, artificial intelligence (AI) techniques have risen to prominence as powerful tools for healthcare applications. Machine learning (ML) algorithms are adept at recognizing patterns in sensor data and images, enabling more accurate and context-aware detection of health events like falls. Early rule-based or threshold-based fall detectors, which have often suffered from either too many false alarms or missed events, are being supplanted by AI models that can learn complex features distinguishing falls from normal activities [9, 10]. Beyond fall detection, AI is increasingly employed in elder care for a wide range of purposes: predicting and preventing health crises, assisting in diagnosis of age-related conditions, and providing personalized support or rehabilitation. Notably, recent advances in *generative AI* and large language models (LLMs) have opened new possibilities in senior care. Generative AI-powered chatbots and virtual assistants can help monitor high-risk seniors remotely and provide companionship to reduce loneliness [11, 12]. For example, AI conversational agents can check on an older person's daily status, remind them to take medications, or engage them in dialog to alleviate social isolation. In the background, these AI systems can analyze conversational cues or sensor data to detect signs of health decline, enabling early interventions.

Large language models such as ChatGPT have demonstrated an ability to interpret health-related queries and generate human-like responses, which could be utilized for health education, cognitive training, or triaging medical issues for older adults [8, 13]. The integration of AI and especially generative AI into elder care holds great promise for improving quality of life—offering older adults greater independence, safety, and social connectivity. However, it also introduces new considerations around ethics, privacy, and accessibility, which researchers and practitioners must carefully address [14, 15].

In light of these trends, the convergence of advanced sensing technologies, AI algorithms, and edge computing platforms has paved the way for next generation fall detection systems. An ideal solution would accurately detect falls in real time, minimize false alarms, respect the user's privacy and comfort, and function reliably in everyday living environments. This chapter presents an efficient and reliable vision-based fall detection algorithm aimed at enhancing elderly care

through timely and accurate fall alerts. We build on recent progress in computer vision and human pose estimation to create a system that achieves high precision without the need for expensive computing hardware. The following sections provide a comprehensive overview of related works in fall detection (covering vision-based approaches, sensor-based approaches, pose estimation techniques, ML models, and deployment challenges), then detail the proposed methodology and system architecture, followed by experimental results and discussion of the outcomes. The goal is to demonstrate that our approach can meet the practical requirements of real-time fall detection for digital health applications, ultimately contributing to safer independent living for seniors.

In the context of telemedicine, the proposed AI-driven fall detection system offers substantial advantages for remote health monitoring. By continuously analyzing video streams locally and issuing real-time alerts without the need for constant clinical supervision, this system enables caregivers and healthcare providers to monitor elderly individuals from a distance. Such decentralized monitoring reduces hospital dependency, allows timely intervention, and supports independent living—core goals of telehealth initiatives. Therefore, this work directly contributes to the broader development of remote elderly care within telemedicine frameworks.

2. Related work

Researchers over the past decades have extensively explored fall detection, producing a rich body of literature and a variety of technological approaches. Broadly, existing fall detection methods can be grouped into three categories based on the type of data and sensors used: (1) vision-based approaches, (2) sensor-based approaches (including wearable and ambient sensors), and (3) hybrid or pose estimation-based approaches that often combine vision with ML on human skeletal data. In addition, considerable effort has been devoted to developing suitable ML models for fall classification and deploying these solutions on resource-constrained hardware at the network edge. In this section, we review representative works in each of these areas and discuss the strengths and limitations relevant to designing an efficient real-time fall detector.

2.1 Vision-based methods

Vision-based fall detection relies on analyzing image or video data (typically from RGB cameras, depth cameras, or thermal cameras) to recognize when a person has fallen. These methods are appealing because they do not require the monitored individual to wear any device, making them non-intrusive in daily life. Early vision-based systems applied traditional computer vision techniques to detect falls. For example, some approaches tracked the human body's silhouette or bounding box in the video and identified a fall by characteristic changes such as a sudden drop in the person's vertical position or aspect ratio [16]. Charfi et al. [16] extracted spatio-temporal descriptors from video and used classifiers (Support Vector Machines and AdaBoost) to differentiate falls from normal activities, achieving real-time detection with modest hardware requirements. Other classic methods involved background subtraction to detect a moving person and then applying heuristics—for instance, a person lying on the floor would appear as a broad, low-height shape in the image, triggering a fall alarm [16]. These traditional vision techniques can work in controlled settings,

but they often struggle with variations in environment and are sensitive to lighting changes, shadows, or occlusions. As a result, their robustness in complex real-world scenes is limited.

More recently, deep learning has revolutionized vision-based fall detection by enabling automatic feature learning from large datasets of fall and non-fall video examples. Convolutional Neural Networks (CNNs) and other deep models can recognize subtle motion and posture patterns associated with falls. For instance, Abdo et al. [7] proposed a fall detector using the RetinaNet CNN for person detection combined with a MobileNet-based classifier to identify falls, showing improved accuracy over hand-crafted feature methods. Another notable direction is to use 3D CNNs or video-based models that capture temporal information across frames. Tran et al. [17] demonstrated that 3D convolutional networks can automatically learn spatiotemporal features for human action recognition in video; such models have been applied to fall detection, as they can encode the motion dynamics of a falling person in addition to static posture cues. Sun and Wang [18] introduced a vision system that utilizes human posture estimation to assist fall detection, reflecting a trend of combining deep learning-based pose recognition with fall classification. Overall, vision-based methods augmented by deep learning achieve high detection rates in experimental settings, with reviews reporting substantial performance gains using CNNs on benchmark fall video datasets [9]. For example, Keskes and Noumeir [10] applied a spatio-temporal Graph Convolutional Network (ST-GCN) on sequences of human pose skeletons extracted from video, reaching competitive accuracy in detecting falls. The main advantages of deep learning vision approaches are improved accuracy and the ability to handle diverse scenarios by training on large data.

However, they also demand higher computational power (often requiring GPUs for real-time processing) and may still face challenges with camera occlusion, multiple people in the frame, and privacy concerns due to continuous video monitoring. Some recent works tackle the occlusion issue by model-based solutions—for instance, Khalili et al. [19] developed a fall detection algorithm for closed circuit television cameras that remains effective even when the subject is partially occluded, using clever background modeling and temporal reasoning. Vision-based systems must balance the coverage and detail provided by cameras with these practical limitations. In summary, vision methods form a key pillar of fall detection research, offering non-contact monitoring and rich information, and their capabilities continue to expand with advancements in computer vision and AI.

2.2 Sensor-based methods

Sensor-based fall detection methods involve measuring an individual's motion or physiological signals using dedicated sensors, rather than cameras. The most common sensor-based approach utilizes *wearable sensors*, such as accelerometers and gyroscopes worn on the body (e.g., in a smartwatch, smartphone, belt, or pendant) to detect the sudden movements characteristic of a fall. These systems typically monitor acceleration in three axes and look for a rapid large change in acceleration (impact) followed by a period of inactivity, which is a signature of a hard fall to the ground. Numerous studies have validated the effectiveness of wearable accelerometer-based fall detectors [20]. For example, Qian et al. [20] developed a real-time fall detection system using a tri-axial accelerometer in the context of IoT; their device transmitted sensor data to a cloud platform which applied ML to distinguish falls from activities of daily living. Wearable sensors offer advantages of being low-cost, lightweight, and

capable of continuous operation. They also preserve privacy better than cameras, since no visual data is recorded. However, a significant drawback is that the user must remember to wear the device consistently and it must maintain contact to function properly. Older adults may forget or refuse to wear sensors all the time, or the device may be improperly worn, reducing reliability. Additionally, false alarms can occur in certain normal movements that mimic a fall's acceleration profile (such as quickly sitting down or dropping the device on a table) [6]. Researchers have improved wearable fall detection accuracy by fusing multiple sensors (combining accelerometer with gyroscope, magnetometer, barometer, etc.) and by applying pattern recognition algorithms to sensor signal features rather than simple thresholds [20, 21]. Despite these refinements, wearable approaches ultimately face the compliance challenge and some burden on the user.

Besides wearables, there are *ambient sensor* methods for fall detection that utilize devices installed in the environment. These can include pressure sensors in the floor or furniture, acoustic sensors (microphones) listening for the sound of a fall or a cry for help, infrared motion sensors, and even radar-based sensors that detect human movement and posture via radio waves [3]. Ambient sensors operate without requiring any action by the individual, thus avoiding the compliance issue of wearables. For instance, some smart home systems use acoustic classifiers to detect the distinctive “thud” of a person falling or use pyroelectric infrared sensors to sense unusual inactivity or positions.

Kepski and Kwolek [22, 23] proposed a hybrid system combining a body-worn accelerometer with a Microsoft Kinect depth sensor placed in the environment; the depth sensor could verify a fall by detecting a person lying on the floor, thereby improving overall reliability. Another approach by Htun et al. [24] introduced a “virtual grounding point” concept using environmental sensors to differentiate abnormal events like falls from normal movements, showing that environmental context can assist in robust detection. However, purely ambient sensor-based methods are relatively uncommon in literature compared to camera or wearable methods. This is partly because they can suffer from high false alarm rates (e.g., a loud noise might be misinterpreted as a fall) and may require extensive instrumentation of the living space which can be costly and complex to install [25, 26]. Ambient sensors like radar are an active research area for non-intrusive monitoring, but practical deployments often integrate them with other modalities.

In summary, sensor-based methods (both wearable and ambient) provide viable solutions for fall detection with their own trade-offs. Wearables offer direct measurement of body motion with high sensitivity but depend on user compliance, whereas environmental sensors allow unobtrusive monitoring but face challenges in coverage and accuracy. Many modern fall detection systems attempt to combine data from multiple sensors to capitalize on their complementary strengths, as exemplified by several IoT-based prototypes that use sensor fusion and hierarchical decision-making to reduce false alarms [6]. Regardless of the approach, sensor-based systems remain an important class of solutions, particularly for scenarios where camera use is not feasible due to privacy or environmental constraints.

2.3 Pose estimation and hybrid approaches

A notable trend in recent years is the use of human *pose estimation* techniques for fall detection. Pose estimation refers to algorithms that locate key points of the human body (joints like head, shoulders, knees, etc.) from sensor data, most often

from images or videos. By analyzing the configuration and movement of these key points, a system can infer whether a person is in a fallen posture or undergoing a fall motion. This approach essentially merges vision-based and feature-based methods: it uses computer vision (or other sensors) to extract a high-level representation of the human body's pose, and then applies analytical or ML methods on that representation to detect falls.

Several research efforts have leveraged pose estimation models like OpenPose [27], MediaPipe BlazePose [28], or AlphaPose to assist fall detection. These models provide real-time coordinates of a person's skeleton on each video frame. For example, OpenPose can output the 2D positions of major joints of all people in a camera view. A fall detection algorithm can then compute features from these joint positions, such as the orientation of the torso, the distance of the head from the floor, or sudden changes in limb velocity. Sun and Wang [18] implemented a system where a pose estimation network first determines the human body posture; then by tracking how the posture changes (e.g., going from upright to lying down quickly), the system flags falls. Similarly, Alam et al. [29] proposed a lightweight fall detection framework using pose landmarks: they reduced the complexity of the pose model to run on portable devices and still achieved accurate fall recognition.

One advantage of pose-based methods is that they focus on human movement patterns while being somewhat invariant to the subject's appearance or the background. In other words, by reducing video to skeleton key points, the method can maintain privacy (the video need not be stored or transmitted, only the abstracted pose) and can be more robust to lighting or clothing differences.

Moreover, analyzing pose sequences allows leveraging domain knowledge from biomechanics—for instance, researchers have long noted that the velocity and acceleration of the torso or head are discriminative features for falls [30].

Indeed, Wu's biomechanical study [30] found that fall motions could be reliably distinguished from activities like walking based on vertical velocity profiles. Such insights can be encoded as features derived from pose data.

A representative hybrid approach is the one by Wang et al. in a prior study [6], where a two-stage fall detection pipeline was used: first, a pose estimation (BlazePose) model extracts skeletal landmarks of the person; then a ML classifier (Random Forest) evaluates these landmarks over time to decide if a fall occurred. In their system, features like the person's height relative to the camera, the aspect ratio of the bounding contour, the centroid's vertical displacement, and the speed of descent were critical for accurate detection [6]. The use of BlazePose [28], in particular, allowed on-device, real-time pose tracking, making the solution feasible on edge devices. Other works have combined object detectors like YOLO with pose estimation: for example, Tirziu et al. proposed a YOLOv5 + MediaPipe framework where YOLO first detects the presence and location of people in the frame and then MediaPipe Pose provides the key points for those people, which are analyzed to detect falls, followed by an alert mechanism. This kind of system can take advantage of YOLO's efficiency in handling multiple people and MediaPipe's pose accuracy.

Pose estimation-based fall detection has shown excellent accuracy and a good balance between complexity and performance. However, challenges remain. These include difficulty in tracking people under occlusion, errors in multi-person environments, variation in camera viewpoints, and the computational cost of running pose models on every frame. These issues may reduce system reliability in uncontrolled real-world settings.

Occlusions or multiple people in view can confuse pose trackers (although multi-person pose estimation algorithms are improving steadily). The computational load of running a pose model on every frame can be high, though models like BlazePose are optimized for speed on CPUs and mobile devices. Another challenge is the generalization across different camera angles and individual body types—pose models are typically robust, but extreme view angles (top-down cameras vs. horizontal cameras) might require adjustment or training. Nevertheless, the ability of pose-based methods to maintain privacy (by not needing to store raw video) and to provide interpretable features (clinicians can understand joint angles and velocities) makes them very appealing for real-world adoption. As a result, human pose estimation has become an essential component in many state-of-the-art vision-based fall detection systems and continues to attract research attention.

2.4 Machine learning models and edge computing

Regardless of the sensing modality used (cameras or other sensors), an effective fall detection system needs a robust *classification model* at its core to distinguish falls from normal activities. A wide range of ML models have been explored for this purpose, from simple threshold-based logic to complex deep neural networks. In early works, thresholding was commonly applied to features like acceleration magnitude or body tilt angle to detect falls. While straightforward and low-cost, threshold methods often fail to generalize to diverse individuals and environments. Consequently, researchers moved towards data-driven ML algorithms that can learn optimal decision boundaries from training data.

Classic supervised learning algorithms such as Support Vector Machines (SVM), Decision Trees, k -Nearest Neighbors (kNN), and Naïve Bayes classifiers have all been tried in fall detection literature [25, 26]. These models take in features extracted from sensor signals or images—examples include mean and peak values of acceleration, time duration of a possible fall event, orientations from gyroscopes, or shape descriptors from images—and output a prediction of fall vs. non-fall. SVMs, for instance, were favored for some time due to their effectiveness on smaller datasets and ability to handle high-dimensional feature vectors; they have been used especially in posture-based fall classification tasks, where features might be angles or ratios representing body pose [25]. Decision trees (and ensemble variants like Random Forests) provide interpretable rules and have been used to correlate physiological data (like changes in blood pressure or heart rate) with falls in some studies [25]. Naïve Bayes offers a fast solution with low computational needs, suitable for running on embedded edge devices, though its accuracy can be lower than other methods [25]. Overall, these traditional ML models have relatively low computational footprint and can be deployed on devices like microcontrollers or smartphones. However, they usually require careful feature engineering by domain experts to achieve good accuracy, and their performance may degrade if the real-world data distribution deviates from the training data.

In recent years, *deep learning* models have gained prominence in fall detection, mirroring their success in broader areas of computer vision and signal processing. Deep learning can automatically learn complex feature representations from raw input data, obviating the need for manual feature design.

Researchers have applied deep neural networks to both wearable sensor data and video data for fall detection. For wearable data, one approach is to use deep recurrent

networks or Temporal Convolutional Networks that can model time-series patterns in accelerometer signals. For example, a Long Short-Term Memory (LSTM) network could learn the sequence pattern of acceleration preceding a fall. On the vision side, CNN-based architectures (2D or 3D) are employed, as discussed earlier. One example is the PEFDM system by Li et al., which uses a deep CNN for pose extraction and fall detection in one framework [9, 29]. The advantage of deep learning is its high capacity for capturing subtle patterns and interactions (like the combination of speed and orientation that signifies a fall as opposed to bending down intentionally). Indeed, Alam et al. [9] review various deep learning-based fall detection systems and conclude that these methods generally outperform classical ML in detection accuracy. However, deep models are typically more computationally intensive and often require more data to train to avoid overfitting. In the context of falls, obtaining vast amounts of real-world fall data is problematic (falls are rare and risky to stage with older people), so many works rely on simulated falls by young volunteers or augmentation techniques, which might not cover all real scenarios [6]. This presents a challenge for deep learning approaches to truly generalize. Nonetheless, hybrid strategies are emerging, such as using deep learning for part of the pipeline (e.g., feature extraction via a deep pose model) and a simpler classifier on top for the final decision, combining the best of both worlds.

Another important aspect is the *computing platform* on which the fall detection algorithm runs. To be practical for real-time use in elder care, the system often needs to operate on edge devices (like a home hub, smartphone, or wearable microcontroller) rather than relying solely on cloud computing. Edge computing is favored for fall detection because it can significantly reduce the response time (latency) and continue functioning even without internet connectivity, which is crucial for emergency detection [20, 21]. Moreover, processing data locally on the edge helps preserve privacy by not constantly streaming sensitive data (videos or personal accelerometer data) to external servers [14, 31].

Many recent fall detection studies have addressed the deployment challenges by designing lightweight algorithms suitable for edge devices. Lin et al. [21] implemented an AI-based fall detection on an edge computing platform, using efficient neural network models to analyze sensor data and achieving real-time performance with low energy consumption. Their approach highlights that careful model optimization (e.g., using fewer parameters, quantized networks, or efficient architectures) can make sophisticated detection feasible on devices like Raspberry Pi or even microcontroller units. Edge-AI approaches have also been combined with communication technologies like LoRaWAN to create distributed fall detection networks that cover large areas without burdening any single device [31].

One inherent trade-off in edge deployment is that the model must be small enough to run on limited hardware, which might impact accuracy. This has led to research into model compression and on-device learning. Some systems use a two-tier architecture: a simple fall detector running continuously on the edge, which if triggered, can activate a more powerful analysis either on a more capable local device or via the cloud for verification [20, 21]. This kind of fog computing approach balances the load. For example, a smartwatch might detect a potential fall and send an alert to a home gateway which then examines home camera footage to confirm the fall, combining edge immediacy with cloud-level processing when needed. The ultimate aim is to maximize the speed and reliability of detection while minimizing resource use.

In summary, a diverse array of ML models have been applied to fall detection, evolving from simple thresholds to complex deep networks. Coupled with the push

towards edge computing, recent solutions strive to maintain high accuracy with low latency and resource requirements. As edge hardware continues to improve and specialized AI accelerators become common in mobile devices, we can expect fall detection algorithms to become faster and more autonomous, running entirely within a user's home or wearable device without external dependencies. The challenge remains to ensure these models are rigorously validated on real-world data and that they incorporate the necessary safeguards (such as addressing bias or providing explainability) to be trusted in healthcare contexts [14, 15].

2.5 Deployment challenges

While significant progress has been made in developing fall detection technologies, there are numerous practical challenges that must be addressed before such systems can be widely deployed in elderly care settings. One major concern is *usability and acceptance*. Any monitoring system for older adults must be unobtrusive and respect the individual's comfort and dignity. Camera-based methods, for instance, often raise privacy issues—older persons (and their families or caregivers) may feel uncomfortable with continuous video surveillance in private spaces like the home. Ensuring data security and privacy is paramount; streams from vision systems should be encrypted and processed locally when possible to prevent unauthorized access or breaches [14]. Some recent approaches attempt to mitigate privacy concerns by using depth cameras (which do not capture identifiable color images) or by processing video to extract only abstract features (like silhouettes or pose skeletons) and discarding the raw images [19]. Nonetheless, transparency with users about what data is collected and how it is used is crucial for acceptance.

For wearable and sensor-based systems, the challenge is that they must seamlessly integrate into a user's daily routine. Devices need to be comfortable, easy to wear, and have sufficient battery life to minimize maintenance. Many seniors are not accustomed to wearing gadgets all the time, so designs resembling normal attire (like smart insoles or belts) are being explored to improve adherence.

Even so, a fraction of potential users may refuse or forget to wear the device consistently, which can limit effectiveness. Training and educating users and caregivers on the importance of keeping sensors on (or cameras unobstructed) is an important part of deployment.

Another challenge is *accuracy and false alarms* in real-world environments. An algorithm that works well in a controlled lab or on curated datasets may face new variables in homes: pets moving around, visitors, furniture rearrangements, poor lighting, etc. These can all trigger false positives in a naive system (for example, a pet might be mis-detected as a fallen person by a camera). False alarms are more than a nuisance; frequent false alerts can erode the user's trust in the system and lead them to disable it or caregivers to ignore the alerts. On the other hand, false negatives (missed falls) are dangerous as they defeat the purpose of the system. Achieving a high detection rate (sensitivity) while keeping false alarms (specificity) low is a delicate balance. Many studies report high performance metrics on certain datasets, but these may not directly translate to similar performance in different real-world contexts due to dataset bias [28, 29]. In fact, a known issue is the use of young volunteers to simulate falls in datasets—their way of “falling” may differ from how an elderly person would fall, both in speed and in pre-fall behavior. This can lead to models that are tuned to detect the dramatic falls of young actors but might miss slower falls (e.g., a controlled slide to the ground) that an older adult might experience [6]. Some research has

highlighted these differences and suggested that incorporating data or knowledge specific to elderly movement patterns can improve model performance for the target demographic [6].

To address false alarms, many systems incorporate context-awareness or multi-modal data. For instance, combining an accelerometer with a camera: if the accelerometer indicates a possible fall, the camera can cross-verify if the person is actually on the ground. Contextual information such as time of day, known activity patterns of the user, or the presence of a second person in the environment can also inform the decision (for example, a fall alert might be suppressed if the system detects the user is currently in bed rather than walking). Such context integration can reduce false positives but adds complexity to the system.

Integration with healthcare workflows is another deployment consideration. A fall detection system should not exist in isolation; it needs to effectively notify someone who can help. This could be an alarm to a caregiver in the next room, a text message or call to family or a monitoring service, or even an automatic call to emergency responders if no one else is available. Ensuring that the alert mechanism is reliable (no missed communications), quick, and directs help to the right location is part of the challenge. Moreover, systems should be designed to avoid alert fatigue—e.g., by tiered alerting (first alert the user if they are conscious and can cancel a false alarm, then alert a caregiver, then emergency services as a last resort). The IEEE 11073 Personal Health Device standards and similar guidelines can be looked at for integrating such devices into health information technology systems.

There are also technical challenges like *power consumption* and maintenance. Devices operating continuously must either have long-lasting batteries or a convenient recharging method. Sensor drift or camera calibration might degrade over time, so periodic maintenance or self-check routines are helpful. If the system relies on an internet connection (for cloud processing or alerting), then network reliability becomes an issue—an ideal fall detector should still function during network outages (at least to raise local alarms). Edge computing addresses some of this by localizing processing, but not all systems can run entirely offline (e.g., if using a cloud AI service).

Finally, one must consider *ethical and bias issues* when deploying AI in elder care [15, 16]. AI models trained on certain populations may not perform well for others; for example, a vision model trained primarily on younger subjects might misclassify an older person using a walker. Datasets should include diverse ages, body types, ethnic backgrounds, and environmental settings to ensure fairness and robustness. Moreover, the system's decisions should be interpretable to some degree, especially in a healthcare context—caregivers or clinicians might need to know why the system generated an alert (to avoid chasing false leads or to address any hazardous situation that caused a false alarm).

In conclusion, deploying a fall detection algorithm in the real world involves more than achieving high accuracy in experiments. It requires careful human-centric design, reliability in various conditions, integration with response protocols, and safeguarding user trust through privacy and low false alarm rates. Researchers and engineers are actively working on these challenges, and pilot trials in smart homes and assisted living facilities are providing valuable feedback. The continued collaboration between technologists, healthcare providers, and end-users (older adults) is essential to refine these systems.

Addressing these deployment challenges will ultimately determine the impact of fall detection technology on enhancing safety and care for the elderly.

3. Methodology

In this chapter, we present the design and implementation of a real-time fall detection algorithm that prioritizes computational efficiency and reliability. The system is designed for deployment on modest hardware, such as a standard laptop CPU or edge device, without sacrificing accuracy.

The overall methodology combines traditional background subtraction techniques with modern human pose estimation. It then uses a ML classifier to robustly identify fall events based on human biomechanical features.

Figure 1 provides a schematic overview of the system pipeline, which can be summarized in three major components: *motion detection*, *pose estimation with feature extraction*, and *fall classification*. The input and output modules are shown in blue, the motion detection process in green, the origin of the extracted features in red, and the classifier in yellow.

3.1 Motion detection via background subtraction

The first step of our algorithm focuses on detecting moving people in the video feed, in order to efficiently isolate regions of interest for further analysis. We utilize a background subtraction method to segment the moving foreground (potentially a person) from the static background in each frame. Specifically, we adopt an adaptive Gaussian mixture model (GMM) approach for background modeling as proposed by Zivkovic and van der Heijden [32]. This method dynamically updates a statistical model of the background for each pixel and identifies pixels that do not fit the model as foreground. The adaptive nature of the model allows it to handle gradual lighting changes and periodic background motions (like rustling curtains) by learning multiple Gaussian modes per pixel.

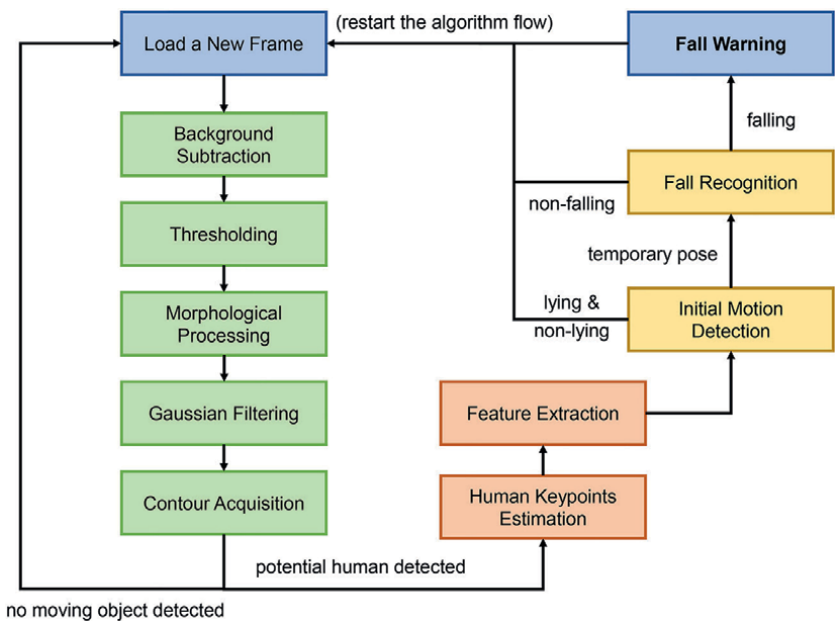


Figure 1.
System architecture of the proposed fall detection algorithm.

After computing the foreground mask via the GMM background subtractor, we apply a series of image processing steps to refine the detection of the human silhouette. First, we perform thresholding using Otsu's method [33], an automatic threshold selection technique that finds an optimal grayscale cutoff to separate foreground and background pixels. Otsu's method is well-suited here as it chooses the threshold that minimizes intra-class variance, effectively differentiating the darker moving object (person) from a lighter background, or vice versa, without manual tuning [33, 34]. The result is a binary silhouette of the moving object. Next, we apply morphological operations (specifically, a morphological opening followed by a closing) to the binary mask to remove noise and fill small holes [34]. These operations, defined in Gonzalez and Woods' image processing framework [34], help to produce a clean contiguous blob representing the person.

Once we have a cleaned-up foreground mask, we find contours and bounding boxes around connected components in the mask. At this stage, assuming at most one person is in the camera's field of view (a reasonable assumption for many indoor eldercare scenarios, or can be enforced by monitoring one person at a time), we select the largest contour or bounding box as the human subject. This gives us the approximate location and extent of the person in the frame, as well as basic shape information (such as the height and width of the blob). If no moving object is detected (e.g., the person is completely still or out of frame), the system will treat it as no fall event for that frame and continue to monitor. The motion detection component significantly reduces the amount of data to process in subsequent steps by focusing the computation on regions where relevant activity (movement) is occurring. It also provides initial measurements like the person's silhouette dimensions and position, which will be used as part of the feature set for fall classification.

3.2 Pose estimation and feature extraction

The core of our approach lies in analyzing the human subject's posture and motion to determine if a fall has taken place. For this, we leverage a state-of-the-art pose estimation model to obtain key point locations of the person's body.

We integrate Google's BlazePose model [28], a lightweight yet robust 2D pose estimator originally designed for mobile devices, which is capable of tracking 33 anatomical key points (including major joints and landmarks like eyes, ears, etc.) on the human body in real time. BlazePose was chosen for its excellent balance between accuracy and speed on CPU, enabling our system to run without requiring a dedicated GPU.

In each frame where the motion detector has identified a person, we apply BlazePose to the region of interest. Specifically, we feed the cropped image of the person (using the bounding box from the previous step, possibly expanded by a margin) into the BlazePose network. The model returns normalized image coordinates for each key point (e.g., positions of the head, neck, shoulders, elbows, wrists, hips, knees, ankles, etc.). We then map these normalized coordinates back to the original frame scale to get real pixel coordinates of the body joints. At this point, we have the pose skeleton of the person superimposed on the video.

With the sequence of pose data over time, we construct a set of *biomechanical features* that are indicative of a fall. Our feature design is informed by prior work and common characteristics of falls:

- *Body orientation and aspect ratio*: We calculate the aspect ratio of the person's bounding box (height divided by width). During a fall, a person often goes from an upright orientation (tall, narrow bounding box) to a horizontal lying

orientation (short, wide bounding box). A sudden change in aspect ratio can signal a fall [7]. We also note the angle of the body's principal axis if needed (though in our case aspect ratio suffices as a proxy).

- *Centroid height*: Using the pose key points, we estimate the person's overall centroid or center of mass. We track the vertical position (height from the floor or bottom of the frame) of this centroid. A fall will usually cause a rapid downward shift in the centroid. We incorporate a feature that captures the relative height of the person's centroid compared to a typical standing height for that individual. This can be normalized against the person's initial height when upright.
- *Velocity and acceleration*: We compute the vertical velocity of the torso or centroid between consecutive frames. A high downward velocity followed by near-zero velocity (when the person hits the ground and lies still) is a strong indicator of a fall event [30]. We also consider the vertical acceleration or the magnitude of acceleration from the accelerometer (if available in a wearable device scenario) to support this feature. The importance of velocity in distinguishing falls is well-documented in biomechanics (e.g., [30] highlighted how fall motions have distinct velocity profiles).
- *Pose key point distances and angles*: We derive several features from the skeletal configuration given by BlazePose. One useful feature is the angle between the torso and the ground plane—after a fall, the torso often lies nearly flat. We approximate this by the angle between a vector from shoulders to hips and the vertical axis. Similarly, we examine the knee and hip joint angles; a fall might involve unusual postures like legs bent at certain angles. We also measure distances such as head-to-floor (approximated by head key point y-coordinate relative to floor) or spread of limbs. Some falls result in the person's limbs splayed outward which could be reflected in larger distances between, say, left and right wrist or left and right ankle compared to normal standing.
- *Inactivity duration*: We maintain a counter for how long the person has been immobile after a detected motion. If the pose key points show very little change over a short time window after a sudden movement, it suggests the person is lying on the ground unconscious or immobilized.

Many systems use a post-fall inactivity period of a couple of seconds as confirmation of a fall. We integrate a simplified version: if after the drastic movement the pose remains relatively static for N frames, it strengthens the fall hypothesis.

These features are computed for each frame (or over short temporal windows) and fed into our classifier. It is worth noting that while BlazePose provides 33 key points, our algorithm does not necessarily use all of them—using too many raw key point coordinates can make the model more complex and possibly less generalizable. Instead, we focus on a subset of meaningful features (as listed above) that summarize the pose and motion in relation to falling. This not only reduces computational load but also tends to increase the model's interpretability and reduce overfitting.

3.3 Classification with Random Forest

To make the final decision on whether a fall has occurred, we employ a ML classifier that analyzes the extracted features across time. Specifically, we use a *Random*

Forest classifier [35], which is an ensemble of decision trees. The Random Forest was chosen for several reasons: (1) it can handle both continuous and categorical features well and is not sensitive to feature scaling; (2) it provides good accuracy while remaining relatively fast to train and run, which is beneficial for real-time inference; (3) the ensemble nature (averaging multiple decision trees) makes it robust to noise and less likely to overfit than a single complex tree; and (4) it offers some insight into feature importance, which aligns with our goal of understanding which biomechanical cues are most indicative of falls.

We trained the Random Forest on a labeled dataset comprising examples of falls and non-fall activities. The training data was derived from public fall detection datasets, primarily the University of Rzeszow (UR) Fall Detection Dataset and the Multiple Cameras Fall Dataset (Le2i) [16, 36]. These datasets include videos and sensor readings of actors performing falls as well as normal daily activities (walking, sitting, picking up objects, stumbling but not falling, etc.). We extracted the same features described above from these datasets to form the training feature vectors. To account for different camera perspectives and individual differences, we augmented the training data with slight variations (e.g., adding noise to feature values, simulating different heights by scaling coordinates) and ensured that both frontal and side-fall scenarios were represented.

During training, each tree in the Random Forest learned decision rules on subsets of features to separate falls from non-falls. For example, one tree might learn a rule like “if aspect ratio drops below X and vertical velocity exceeds Y, classify as fall,” whereas another tree might focus on “if centroid height drops by more than Z within 1 second, classify as fall.” By aggregating many such trees, the Random Forest can capture a broad range of fall signatures. We empirically tuned the number of trees and tree depths to avoid overfitting. In our implementation, 100 trees with a maximum depth of 5 were sufficient to achieve strong performance on validation data, while keeping inference time per frame very low (on the order of a few milliseconds).

For real-time operation, the classifier evaluates features in a sliding temporal window (for instance, looking at the trend over the last 1–2 seconds of data). If the classifier’s output exceeds a certain threshold (meaning it strongly votes for a fall) at any point, the system triggers a fall alert. To be robust against single-frame anomalies, we can require the classifier to indicate a fall for a small number of consecutive frames before confirming. In our tests, however, the Random Forest output was stable enough that a single detection was typically reliable due to the integration of motion and inactivity cues.

By using a Random Forest on engineered features rather than a deep learning classifier on raw data, we keep the computational requirements low. The feature extraction (especially pose estimation) does the heavy lifting in terms of computation. The Random Forest’s evaluation is trivial in comparison, involving a series of simple threshold checks and comparisons as it traverses the tree conditions. This design choice aligns with our goal of an *edge-deployable fall detector*: the most expensive step is the pose model, but we specifically chose BlazePose for its real-time edge performance. The rest of the pipeline (background subtraction, feature calc, Random Forest) can easily run on a CPU in real-time.

In summary, our methodology integrates the following: background subtraction to detect motion regions, BlazePose to extract human pose key points, a tailored set of biomechanical features capturing fall characteristics, and a Random Forest classifier to make the fall/no-fall decision. This combination exploits the strengths of both traditional and AI-based techniques, resulting in a system that is both efficient and

effective. In the next section, we evaluate this approach on benchmark datasets and discuss its performance in terms of accuracy and speed, as well as its generalization to various scenarios.

4. Results and evaluation

We evaluated the proposed fall detection algorithm on two public datasets that are commonly used as benchmarks in this domain: the *UR Fall Detection Dataset* and the *Le2i Fall Detection Dataset*. These datasets contain a variety of simulated falls and normal activities captured in different environments, allowing us to test both accuracy (correctly detecting falls while avoiding false alarms) and robustness (working under different conditions). All experiments were conducted on a standard laptop with an Intel Core i7 CPU (no dedicated GPU), to demonstrate the real-time capability on edge-like hardware.

4.1 Accuracy and performance metrics

The primary metrics used to quantify detection performance were *accuracy*, *sensitivity* (recall for falls), *specificity* (recall for non-falls), and *F1-score*. Accuracy is the overall proportion of correct classifications (fall or no fall). Sensitivity measures the percentage of actual falls that were correctly detected, which is critical for safety (missing a fall can have serious consequences). Specificity measures the percentage of normal activities correctly identified as non-falls, reflecting how well false alarms are avoided. The F1-score provides a balance between precision and recall.

Our algorithm achieved an overall *accuracy* of 89.99% across the combined test set of the two datasets. In particular, the sensitivity was approximately 91% for detecting falls, and specificity was around 89% for non-fall events.

This indicates that the system was able to catch the vast majority of falls while only misclassifying about 11% of benign activities as falls. These results are on par with, and in some cases superior to, recently reported approaches that use deeper models or more complex setups. The high sensitivity is especially important—it means the system is very likely to detect a fall if one occurs, aligning with the requirement of prompt emergency alerting.

We also compared our approach's precision (the proportion of detected alarms that were actual falls) which was around 88%. The slightly lower precision (compared to recall) indicates that some false alarms did occur, though on inspection many of these were borderline cases (such as a person quickly sitting on the floor, which can resemble a fall in some features). We discuss later how such false positives might be mitigated by additional context or confirmation mechanisms.

4.2 Real-time performance

One of the key contributions of this work is demonstrating that fall detection can be done in real time on CPU-only hardware by carefully choosing and integrating algorithms. We measured the execution time per frame of video for each component of the pipeline. On the laptop CPU (an 8-core Intel i7 @ 2.6 GHz), our system processed frames at an average of 29.7 *frames per second* (FPS). This essentially corresponds to real-time processing for a typical webcam video stream (which is usually 30 FPS). The breakdown of computation is roughly as follows: background subtraction

and preprocessing took about 5–10 ms per frame, the BlazePose pose estimation took about 20–25 ms per frame, and feature calculation plus Random Forest inference took less than 2 ms per frame. When adding up the pipeline, it stayed under 33 ms per frame on average, which is why we observed performance near 30 FPS.

The memory footprint of the model is also small. BlazePose is a lightweight neural network (on the order of a few megabytes for model size), and the Random Forest model is only a few hundred kilobytes. This means the entire algorithm can run on devices with limited memory, such as embedded boards or smartphones, without issues.

It's worth noting that the pose estimation step is the most computationally intensive. If needed, one could further optimize by reducing the frame rate of pose processing (e.g., run pose estimation every other frame) or by using an even simpler pose model. However, in our tests BlazePose provided an excellent trade-off and did not require down-sampling frames given the CPU capability available. On an edge device like a Raspberry Pi 4, preliminary tests showed that using a smaller resolution input (e.g., 320×240 instead of 640×480) and running BlazePose can still achieve about 8–10 FPS, which might be acceptable for detection (given falls are not instantaneous events, a 0.1-second frame interval is workable). Nonetheless, the result of 30 FPS on a laptop indicates that deploying on an edge device with slightly lower performance is feasible, especially if a dedicated accelerator (like a USB Neural Compute Stick or the Neural Processing Units on modern smartphones) is available for the pose model.

4.3 Robustness and generalization

We examined the performance of our algorithm under different scenarios to assess its robustness:

- *Different environments*: The UR and Le2i datasets contain scenes such as an office space with furniture, a home living room, and a lab environment. Our algorithm maintained high accuracy across these, suggesting it generalizes well to different backgrounds. The background subtraction adjusted to new environments after a short adaptation period. In very cluttered scenes, we noticed a slight increase in false positives (probably due to the background subtractor occasionally getting confused by moving shadows or curtains), but the pose-based features often corrected these.
- *Lighting conditions*: We tested some videos with varying lighting (bright vs. dim). The background model can handle gradual illumination changes, but sudden changes (turning lights on/off) could temporarily affect detection. BlazePose relies on the clarity of human outlines; very low light would degrade pose estimation. In our tests, normal indoor lighting was fine, but extreme low-light scenarios are beyond our current scope (infrared cameras or thermal sensors might be needed there, which is another modality).
- *Multiple people*: Our current design assumes one primary person to monitor. If a second person appears, the system might either interpret them as part of the environment or could potentially detect a false fall if they overlap. Multi-person scenes are challenging; however, since BlazePose can handle multi-person pose estimation, an extension of our system could track multiple people and evaluate falls for each. In this study, we focused on single-person monitoring, which is a

common use-case (e.g., an elderly person living alone). Handling multiple people is left for future work, with potential adjustments like running a person detector first to isolate each subject.

- *Simulated vs real falls*: As discussed, one limitation in evaluation is that datasets consist of simulated falls. These are typically exaggerated for clarity and safety of the actor. Our algorithm, having learned from these, successfully detected those falls. We anticipate that in real-life falls (which can sometimes be slower or involve attempting to grab onto something while falling), the system would still catch the key features: a downward movement and unusual final posture. Some subtle falls (like sliding off a chair) might appear slower but would still result in a changed posture that the pose model should pick up. Nonetheless, validating with real-world data would be ideal. In absence of that, we consider our high sensitivity on a variety of simulated falls as a positive indicator of generalization.
- *Comparison with other methods*: We qualitatively compared our approach to a purely wearable-based method and a purely deep learning vision method. Wearable-based threshold detectors (like those in many smartwatches) are very fast and low-power, but in our tests they either missed some falls (especially if the orientation of the sensor wasn't optimal) or had false alarms during vigorous activities. The vision-based deep learning method we tested (using a pre-trained 3D CNN on fall videos) had slightly higher raw accuracy on the specific dataset it was trained on, but it was too slow to run on CPU in real time (processing only 5 FPS on the laptop) and was essentially a black box with no easy way to adjust for our environment. In contrast, our method offers a good balance: accuracy close to deep models, but speed and transparency akin to simpler methods.

4.4 Potential deployment scenario

To illustrate the practical value of our algorithm, consider a deployment in an elderly person's home. A single RGB camera (for instance, a webcam or a camera integrated into a home assistant robot) is positioned to cover the area where the individual moves around frequently (living room or kitchen). Our fall detection software runs on an at-home gateway device (like a mini PC or even a high-end smart router). In normal daily operation, the system continuously monitors the video. If the person goes about routine activities, the system recognizes no falls and remains idle aside from the monitoring. Suppose the person accidentally trips and falls to the ground—within a second, our algorithm detects the rapid motion, the abnormal pose of the person lying on the floor, and triggers an alert. This alert could be configured to immediately call a family member's phone and also emit a siren sound from the device to see if the person is responsive.

If the person is conscious and it was a false alarm, they could cancel the alarm (for example, by standing up and giving a cancel voice command or pressing a button). If not canceled, the system could escalate the alert to emergency medical services after, say, 30 seconds. Because the algorithm is efficient, it could run 24/7 on a small device without requiring cloud computing, thereby protecting privacy (the video never leaves the home). In such a scenario, the 89.99% accuracy means the majority of true falls will be caught, and occasional false alarms might happen only rarely. The almost 30 FPS processing ensures that even fast falls are captured in time.

5. Conclusion

In this chapter, we presented an enhanced fall detection algorithm tailored for real-time performance and reliability in elderly care applications. The proposed method synergistically combines classical image processing (background subtraction and morphological filtering) with advanced AI (BlazePose human pose estimation and a ML classifier) to achieve high accuracy in recognizing fall events from video streams. By focusing on critical biomechanical features of falls and using an efficient Random Forest model, our system was able to reach nearly 90% detection accuracy and maintain real-time operation at ~30 FPS on consumer-level hardware. This indicates the approach is well-suited for deployment on edge computing platforms, such as home monitoring devices or wearable-assistive gadgets, without the need for specialized processors.

One of the key contributions of this work is demonstrating that useful fall detection does not necessarily require heavy deep learning models running on cloud servers; rather, a thoughtful integration of lightweight methods can meet the dual objectives of accuracy and speed. This has important implications for digital health and assisted living technologies: an on-device fall detection system preserves user privacy and continues to work during network outages, making it a practical component of independent living solutions for seniors. Our results suggest that the system generalizes across different indoor environments and can robustly handle various fall scenarios. In qualitative terms, it provides a good balance between minimizing missed falls (high sensitivity) and minimizing false alarms (high specificity), which is crucial for user trust and safety.

There are several avenues for future work to further improve and expand upon this research. First, addressing multi-person fall detection is a logical next step—this may involve integrating a multi-person tracker and running separate pose estimations, or switching to an instance of a multi-person pose model like HigherHRNet or a Transformer-based pose estimator [27, 28], and then distinguishing which person (if any) has fallen. Second, incorporating additional sensor data could enhance reliability; for example, combining our vision-based system with a wearable accelerometer on the person could drastically reduce false alarms, since both vision and sensor would have to agree on a fall. Such sensor fusion approaches can leverage the strengths of each modality. Third, it would be valuable to collect more real-world data, perhaps through pilot studies in elder care facilities, to fine-tune the system on genuine falls and a wider range of normal activities of older adults. This could also allow exploring personalized models that adapt to an individual's typical movements and health conditions (for instance, some older people might frequently use furniture for support in a way that looks like a fall, and the system could learn their pattern to not trigger).

From a technical perspective, future improvements in pose estimation (like faster or more accurate models) will directly benefit our algorithm. As new lightweight pose models emerge, they can be swapped into our pipeline. Similarly, the Random Forest classifier could be replaced by other techniques like one-class SVM or anomaly detection methods to possibly detect falls as deviations from normal behavior without requiring as many fall examples for training. However, our current approach already yields strong results and is explainable to some extent, which is a desirable property for a health monitoring tool.

Beyond fall detection, this type of system can be part of a broader digital health solution. It could work alongside other tools such as medication reminders, heart rate monitors, or cognitive screening apps. Together, they would form an integrated system to support safe and independent living.

To achieve this, collaboration is needed across disciplines. Engineers, caregivers, clinicians, and social workers must work together to design systems that are not only accurate but also acceptable and helpful to the older population.

In conclusion, the work demonstrates a concrete step towards enhancing elderly care through technology: providing a reliable “digital guardian” that watches over vulnerable individuals and alerts for one of the most critical emergencies (falls). The algorithm’s efficiency and accuracy make it a viable candidate for real-world implementation, potentially increasing the response speed to fall incidents and thereby reducing the risk of long lie times and complications. As the population aging trend continues worldwide [37, 38], such AI-driven solutions will play an increasingly important role in supporting independent living and improving the quality of life for older adults. We envision that integrating systems like ours into smart home ecosystems and wearable devices can create a safer environment where seniors are empowered to live alone with confidence that help will be on the way if a serious fall occurs. Further interdisciplinary collaboration between engineers, healthcare professionals, and caregivers will be key to successfully translating these technological advancements into daily elder care practice, ensuring they meet the needs and values of the older population.

Acknowledgements

This Book Chapter is funded by one of the UKRI APRIL (AI for Productive Research) Hub sub-project AI-CASP.

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Perspective Chapter: AI for Telemedicine in Africa and Beyond

Charles Kamotho and Frederick Bukachi

Abstract

Healthcare provision has morphed from individualized home doctor visits (as was practiced by the Greeks and later in the Europe of René Laënnec), to hospital-based care (beginning famously in Mesopotamia, near the modern city of Baghdad), to telemedicine—now a global phenomenon—to the uptake of artificial intelligence (AI). While Africa lagged behind in the construction of hospitals, it has the opportunity to surge ahead and leapfrog in its search for a solution to the triple burden of healthcare it faces, namely, the continuing presence of infectious diseases; the fast rise in lifestyle or noncommunicable diseases (NCDs); and the wide human resource gaps for qualified healthcare workers. The COVID-19 pandemic led to greater uptake of telemedicine. But Africa is a kaleidoscope of populations, disease demographics, cultures and beliefs, not to mention dietary habits. AI-enabled telemedicine will facilitate understanding by, and therefore confidence in, the healthcare providers by clients in Africa and beyond. This chapter delves into concepts that are fundamental to ensuring success in the use of AI for telemedicine in Africa.

Keywords: telemedicine, artificial intelligence, noncommunicable diseases, COVID-19, Africa

1. Introduction

Telemedicine, bolstered by artificial intelligence (AI), has emerged as a transformative force in healthcare globally. For Kenya and the rest of Africa, it offers a critical opportunity to leapfrog historical challenges in health service delivery: limited infrastructure, inadequate workforce, and high disease burdens (both communicable and noncommunicable). AI-driven telemedicine promises to bridge these gaps through scalable, data-driven, and remote healthcare solutions.

This chapter explores the evolution of healthcare in Africa, emphasizing how AI-enabled telemedicine can be successfully employed to reduce the dependency on traditional brick-and-mortar facilities and thus make universal healthcare and universal health coverage possible. With mobile phone penetration and digital infrastructure improving, Africa stands at the cusp of a healthcare revolution, where consultations, diagnostics, and treatment can increasingly happen at home or work, enhancing access and patient convenience.

The benefits are significant: improved efficiency, personalized care, wider coverage, and reduced costs. In Kenya, where the doctor-patient ratio is approximately 1:8000, far below the WHO-recommended 1:1000, telemedicine can expand the reach of existing professionals. Yet challenges remain: limited Internet access in rural areas, regulatory and legal ambiguities, cultural resistance, and the need for ethical data use.

Ethically and legally, the rise of AI demands strong safeguards: patient consent, data privacy, algorithmic transparency, and de-biasing. AI must serve to support, not supplant, the crucial trust-based relationship between healthcare provider and patient. Done right, AI and telemedicine will redefine not only healthcare access in Africa but global paradigms, paving the way for predictive, preventive, and person-centered medicine.

2. The beginnings of medicine: Globally and in Africa

Sir Winston Churchill (November 30, 1874–January 24, 1965) is famously quoted as having said: “The further back you can look, the further forward you are likely to see.” In this case, the further we can look into the history of medicine, the more into the future we shall be able to peer, with a better understanding of the present day. An example of one with such an attitude was Sir William Osler.

Professor William Osler (July 12, 1849–December 29, 1919) is known as the father of internal medicine in the United States (U.S). He was one of the four founders (1889) of Johns Hopkins University, whose faculty of medicine is rated among the best in the U.S. An expert in *angina pectoris*, he described in 1910 the relationship between heart disease and work stress [1], which is associated with urbanization, a process that is accelerating in Africa today.

“William Osler was generally regarded as the greatest and most respected physician of his time. [...] An outstanding clinician who emphasized bedside teaching and observation, he possessed extraordinary charm that inspired many disciples. As Professor of Medicine at 4 institutions in 3 countries, he exerted a profound influence on medical education. He was a prolific writer and his textbook became the most popular and widely read treatise on medicine in the world. He also was a medical historian, a classical scholar, and an avid bibliophile. He emphasized the value of hard work and ongoing education. His compassion and concern for patients and colleagues reflected his personality. Osler’s wisdom is as relevant now as in his era [2].”

While founding Johns Hopkins School of Medicine, Osler sought to delve into the history of medicine and essentially look as far into its past as anyone ever had. The result was his book, *A Concise History of Medicine*, published in 1919. Among other things, the book establishes “the first figure of a physician to stand out clearly from the mists of antiquity [3]”: Imhotep.

Imhotep was born in the twenty-seventh or twenty-sixth century BC in Memphis, Egypt. He was a vizier, sage, architect, astrologer, and chief minister to Djoser (who reigned 2592–2566 BC, the first king of Egypt’s third dynasty). He is considered to have been the architect of the step pyramid built in the city of Memphis. Ancient documents illustrating Egyptian society and medicine during the Old Kingdom (2543–2120 BC) show that the chief magician of the pharaoh’s court also frequently served as the nation’s chief physician.

Osler established those African roots of global medical practice, after also scouring through the contributions of the Asians, the Chinese, and the Muslims. He is known

to have taught that: “The good physician treats the disease; the great physician treats the patient who has the disease.” “Listen to your patient, he is telling you the diagnosis.” “The practice of medicine is an art, not a trade; a calling, not a business.” These tenets are applicable even in today’s era of technology.

3. Technology for healthcare

Technology has an role to play in various aspects of healthcare including the following:

3.1 Health optimization

Health in antiquity was understood as the absence of disease. In modern times, however, human performance optimization and enhancement have been studied extensively by the military and elite sports experts; this includes studies of human physiology, nutrition, and mental wellness. Technology has been employed in the use of exoskeletons, augmented reality and virtual reality; biomonitoring and sensing; training; nutrition; pharmaceuticals; sensory enhancement and communication; language translation; implantable biosensors; smart textiles with multifunction capabilities; personalization; human machine teaming; tele-existence and robotics [4].

3.2 Enhancement of diagnostics

The scientific method, a fundamental way of gaining knowledge in the diagnosis of disease [5], has already undergone radical changes [6]. Yet these are negligible compared to how AI will introduce fundamental changes.

An early and key advancement in the use of technology for disease diagnosis was the invention of the stethoscope by René-Théophile-Hyacinthe Laënnec in 1816 “to diagnose diseases [6].”

The mantra of diagnostics is that “one cannot diagnose what one does not know.” A thorough understanding of symptoms, signs, and causes of a disease condition is required for one to make a correct diagnosis. One may otherwise be presented with the signs and symptoms and yet not recognize the pattern, and hence the disease. Technology assists in detecting signs, such as elevated body temperature, and in isolating the causes, such as in microbiology.

With technological advancements, a particular disease entity may be associated with particular technological characteristics that are deemed pathognomonic of a specific disease. An example could be raised ST segments on an electrocardiogram, as occurs in a heart attack. Such tests are said to have a certain level of sensitivity and specificity for that disease condition.

However, the above notwithstanding, another mantra says: “treat the patient, not the X-ray [7].” This emphasizes the importance of focusing on the patient’s overall condition and specific symptoms, rather than relying solely on findings of the X-ray, in this case. No single diagnostic study gives the full picture of the condition of a patient. It is imperative, therefore, to listen to patients keenly, to understand their symptoms, to perform a careful physical examination, and thus develop a comprehensive diagnosis.

3.3 Technology for the prevention and cure of diseases

The field of pharmacology has seen improvements in leaps and bounds. Key landmarks were the discovery of insulin, the discovery of Penicillin by Dr. Alexander Fleming, and the development of antihypertensive therapy.

Insulin, a mainstay in the treatment of diabetes, was discovered by Sir Frederick G. Banting and Charles H. Best at the University of Toronto in 1921 [8]. With researchers J. B. Collip and John Macleod, colleagues of Banting and Best, they were able to produce a more refined and pure form of insulin. Soon thereafter medical firms started large-scale production of insulin.

The accidental discovery of Penicillin in 1928 in the UK by Alexander Fleming [9], its further study at Oxford University by Howard Florey and Ernst Chain in 1937, and the development of its mass production in Peoria, Illinois, USA, led to the eventual victory of the U.S. and Allied Forces in the Second World War. This was because the soldiers in the trenches could now survive bacterial infections. The discovery of Penicillin ushered in the era of antibiotics.

While the awareness of sustained elevation in blood pressure (hypertension) dates back to the Chinese Yellow Emperor's Classic of Internal Medicine (2600 BC), the development of modern antihypertensive therapy was only precipitated by the unfortunate death of President Franklin Delano Roosevelt from a massive hypertensive stroke, years later, in 1945. This episode brought focus closer to the study of cardiovascular disease, and spurred the design of the Framingham Heart Study, the longest-running cardiovascular epidemiological study, which began in 1948 and has followed three generations of participants.

Health insurance companies also took note of the predictive importance of high blood pressure and began to utilize it to calculate life insurance policy premiums, and even to reject potential customers [10]. The health insurance industry was clearly well awake and alert, and was not to be left behind by these discoveries for the management of infectious and noncommunicable diseases.

3.4 Access to care

The fourth aspect of technology, increasing access to care, is the ambit of telemedicine, which we shall delve into it deeply later in this document.

3.5 Cost of care

Investments in technology have often meant a large cost burden, given the heavy investments in pharmaceutical research and development, in the development of highly sophisticated imaging tests, and in the putting up of high-level hospitals to house them. All these affect the pricing of medical services. Healthcare has progressively become more and more expensive.

3.6 Technology and human nature

While technology is changing at breathtaking speeds, human nature remains constant. Hence, the old cliché says: you cannot change human nature. Certain fundamental aspects of it, such as the desire for connection and the capacity for empathy, remain unchanged over time. Longevity may vary, as may the average height, or even genetic features leading, for example, to the development of fair skin to enable the

development of Vitamin D in northern Europeans. But those basic characteristics remain [11]. This must be kept in mind in the practice of medicine, for both the patients as well as the health practitioners.

4. Healthcare in Africa today

Africa is the second-largest continent in the world and is also the youngest, with about 70% of population below 30 years of age [12]. Indeed, by the year 2050, most of the world's youth will be African [13]. With such demographics, and information technology (IT) and AI being within the purview of the youth, Africa has the potential to not only be a major producer of AI products and software but also its largest consumer.

The World Health Organization (WHO) reported in 2018 a high improvement in health in the African region [14]. “There has been a significant improvement in the state of health in the region with healthy life expectancy—time spent in full health—in the region increasing from 50.0 years to 53.8 between 2012 and 2015—the most marked increase of any region in the world.

The top killers are still lower respiratory infections, HIV, and diarrheal disease. However, Universal Health Coverage (UHC) requires all conditions affecting a population, not only priority conditions, to be improved. Chronic diseases like heart disease and cancer are claiming more lives, with a person aged 30 to 70 in the region having a one in five chance of dying from NCDs [14].

African countries need a higher density of health workers, including physicians, to achieve UHC. More acute investment in the health workforce and having facilities close to patients are critical to determine good access, but on average, there are only two physicians per 10,000 people. While the WHO recommends a target doctor-to-population ratio of 1:1000 [15], Kenya, for example, has a ratio of approximately 1:8000 [16]. However, the shortage of qualified healthcare workers has been a global phenomenon, including in the U.S. [6].

Similarly, the average number of hospital beds per population in Africa is about 10 per 10,000 population, while the global average is 27 beds per 10,000 population [17]. Incidentally, most hospital beds in Kenya, for example, are occupied by patients with chronic diseases, such as hypertension, diabetes, and cancer [18].

Countries are failing to provide essential services to two critical age groups: adolescents and the elderly. This has to do with the inadequate performance of health systems. The better the performance, the higher the sustainable state of health. However, the health systems, the people, institutions, and resources needed to deliver health-related services, are only performing at 49% of their potential capacity [14].

Spending on health is low in the region, and increased investments are important, but it is not only how much funds are spent, but also what they are spent on. A minimum of 5% of GDP is required to achieve UHC [19]. The Abuja Declaration calls for a minimum of 15% of annual government expenditure on healthcare [20].

It is estimated that an average of 39% of health budgets in Africa is spent on medical products, while expenditure on health workforce (14%) and infrastructure (7%) is low. In contrast, countries with well-performing health systems invest up to 40% in their health workforces and 33% in infrastructure [21].

The opportunity exists, therefore, of leapfrogging these shortages both of health-care workers and of hospital beds by harnessing technology that would make better

use of the doctors already trained and by developing a new approach to healthcare that is not necessarily hospital-based. By harnessing technology, many patients could be dealt with as outpatients, rather than needing to be admitted.

Healthcare today is largely hospital-based. The Middle East, with its Islamic culture and desert landscapes, was the home to the concept of a general hospital. The earliest one was built in 805 AD in Baghdad by Harun al-Rashid. This knowledge and way of practice were exported across the Maghreb in North Africa, and eventually into Europe, through Italy and Spain. But now the move is back to home-based or even work-based care. This is where telemedicine could play a vital role in Africa's quest for universal healthcare and UHC.

While 2007 saw Kenya launch multi-award-winning M-PESA, the world's first large-scale mobile money transfer system, which overcame challenges of access to banking services, the coming years are likely to see Africa develop telehealth and AI systems that will overcome challenges of access to healthcare, making remote healthcare more feasible, thus requiring less of brick-and-mortar hospitals. This is Africa's potential route to UHC.

5. Universal health coverage in Africa

UHC means that all people have access to the full range of quality health services they need, when and where they need them, without financial hardship. It covers the full continuum of essential health services, from health promotion to prevention, treatment, rehabilitation, and palliative care across the life course [22]. The delivery of these services requires skilled health and care workers at all levels of the health system, who are equitably distributed, adequately supported with access to quality assured products, and enjoying decent work.

Protecting people from the financial consequences of paying for health services out of their own pockets reduces the risk that people will be pushed into poverty because the cost of needed services and treatments requires them to use up their life savings, sell assets, or borrow—destroying their futures and often those of their children. This may manifest, unfortunately, even in neglect of the elderly sick. Yet UHC is a fundamental human right and commits to ensuring the highest attainable level of health for all.

Achieving UHC is one of the targets the nations of the world set when they adopted the 2030 Sustainable Development Goals (SDGs) in 2015. At the United Nations General Assembly High Level Meeting on UHC in 2019, countries reaffirmed that health is a precondition for and an outcome and indicator of the social, economic, and environmental dimensions of sustainable development.

Prior to the COVID-19 pandemic, progress toward UHC was already faltering. At the height of the COVID-19 pandemic in 2021, essential services were disrupted in 92% of countries across the Globe [22]. As a foundation for and way to move toward UHC, WHO recommends reorienting health systems using a primary health care (PHC) approach. PHC is the most inclusive, equitable, cost-effective, and efficient approach to enhance people's physical and mental health, as well as social well-being. It enables universal, integrated access to health services as close as possible to people's everyday environments. It also helps deliver the full range of quality services and products that people need for health and well-being, thereby improving coverage and financial protection. Significant cost efficiencies can be achieved, and

most (90%) essential UHC interventions can be delivered through a PHC approach. Some 75% of the projected health gains from the SDGs could also be realized through PHC, including saving over 60 million lives and increasing average global life expectancy by 3.7 years by 2030 [22]. One of the PHC services available should be telemedicine.

6. Telemedicine for UHC in Africa

Telemedicine, telehealth, and mobile health are all aspects of remote healthcare.

Telemedicine is the use of telecommunications technologies to provide healthcare services remotely. Telemedicine can be synchronous or asynchronous. While telemedicine refers specifically to the provision of clinical services remotely, telehealth includes nonclinical services such as patient education, capacity building of healthcare workers, and administrative meetings for healthcare, in addition to the clinical services. Mobile health (mHealth) is the use of mobile devices such as mobile phones or tablets to support medicine and public health efforts. While the term “digital health” was previously used to include all the above, it is now coined more with the use of wearable health devices, for health optimization and telemonitoring. E-health encompasses all the above, plus the use of electronic health records, and the use and processing of electronically saved health data by the likes of health insurance companies or health ministries.

Kenya is among the countries at the forefront of telemedicine adoption in Africa [23]. Telemedicine at the PHC level has already been shown to be effective in managing chronic diseases in Kenya [24]. In Kenya, the COVID-19 pandemic was the tipping point for the uptake of telemedicine [25, 26]. The pandemic led to the shutdown of both public and private hospitals and clinics in Kenya, isolating patients from their caregivers, but demands by patients led insurance companies to finally accept telemedicine.

While in-person, physical consultations remain the ideal, telemedicine works for patients who have poor access to in-person consultations, as was observed during the pandemic. Even after the pandemic, the in-person mode need not be the only way to provide care, nor necessarily the first mode of contact.

The physical consultation enables the development of a complete and thorough medical history. This is the source of up to 80% of data to make the medical diagnosis [27]. The quality of the information obtained will depend on the rapport developed between the doctor and the patient. The in-person consultation is where trust can be developed, amid open communication, both verbal and nonverbal. The physical examination will then involve inspection (allowing assessment of appearance, body language, mood, changes, and anatomical features), palpation, auscultation, and percussion of the patient, all which provide another 10% or so of vital information toward making the diagnosis. The remaining 5–10 of information comes from the diagnostic tests.

Video telemedicine allows for medical consultation and also for inspection to a certain extent. The fact of the patient and doctor seeing each other virtually allows for a relatively complete history. Phone consultations rely solely on the voice of the patient and on the history that is gathered. The less data from clinical observation or from the history, the more experience is required on the part of the healthcare provider. Video telemedicine is the preferred mode, where possible.

Telemedicine offers an opportunity to leapfrog both the lack of hospitals as well as the human resource shortages. While telemedicine uptake is growing in Kenya, some challenges persist in its uptake in certain quarters [28].

One of the effects of telemedicine is that patients can be attended to in their normal environments and homes. The inconvenience, time, and cost of having to travel for medical care are being eliminated by telemedicine, meaning that more and more clients can be attended to even from their homes. This also reduces the carbon footprint of healthcare.

For telemedicine to be successful and sustainable, even with the uptake of AI, the patient journey must prioritize patient safety [29] and respect those basic tenets that Osler described earlier: namely, the importance of the clinical history [27, 29], the need for human connectivity, and the capacity to provide empathy.

7. AI for telemedicine

While telemedicine on its own could mean a reduction in data (e.g., patient observational data from the limited clinical examination) made available to the healthcare provider, AI for telemedicine offers new possibilities for making more accurate diagnoses and better clinical decisions.

AI is actually revolutionizing healthcare, and more so, telemedicine. AI is improving diagnostics, real-time monitoring, and patient engagement *via* telemedicine. Predictive analytics and personalized treatment plans are a result of the data acquired through AI. According to IBM, artificial intelligence is “technology that enables computers and machines to simulate human learning, comprehension, problem solving, decision-making, creativity, and autonomy [30].”

Britannica describes AI as the ability of a digital computer or computer-controlled robot to perform tasks commonly associated with intelligent beings. The term is frequently applied to the project of developing systems endowed with the intellectual processes characteristic of humans, such as the ability to reason, discover meaning, generalize, or learn from past experience. Despite continuing advances in computer processing speed and memory capacity, there are as yet no programs that can match full human flexibility over wider domains or in tasks requiring much everyday knowledge. On the other hand, some programs have attained the performance levels of human experts and professionals in executing certain specific tasks, so that artificial intelligence in this limited sense is found in applications as diverse as medical diagnosis, computer search engines, voice or handwriting recognition, and chatbots [31].

AI includes machine learning, natural language processing, ChatGPT, and computer vision. It can facilitate clinical decisions by suggesting diagnoses or therapeutic pathways. Machine learning algorithms would allow learning from experience, such that appropriate decisions could be made from the accumulated data received previously.

AI is augmenting key aspects of telemedicine, such as the following:

7.1 Predictive analytics

This is use of historical data and machine learning to predict future health events for a particular person or demographic. The risk of such events is computed, and thus, appropriate proactive measures can be taken to mitigate those

risks. This is critical in preventive care, for an individual or for, say, disease outbreaks in a given region.

7.2 The medical consultation

AI has the potential to enhance the patient and doctor experience during the medical consultation. AI could smartly provide health information about the patient and his or her environment to enhance understanding of the patient by the caregiver, thus making it easier to demonstrate empathy toward the client. Simultaneous translation of the conversation could allow for cross-cultural telemedicine consultations. Enhanced 3D video could give an immersive experience. The patient's clinical history remains significant to arrive at an accurate diagnosis, even in this day and age of AI-assisted medical diagnostics.

7.3 Chatbots

Chatbots and virtual agents facilitate self-directed patient-professional interactions. They are useful to answer frequently asked questions.

7.4 Patient monitoring

In remote patient monitoring, AI gathers data from wearables and other health applications and allows real-time feedback. This is particularly useful in chronic disease management, enabling early diagnoses and prompt action.

7.5 Diagnostics

By merging and amalgamating the data from genetics, the clinical history, and previous health records, with that from diagnostic (tele)monitors, AI can help the care provider arrive at an accurate diagnosis. Primacy remains in managing the patient holistically, ensuring that the symptoms are resolved, and avoiding overtreatment of patients for spurious, unimportant findings, all of which are subject to the clinical eye of the trained healthcare provider.

7.6 Therapeutics

AI can gather data from one particular patient and monitor, say, blood pressure control in a hypertensive or blood sugar control in a diabetic, and conclude, from various readings of the parameters, what doses of medication work best for that particular patient. Something similar for infectious diseases and their treatment. Nutrition plans could also be developed that way, even considering one's genetic makeup. These are examples of personalized patient care using AI.

In large populations, AI may gather information from the individuals and make recommendations as to what classes of drugs work best for them, including infectious diseases, gathering data about antimicrobial resistance in given locations.

7.7 Telesurgery

A fast-growing area is remote surgery: AI will enhance aspects such as the tactile experience using robotic telesurgery.

7.8 Research

Experiments and research are all about gathering data, particularly to understand cause-and-effect relationships, or the effectiveness of particular drugs. While traditional research and development (R&D) has been a cost-intensive affair, AI can be harnessed by telemedicine to gather *in vivo* and real-life data to show, for example, any cause-effect relationship between particular environmental factors and the presence of a particular disease; or even the effectiveness of a particular (class of) drug(s) in a given population for a given condition. The results would be more generalizable than previously.

Such investments in AI for telemedicine in health will thus result in faster development of more effective medicines, save pharmaceutical companies high R&D costs, and reduce the overall cost of care. This will pave the way to UHC.

8. Data, the new gold

The 2017 article in *The Economist* [32] that coined this term referred to the titans of data—namely Alphabet (Google’s parent company), Amazon, Apple, Facebook, and Microsoft—the five most valuable listed firms in the world then. They collectively racked up over \$25 billion in net profit in the first quarter of that year. Today, the list is largely unchanged, with Apple, NVIDIA, Microsoft, Amazon, and Alphabet having a total market capitalization of \$14 trillion [33].

Health data, specifically that gained in real-life situations, is particularly valuable, given the size of the pharmaceutical industry. Patients are a primary source of data in healthcare, providing information through electronic health records, patient-reported outcomes, and surveys. This data is crucial for research, quality improvement, and understanding the patient experience.

Data is the basis for the AI revolution. The more data and the more accurate it is, the better the AI models will be, and the more reliable their outputs. AI models learn and make predictions based on the data they are trained on. Thus, data can be used to train the AI models (training data); to evaluate the performance of trained models (test data); to validate the final AI model and ensure its generalizability (validation data).

Data may be structured (organized in a tabular form like spreadsheets or databases); unstructured (data without a predefined structure, such as text documents, images or audio); it may be numeric (like age or temperature), categorical (like color or gender); image data; text data; time series data; audio data; or even sensor data (data collected by sensors, used for say telemonitoring).

9. Ethics for AI in health

Ethics for AI involves establishing the guiding principles for the development and responsible use of AI, ensuring it benefits society while minimizing risks. It encompasses aspects such as bias, transparency, accountability, privacy, and the potential societal impact of AI in health, particularly in terms of fairness and safety [34].

9.1 Bias

Bias in the AI training database results in continued bias in the output. It is imperative to continually use authentic data that has as little bias as possible, and to de-bias technology that is detected to be biased [35]. Transparency into the AI decision-making process adds to the building blocks of trust and accountability [36].

9.2 Data privacy

The right to privacy is not only an important ethical consideration but is also a fundamental human right that is enshrined, for example, in the Constitution of Kenya, under Article 31. Privacy is a critical safeguard for life, protecting individuals from various risks and promoting personal autonomy. It allows people to make decisions about sharing information.

Privacy ensures security and protects individuals from harm: it safeguards individuals from identity theft, stalking, and other forms of harassment or harm that can occur when personal information is exposed or breached. It prevents manipulation by allowing individuals to control their information and avoid being manipulated or influenced by others. Privacy is essential to protect one's reputation and prevent the spread of misinformation or negative portrayals. It promotes autonomy, empowering individuals to make choices about their personal information and allowing them to control their online and offline presence. Privacy supports well-being, contributing to a sense of safety and security, which are essential for overall well-being, mental health, and creativity.

In general, personal health data belongs to the individual who is the subject of the information. Medical providers may own the physical, tangible, or electronic health records, but the individual has the right to access those records. Collection or sharing of data by a third party—say for research purposes—therefore requires the informed consent of the individual source of the data.

9.3 Voluntary consent

The first of the 10 points of the Nuremberg Code states that: “The voluntary consent of the human subject of any research is absolutely essential. This means that the person involved should have legal capacity to give consent; should be so situated as to be able to exercise free power of choice, without the intervention of any element of force, fraud, deceit, duress, overreaching, or other ulterior form of constraint or coercion; and should have sufficient knowledge and comprehension of the elements of the subject matter involved as to enable him to make an understanding and enlightened decision [...]” [37].

Health technologies must be carefully scrutinized, therefore. Those who infringe on any of the above principles are to be considered unethical. Care must be taken with devices that employ sensors that are implanted on or under the skin, or in the bloodstream, that are not easily removable, and that may infringe on personal autonomy and privacy.

An example of such technologies that infringe on ethical principles is one that uses nano sensors to detect body activity in relation to a given task, all linked to cryptocurrency to reward those who fulfill the task. Its patent was sought around the outbreak of the COVID-19 pandemic [38]. Another uses a skin sensor to continuously gather medical

information, including body temperature and a variety of biochemical markers [39]. The same applies to those who coerce with promises of monetary compensation to gain consent from subjects, for example, the World coin saga in Kenya in 2023 [40].

While patients are a source of data, they should not be viewed only as such the primacy of the human person remains.

9.4 Patient-centered care

Patient-centered care prioritizes the individual’s preferences, needs, and values throughout their healthcare journey, emphasizing a collaborative approach between each patient, their family, and their healthcare professionals. This respects patient values and preferences; it involves the patient in decision-making; promotes open communication and engagement; encourages healthcare professionals to demonstrate empathy and compassion; and focuses on well-being. These aspects of patient-centered care are illustrated in **Figure 1** below. (Adopted from Access Skills [41]).

9.5 Human-centered design

This is a creative approach to the development of technology that emphasizes understanding and addressing human needs and behaviors throughout the design process. Key principles include: empathy, focus on the user, iterative design, collaboration, and a broad range of solutions.

9.6 Unhealthy use of health AI

The problematic social media use (PSMU) in adolescents is a rising phenomenon often associated with a higher perception of psychological stress and comorbid



Figure 1.
Person-centered care.

psychiatric disorders like depression [42]. This is a well-defined problem in the International Classification of Diseases 11 (ICD-11).

With the development of large language models and the ease of “converse” with health AI apps, it is likely that we will see the development of a new disorder, termed problematic medical media use. Poor access to doctors, coupled with the availability of Internet services, is already promoting the use of “Dr” Google, as is observed in the UK [43]. With the increasing sense of isolation among individuals, health AI apps could easily be the source of consolation for many a patient, getting them to even develop a “relationship” with such apps. But can one have such a relationship with an app, or can health AI apps replace doctors?

Healthcare is based on a trusting professional relationship between patient and healthcare provider. Human connectivity and the capacity to provide empathy are fundamental. Trust is needed in healthcare: from a clinical perspective, patients have reported more beneficial health behaviors, fewer symptoms, higher quality of life, and being more satisfied with treatment when they have higher trust in their healthcare professional [44]. Indeed, that rapport becomes a critical factor in determining a patient’s likelihood of adhering to recommendations [45].

Trust in itself is a function of character, competence [46], and consistency. In healthcare, competence is shown by one’s qualifications. Character is about one’s values.

Competence (or ability) is shown in a range of skills, talents, and knowledge, and can be innate or developed through education and experience. It can be categorized as cognitive abilities (analytical thinking, problem solving, and creativity), physical abilities (physical coordination, strength, and endurance), as well as emotional abilities (the capacity to understand and manage emotions, often referred to as emotional intelligence).

Character refers, rather, to the attributes and traits that define an individual’s moral compass. Key components of character include: integrity (adhering to moral and ethical principles), resilience (the ability to bounce back from setbacks and maintain a positive attitude), empathy (understanding and sharing the feelings of others, fostering connection and collaboration), and accountability (taking responsibility for one’s actions and their consequences).

Granted that an AI app can be well-trained. But can it have values that determine its character?

Note that while large language models (LLMs) have been shown to outperform real doctors at the U.S. Medical Licensing Exam or even in diagnostic accuracy, a recent study shows that AI falls short as a clinical assistant [47]. LLMs require strategic integration to enhance clinical decision-making without replacing human expertise. Indeed, AI will be able to guide doctors as a useful tool, not on its own.

Chat boxes, therefore, should not replace human conversations. AI has its place in healthcare, but not even the smartest machine can replace the human-to-human interaction in a medical consultation. Such awareness will safeguard mental health and avoid hypochondriacs misusing AI, leading to prescriptions that are not only unnecessary but can jeopardize their health.

10. Other aspects of AI in healthcare in Africa

Successful implementation of AI for telemedicine in Africa will also depend on a number of factors, described in **Table 1** below.

Legal frameworks for AI in telemedicine	Legal frameworks must evolve to address liability, jurisdiction, and compliance in AI-powered telemedicine; they should cater to telehealth licensing, malpractice, and data governance.
Cross-border telemedicine regulation	Cross-border regulation and digital health governance are emerging needs, particularly in this era of the African Continental Free Trade Area (AfCFTA). Policies must address jurisdictional authority, especially in regional consultations.
AI liability	Principles of accountability should be developed where AI recommendations influence or result in harm, clarifying doctor vs. developer responsibility.
Standards and accreditation	Telehealth platforms and AI algorithms must be approved by medical boards or regulators to ensure quality and safety.
Infrastructural requirement	AI and telemedicine systems rely heavily on: stable electricity supply, especially in rural and remote areas. Harnessing of solar and wind power; reliable Internet connectivity, including last-mile broadband access; interoperable digital infrastructure, such as electronic health records (EHRs), cloud storage, and cybersecurity systems; and public-private partnerships and targeted infrastructure investment are key to closing these gaps.
Job creation	AI in healthcare can be a significant driver of job creation across multiple domains: health informatics specialists, AI trainers, and data scientists; remote care coordinators, virtual health assistants, and telemedicine nurses; maintenance and support technicians for digital health equipment; ethics and compliance officers, responsible for overseeing AI use in clinical settings. Upskilling programs, especially for youth and women, can ensure inclusive participation in the growing digital health economy. Governments, academic institutions, and private sector actors must collaborate on workforce development initiatives that align with emerging health tech demands.

Table 1.
Implementation factors for success with AI in telemedicine.

11. The future of telemedicine

Future directions for AI innovation include more use of emerging technologies such as 5G, blockchain, and Internet of Medical Things (IoMT), among others, that “will usher in a new era of remote healthcare delivery [36].”

With the changes taking place, healthcare will become more and more preventive, more out-of-hospital, more data-based, and more accurate. It will also become more cost-effective and affordable, allowing health insurance to make UHC possible.

Moreover, AI will improve user experience for both the patients and caregivers, among other things, by facilitating knowledge of the client and his environment by the caregiver, which will contribute to that trust that is the substrate of medical care.

With recent investments in space travel, space telemedicine will become the new frontier. Principles of AI for telehealth developed in Africa will be applicable even in outer space.

12. Conclusion

Investments in AI for telemedicine will reduce inefficiencies, reduce the cost of research, and, as such, reduce the cost of care, making it more affordable, particularly for low- and middle-income countries.

The quality of care provided using AI would leapfrog that of purely brick-and-mortar hospitals, particularly for noncommunicable diseases.

AI in telemedicine represents one of the most impactful healthcare innovations of our time. For Africa, it is a powerful tool to resolve healthcare access inequities, improve outcomes, and develop future-proof systems. However, ethical, cultural, legal, and infrastructural factors must be addressed proactively. When implemented responsibly, AI-driven telemedicine can revolutionize healthcare delivery, locally and globally.

Acknowledgements

Nancy Muchangi, MPPM, MSC, CISA, Chief Economist, Ministry of Investments, Trade and Industry, Government of Kenya.

Appendix

A.1 Bandwidth in Africa

Bandwidth access is a critical enabler of telemedicine across Africa. International and national bandwidth capacity is extensive (see **Figure 2**), but actual utilization and last-mile connectivity remain uneven. This poses a significant challenge for effective telehealth delivery, especially in rural areas.

Africa's international Internet bandwidth grew at 44% annually (2018–2022), making it the region with the highest level of Internet growth worldwide (See **Figure 3**).

There is growth in the rural 4G coverage (e.g., Safaricom covers 97% of Kenya). Hence, the Urban-Rural Divide is reducing, but rural areas lack reliable connectivity, making video consultations, remote diagnostics, or real-time patient monitoring difficult. On infrastructure gaps, there is limited fiber reach, as only 57% of Sub-Saharan Africans live within 25 km of a fiber node [50]. High latency and low-quality connections would compromise telemedicine services that require stable, high-bandwidth connections. These are opportunities: recent investments, like community networks (e.g., TunapandaNET) and Starlink satellite Internet, are beginning to close gaps, and this will offer potential for scalable telemedicine solutions even in remote areas.

Internet users in Africa surpassed 570 million by 2022, though penetration was only around 43%, trailing the global average of 66%. International Internet bandwidth across Africa soared from 16.1 Tbps (2019) to 49.6 Tbps by December 2023—mainly fueled by the 43% year-over-year jump in Sub-Saharan Africa to 34.4 Tbps, with North Africa at 15.2 Tbps [48]. TeleGeography reports that international bandwidth has quadrupled since 2020, reaching 1479 Tbps globally by October 2024; Africa alone saw a 41% Compound Annual Growth Rate (CAGR) from 2020 to 2024, marking it the fastest-growing region [49]. Terrestrial fiber networks expanded to 1.34 million km by June 2024—an increase of 58,132 km (+5%) from the previous year, bringing 62.6% of Sub-Saharan Africans within 25 km of fiber nodes [48].

While Africa has made major strides in bandwidth capacity, barriers persist. Inequities in access, infrastructure limitations, and high costs of data and electricity are still the reasons that limit the full potential of the promise telemedicine offers. Targeted investments in last-mile connectivity, subsidized broadband for health

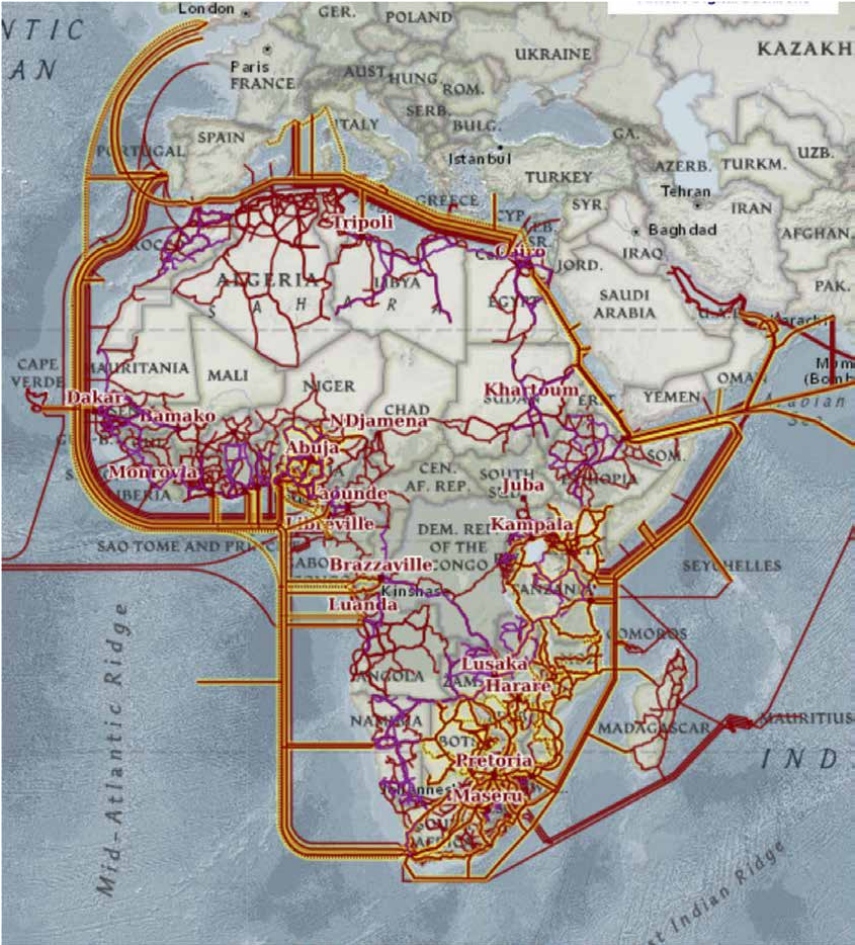


Figure 2.
Africa's Digital Backbone (Adopted from Africa Bandwidth Maps) [48].

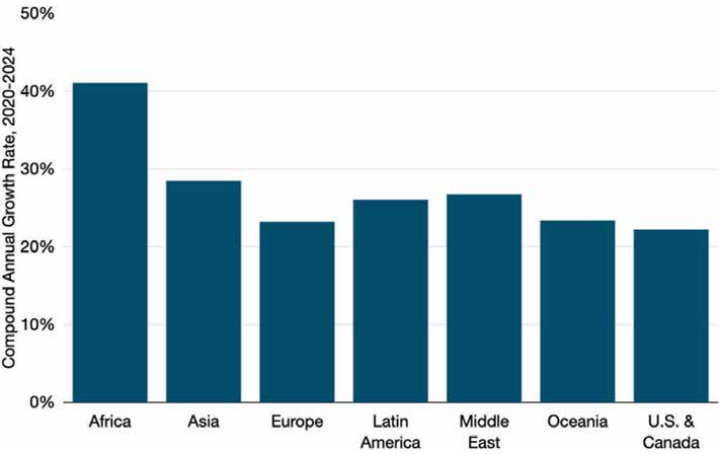


Figure 3.
International Internet Bandwidth Growth by Region (Adapted from Telegeography) [49].

facilities, and support for community-based networks will be most essential to make telemedicine more inclusive and impactful.

A.2 Cost constructs for telemedicine connectivity

Implementing telemedicine at scale will entail various costs as described in **Table 2** below. These costs can be burdensome for low-income populations and under-resourced health systems. A mix of public, private, and philanthropic actors may collaborate. Key models to explore, and some are already at play, are

- a. *Government investment*: whose role is to provide public digital infrastructure (e.g., rural towers, fiber backhaul). It is a public good; health and digital access are national priorities. In Kenya, programs under Universal Health Coverage (UHC) could integrate digital health.
- b. *Donor and multilateral funding*: these could fund pilots, subsidize last-mile efforts, and build capacity, examples are the World Bank, Global Fund, and WHO Digital Health initiatives. Leveraging digital public infrastructure initiatives.
- c. *Private sector/telecoms*: with the role to extend mobile broadband, offer health bundles (e.g., zero-rated services), offer incentives like tax breaks, regulatory support, and social responsibility. A Kenyan example is Safaricom’s partnership for mHealth solutions.
- d. *Community and social enterprises*: contribute by operating local networks, training users, and tailoring solutions. These are more agile and culturally embedded.
- e. *End-users (minimal co-pay)*: the approach here is small user contributions or insurance-based models that must be affordable and not a barrier.

Suggestions for sustainability would be subsidized broadband for health facilities that ensure rural clinics have guaranteed bandwidth. Digital Health in UHC could include telemedicine in public health budgeting and insurance schemes. Cross-border Infrastructure Sharing to harmonize regional efforts to reduce costs, and Satellite Internet Regulation to ensure licensing supports rural inclusion. Public-Private Partnerships (PPP) could incentivize telecoms and startups to invest in rural tech for sustainability.

<i>Cost element</i>	<i>Details</i>
Infrastructure	Fiber optic cables, 4G/5G towers, and satellite Internet (e.g., Starlink)
Devices and equipment	Smartphones, diagnostic kits, and tablets for health workers
Operational costs	Data plans, maintenance, and tech support
Training	Digital literacy for health workers and users
Content and systems	Secure platforms, electronic health records (EHR), and video platforms
Regulation and licensing	Compliance, data protection, and ISP licensing fees

Table 2.
Cost factors for telemedicine in Africa.

A.3 Policy recommendations

- Subsidize broadband for health: Prioritize health facility connectivity in national budgets;
- Strengthen public-private partnerships: Incentivize telecoms through tax relief and co-financing;
- Promote satellite and community networks: Regulate fairly to expand access without deterring investment;
- Embed telemedicine in UHC: Ensure telehealth services are covered and accessible;
- Regional cooperation: Share infrastructure across borders to reduce costs and promote continuity of care.

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Perspective Chapter: Integrating Artificial Intelligence into Telemedicine – Opportunities, Challenges, and Future Directions for Healthcare Delivery

Mustafa Ghaderzadeh

Abstract

The integration of artificial intelligence (AI) and telemedicine has revolutionized the healthcare system and transformed access to medical services. This chapter examines the synergistic relationship between these two technologies and their role in transforming healthcare systems. With its capabilities in big data analysis, pattern recognition, and predictive modeling, AI has improved diagnostic accuracy, clinical decision-making, and personalized treatment planning. On the other hand, telemedicine, by eliminating geographical limitations, enables remote consultations, continuous patient monitoring, and equitable access to specialized care. This chapter first introduces the basic concepts of AI and telemedicine, then examines AI-based innovations such as remote diagnosis systems, wearable devices, and virtual health assistants. The role of AI as a consultant in telemedicine is examined, facilitating real-time data analysis, automated triage, and supporting intelligent decision-making. Although it has many benefits, challenges such as data privacy, algorithmic bias, regulatory hurdles, and the need for systems to cooperate remain. Ethical considerations and the need for human oversight of AI systems are also highlighted. The chapter concludes with future solutions such as federated learning, interpretable AI, and global telemedicine initiatives. Through case studies and policy recommendations, this chapter provides a comprehensive picture of the opportunities and challenges of AI-based telemedicine and demonstrates its transformative potential for the future of healthcare.

Keywords: artificial intelligence (AI), telemedicine, healthcare delivery, remote monitoring, clinical decision support

1. Introduction

Artificial intelligence (AI) and telemedicine are two advanced and transformative technologies in the field of healthcare that, through close integration and cooperation, have been able to shape new models of medical service delivery. In the modern

world, new technologies play a significant role in the transformation of various sectors of human life. One of the areas with high potential for these developments is medicine and health, where, with the emergence of AI, we are witnessing a huge revolution in the provision of medical services and the improvement of the quality of medical care. In this chapter, we will examine the vital role of AI in the field of telemedicine and also the position of telemedicine in AI.

Telemedicine, which refers to the provision of health services remotely, provides many opportunities for patients in remote areas and in need of special care. AI, with its ability to analyze big data, recognize complex patterns, and predict disease trends, is a powerful tool to facilitate the process of treatment and healthcare. On the contrary, the application of AI in telemedicine can provide significant improvements in the processes of diagnosis, patient follow-up, and resource management. In this chapter, we will examine the leading technologies, challenges, and opportunities in these fields and show how the combination of AI and telemedicine can create a healthier and more sustainable future for human societies. Also, the role of doctors and smart technologies together is the key to achieving a higher level of medical care, something that will become closer to reality with continuous effort and innovation.

1.1 Methodology

This chapter provides a comprehensive overview based on a systematic review of the existing literature and relevant case studies concerning AI and telemedicine. The data sources include peer-reviewed journal articles, conference proceedings, and reports published between 2013 and 2025. The chapter synthesizes key findings related to AI-based telemedicine tools, evaluates their implementation across diverse healthcare settings, and highlights emerging trends and innovations in the field.

To guide the discussion, the chapter addresses the following research questions individually:

1. What AI methods and techniques are utilized in telemedicine?
2. How has AI emerged and evolved within telemedicine?
3. What is the role of AI in telemedicine?
4. What are the key applications of AI in telemedicine?
5. What benefits does the use of AI in telemedicine offer to stakeholders?
6. What challenges and ethical considerations arise from the use of AI in telemedicine?
7. What technological examples demonstrate the integration of AI in telemedicine, and what future innovations are anticipated in this domain?

2. Artificial intelligence and telemedicine

2.1 Overview of artificial intelligence methods and algorithms

AI is an advanced and interdisciplinary branch of computer science devoted to the development of systems and algorithms capable of performing tasks that typically

require human intelligence. Such tasks include learning, reasoning, natural language understanding, pattern recognition, and decision-making. In the realm of healthcare, AI, leveraging diverse methodologies such as machine learning, deep learning, and natural language processing (NLP), has ushered in remarkable transformations. Machine learning algorithms, by analyzing vast medical datasets ranging from radiological images to electronic health records, facilitate more accurate disease diagnosis and prognosis. Moreover, NLP enables the extraction of critical information from clinical texts and fosters intelligent communication with patients. The applications of AI in healthcare are extensive, encompassing disease diagnosis, treatment management, continuous patient monitoring, and the optimization of administrative processes. This section introduces the various methods and algorithms of AI, examining the scientific and practical foundations of this technology in the service of healthcare advancement.

AI is a comprehensive concept that encompasses an array of sophisticated algorithms and methodologies. These algorithms empower machines to exhibit intelligent behaviors such as learning, reasoning, decision-making, and content generation. In the following, each of the principal algorithms and methods of AI, along with their unique characteristics, will be discussed in detail [1].

2.2 Classification of artificial intelligence types

AI can be categorized into two main types: (1) Narrow AI (also known as Weak AI), which refers to systems designed to perform a specific, well-defined task such as image recognition or chatbot interactions, and (2) General AI (or Strong AI), which encompasses systems capable of understanding and performing a broad range of complex tasks at a level comparable to human intelligence—this type remains largely theoretical at present [2]. Key Algorithms and Methods in AI include:

2.2.1 Machine learning

Machine learning is a subfield of AI that enables machines to learn from data and improve their performance without explicit programming. Machine learning algorithms are generally categorized into four main types that are organized in **Table 1**.

Type of machine learning	Description	Key algorithms
Supervised learning	Training models on labeled data to predict correct outputs for new inputs	Linear regression, logistic regression, decision tree, Support Vector Machine (SVM), Naïve Bayes, K-Nearest Neighbors (KNN)
Unsupervised learning	Working with unlabeled data to discover hidden patterns and structures	K-means clustering, Apriori algorithm
Semi-supervised learning	Combining labeled and unlabeled data to improve model accuracy	—
Reinforcement learning	Learning optimal policies by receiving rewards or penalties from the environment	

Table 1.
Categorization algorithms of machine learning.

The presented machine learning categories—supervised, unsupervised, semi-supervised, and reinforcement learning—offer distinct approaches applicable to telemedicine. Supervised methods enhance diagnostic accuracy through analyzing medical data, while unsupervised learning aids in personalized treatment by identifying patient patterns. Semi-supervised techniques improve models with limited labeled data, crucial for remote applications. Reinforcement learning optimizes treatment protocols and robotic surgeries, advancing remote care capabilities. Integrating these machine learning paradigms enhances efficiency and personalization in telemedicine, ultimately improving patient outcomes.

2.2.2 Deep learning

Deep learning, a subset of machine learning inspired by the human brain's neural architecture, uses artificial neural networks with multiple layers to learn from complex and unstructured data. It is widely applied in computer vision, NLP, and speech recognition. Key deep learning algorithms include:

- Feed-forward neural network: The simplest neural network with unidirectional data flow.
- Convolutional neural network (CNN): Specialized for processing images and spatial data.
- Recurrent neural network: Designed for sequential data such as text and audio.
- Generative adversarial networks (GANs): Used for generating new, realistic data samples.
- Autoencoders: Employed for data compression and reconstruction.

These algorithms have revolutionized AI by enabling the extraction of intricate and abstract features from data [3, 4].

2.2.3 Generative artificial intelligence

Generative AI refers to a class of algorithms capable of producing new content (such as text, images, audio, and video). By learning from large volumes of sample data, these algorithms can generate outputs that closely resemble real-world data.

- Applications of generative AI include:
- Text generation (such as chatbots and article writing)
- Creation of images and artworks
- Generation of music and audio
- Production of deepfake videos

- Design of new products and chemical compounds
- The most notable algorithms in this field are GANs and transformer-based models [5].

2.2.4 Large language models

Large Language Models (LLMs), such as generative pre-trained transformer (GPT) and bidirectional encoder representations from transformers (BERT), utilize deep neural networks and vast textual datasets to comprehend, process, and generate human language. These models are capable of performing a multitude of tasks, including translation, summarization, question answering, and text generation. Key features of LLMs include:

- Scalability: Enhanced performance with increased data and parameters.
- Multifunctionality: Ability to perform diverse linguistic tasks.
- High-level comprehension and intelligence: Capacity to respond to complex queries and generate meaningful text.
- Information compression: Extraction of essential features from input data.
- Evaluation and benchmarking: Assessed using specialized metrics.
- Social and ethical implications: Issues related to bias, security, and privacy.

These models are recognized as the driving force behind many recent advancements in AI. The accompanying illustration depicts the interrelations among these AI methodologies (**Figure 1**) [6, 7].

Overall, each of these algorithms and methods, with their unique characteristics, has revolutionized the field of AI and found extensive applications across various industries.

2.3 Role of AI in telemedicine

The integration of AI into telemedicine has significantly transformed the delivery of healthcare services, particularly in remote and underserved areas. By leveraging advanced algorithms, machine learning models, and natural language processing tools, AI enhances diagnostic accuracy, streamlines clinical workflows, and improves patient engagement. Below, we explore the key roles AI plays in telemedicine, focusing on five core domains: Automated diagnosis, remote monitoring, clinical decision support, patient engagement, and predictive analytics.

The role of AI in telemedicine has been rapidly expanding, driven by advancements in AI algorithms and increasing demand for remote healthcare solutions. As new technologies emerge, the integration of AI into telemedicine continues to unlock novel applications and benefits across diagnostic, therapeutic, and administrative domains. **Table 2** provides an overview of key AI roles in telemedicine, highlighting the core functions, underlying technologies, and associated advantages. By categorizing these roles, this summary aims to offer a structured perspective for researchers, clinicians, and policymakers interested in leveraging AI to enhance telehealth services.

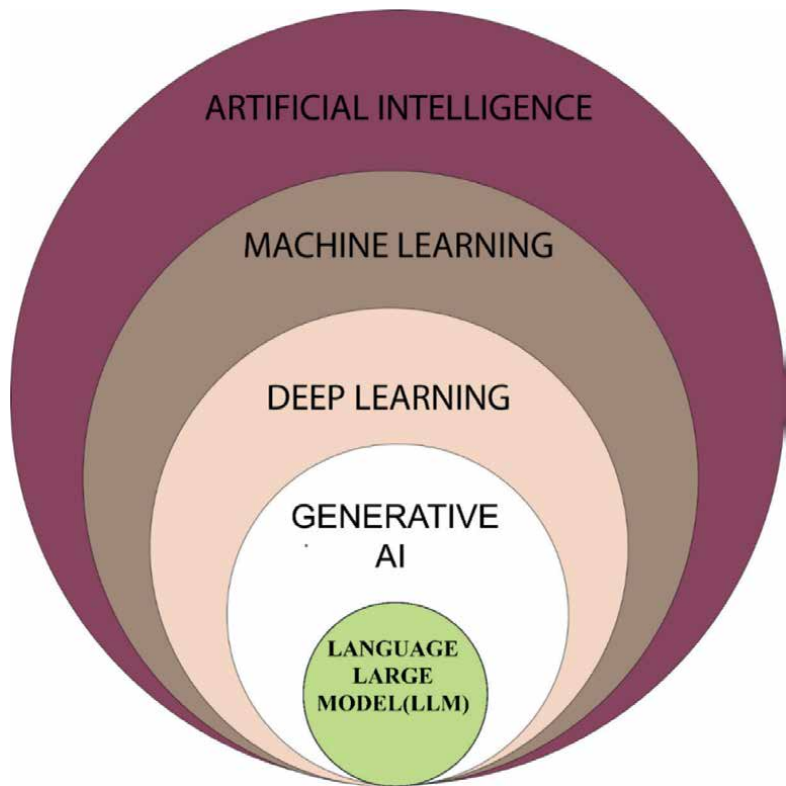


Figure 1.
AI sub methods, including machine learning, deep learning, generative AI, and language large models.

Role	Key AI technologies	Benefits	Challenges
Automated diagnosis	CNNs, deep learning, image recognition	High diagnostic accuracy, reduces the burden on specialists	Requires large, diverse training datasets
Remote monitoring	Wearables, real-time analytics, alert systems	Early detection, continuous care	Ensuring data privacy and device reliability
Clinical decision support	NLP, rule-based models, ML algorithms	Evidence-based recommendations, reduced errors	Integration with existing EHR systems
Patient engagement	Chatbots, LLMs, behavioral analytics	Improved access	User trust and digital literacy barriers
Predictive analytics	Big data, time-series modeling, risk scoring	Proactive care, cost reduction	Interoperability and model generalizability

Table 2.
Role of AI in telemedicine, technologies, benefits, and challenges.

3. Literature review on AI integration in telemedicine

The integration of AI and telemedicine represents a fundamental transformation in the contemporary healthcare system. This chapter examines the evolutionary trajectory of this technological convergence, spanning from early ideas in the

mid-twentieth century to today's complex systems. Telemedicine has evolved from simple video consultations to sophisticated AI-enhanced platforms. Early applications focused on remote diagnostics, while recent developments leverage AI for automation, personalization, and scalability.

3.1 Foundational era (1950-1970)

The earliest instances of telemedicine date back to the 1950s, when leading institutions such as the Nebraska Psychiatric Institute and Massachusetts General Hospital transmitted radiology images *via* telephone lines. During the same period, theoretical foundations of AI were laid through projects like the Dartmouth Conference in 1956. Although these two fields were not directly connected at the time, they established the technological groundwork necessary for future convergence [8].

3.2 Expert systems era (1980-1990)

The 1980s witnessed the emergence of the first practical applications of AI in medicine. Expert systems such as MYCIN (Stanford University, 1976) and INTERNIST-1 (University of Pittsburgh, 1980) demonstrated that algorithms could play an effective role in disease diagnosis. Concurrently, advances in communication technologies enabled telephone consultations, albeit limited and without AI integration [8, 9].

3.3 Digital transformation (2000-2010)

With the expansion of high-speed internet in the late 1990s, telemedicine entered a new phase. Early machine learning systems enabled clinical data analysis. Key developments during this period included: (1) Development of image recognition algorithms for mammography and radiology; (2) Introduction of the first remote patient monitoring systems using simple sensors; and (3) Creation of electronic health databases facilitating AI model training [9, 10].

3.4 Deep learning revolution (2010-2020)

Significant advances in deep learning, especially CNNs, have revolutionized clinical applications. Major achievements included: (1) Achieving 95% accuracy in skin lesion diagnosis using deep learning algorithms (2017); (2) Launch of intelligent systems such as IBM Watson Oncology (2014); (3) Development of medical chatbots like Babylon Health (2013); and (4) Integration of smart wearable devices with data analytics platforms [9, 11].

3.5 Pandemic and post-pandemic era (2020 onwards)

The COVID-19 pandemic accelerated progress in this domain, including the following: (1) Automated symptom-based screening systems; (2) Virtual consultation platforms with preliminary diagnostic capabilities; (3) Utilization of large language models (LLMs) for answering medical inquiries; and (4) Advancement of remote surgery supported by intelligent robotic systems [12, 13].

4. Application of artificial intelligence in telemedicine

4.1 Overview of telemedicine and historical development

Telemedicine began in the early twentieth century with the use of telephone and radio, gradually evolving with the advent of the internet, smart devices, and wireless technologies. Today, this field encompasses a wide range of services, from video consultations to continuous monitoring and chronic disease management. The following outlines the various telemedicine models, in each of which AI can play a significant role in enhancing the quality of medical and clinical services. Telemedicine can be characterized in the following modes:

1. Synchronous: Real-time, direct communication between patient and physician *via* video or telephone;
2. Asynchronous (Store-and-Forward): Transmission of medical data and information for later review;
3. Remote patient monitoring: Use of wearable devices and sensors for continuous health data collection;
4. Mobile health (mHealth): Use of mobile applications and tools for personal health management.

In each of these telemedicine models, AI algorithms can be used to analyze data and respond to clinical signs and stakeholder needs. Practical examples of these applications are discussed below.

4.1.1 AI in synchronous telemedicine models

In this model, live communication is established between the patient and the physician *via* video or telephone. AI can play the following roles:

- Virtual triage: AI-powered chatbots collect and prioritize patient symptoms before the live session, enabling physicians to address urgent cases more quickly.
- Live image analysis: During video consultations, image processing algorithms can detect skin symptoms or abnormal movements and alert the physician.
- Virtual assistant: During the call, AI-based assistants can analyze the patient's electronic health record in real-time and provide treatment suggestions.

4.1.2 AI in asynchronous (store-and-forward) telemedicine models

In this model, data such as images, test results, and medical histories are sent for later review.

Medical image analysis: AI analyzes radiology images, MRIs, retinal scans, and other imaging modalities to identify disease patterns. For example, AI algorithms can detect diabetic retinopathy with remarkable accuracy, enabling immediate initiation of treatment.

NLP: This technology enables the analysis of stakeholder speech (patients and companions) and clinical/nonclinical texts, including patient histories, lab reports, and imaging results. By extracting key information, AI systems can provide concise summaries and important points to physicians, facilitating clinical decision-making—especially useful for managing large volumes of raw data quickly and accurately.

Decision support: Machine learning models analyze historical and current data to offer personalized treatment recommendations and clinical trends. These systems can guide physicians with more precise advice based on previous diagnostic and treatment patterns, reducing the likelihood of error and improving the quality and effectiveness of healthcare.

4.1.3 AI in remote patient monitoring

AI has revolutionized remote patient monitoring by enabling continuous, accurate, and intelligent supervision of patient health status through sensors and wearable devices. This technology plays a crucial role in improving treatment quality, reducing medical errors, and increasing patient satisfaction. Key features include:

- **Continuous data analysis:** Vital signs such as heart rate, blood pressure, blood oxygen level, body temperature, and other important indicators are recorded and analyzed in real-time. AI algorithms review this data instantaneously and, upon detecting dangerous patterns—such as arrhythmias, oxygen desaturation, or abnormal fluctuations—immediately send alerts to the physician or patient, enabling rapid response and timely intervention to prevent serious incidents.
- **Prediction of disease exacerbation:** One of AI's most important capabilities is analyzing temporal trends in data to detect early signs of relapse or worsening chronic conditions. For example, by monitoring changes in blood pressure, glucose levels, and other vital parameters, algorithms can predict the risk of exacerbation in heart failure, diabetes, COPD, and other chronic disorders. These predictions enable preventive actions such as medication adjustment, lifestyle changes, or regular follow-ups, thus preventing deterioration.
- **Medication management:** AI can optimize medication dosages by analyzing individual patient data, considering potential side effects, drug interactions, and personal needs, and adjusting dosages over time. This approach not only reduces adverse effects but also increases treatment efficacy and reduces the need for frequent clinical interventions, thereby improving quality of life and reducing healthcare costs.

Overall, AI in remote patient monitoring is not only a powerful tool for better health management but also a strategic partner in enhancing healthcare system efficiency, reducing medical errors, and delivering personalized care. This technology promises a bright future in digital health, continually expanding the scope and accuracy of healthcare services and empowering patients to better control their health [14–16].

4.1.4 AI in mHealth

In this model, mobile applications and tools are used for personal health management.

AI in mHealth is an emerging platform that provides unique capabilities for comprehensive and individualized health management. Mobile apps and tools play a key role in healthcare, and by leveraging AI, can make diagnostic, monitoring, and intervention processes more efficient. This technology increases patient access to health services and enables continuous and precise monitoring of physical and mental health. Key applications include:

- **Symptom checker apps:** AI-powered applications can identify early disease symptoms by asking multiple questions and analyzing user responses. They can also analyze user voice and images—such as cough sounds, facial features, or movement patterns—for early disease detection. For example, an app might measure and analyze lung capacity by having the user blow into the phone's microphone, issuing alerts if abnormalities are detected. Such tools significantly enhance the ability to rapidly diagnose and assess patients at home.
- **Medication reminders and symptom logging:** A common challenge in health management is adherence to medication regimens and accurate symptom tracking. AI-enabled apps can automatically remind patients to take their medications based on individual data and send alerts to patients and physicians if abnormal symptoms or side effects are detected. These tools not only improve treatment adherence but also enable continuous monitoring of drug effectiveness and treatment progress.
- **Mental health monitoring:** AI in mental health can identify early signs of disorders such as depression, anxiety, and others by analyzing behavioral, textual, and speech patterns. This may include monitoring changes in activity levels, writing patterns, social interactions, and expressed emotions. Based on these analyses, intelligent systems can recommend appropriate interventions, referrals to counselors or specialists, and support programs, playing a significant role in the prevention and management of mental health issues.

In summary, AI in mHealth is a powerful tool that plays a significant role in improving quality of life and self-care. This technology not only enhances individual healthcare and monitoring processes but also, by facilitating access and increasing the efficiency of healthcare systems, helps reduce costs and improve clinical outcomes. With ongoing development and expansion, AI promises a bright future for personalized and intelligent healthcare, empowering patients to manage their health more effectively and enabling broader, more efficient delivery of health services.

4.2 Types of telemedicine services enhanced by AI methods

Telemedicine, as a rapidly evolving domain in healthcare, has been fundamentally transformed by the integration of AI. AI enhances telemedicine services by improving diagnostic accuracy, enabling real-time monitoring, personalizing treatment plans, and streamlining clinical workflows. Below is an in-depth exploration of key telemedicine services that are significantly enhanced by AI technologies [12, 17].

4.2.1 Remote consultation

Remote consultation involves providing medical advice and answering patient questions through video, audio, or text-based communication platforms. With the

incorporation of AI, this service has evolved from simple virtual visits to intelligent systems capable of offering preliminary diagnoses and triage support. The ways that AI enhances remote consultation are:

- Natural language processing (NLP): AI-powered chatbots and virtual assistants use NLP to understand patient queries and provide accurate responses. These tools can guide patients through symptom-checking processes and suggest whether an in-person visit is necessary.
- Large language models (LLMs): Tools like GPT-4 or BERT assist physicians by summarizing patient histories, generating differential diagnoses, and even drafting consultation notes automatically.
- Predictive analytics: AI algorithms analyze historical patient data to flag high-risk conditions during consultations, enabling early intervention.

4.2.2 Remote patient monitoring

Remote monitoring enables continuous observation of patients with chronic conditions such as cardiovascular diseases, diabetes, and respiratory illnesses using sensors and wearable devices. AI plays a pivotal role in transforming raw biometric data into actionable insights. The ways that AI enhances remote Patient monitoring are:

- Real-time data analysis: Wearable devices equipped with AI continuously collect and interpret vital signs such as heart rate, blood pressure, oxygen saturation, and glucose levels.
- Early warning systems: AI models detect abnormal patterns in real-time and issue alerts to both patients and care teams. For example, AI-enabled electrocardiography (ECG) wearables can identify arrhythmias like atrial fibrillation and alert cardiologists before a stroke occurs.
- Personalized alerts and recommendations: Machine learning algorithms tailor notifications based on individual patient profiles, ensuring interventions are timely and relevant.

4.2.3 Remote surgery

Remote surgery is performed *via* robot-assisted systems controlled by expert surgeons from a distance. While still in its infancy due to technical and regulatory challenges, AI is playing an increasingly important role in enabling precision and safety in telesurgery. The ways that AI enhances remote surgery are:

- Robotic assistance and precision: AI-driven robotic arms enhance surgical precision by compensating for hand tremors and optimizing incision depth and angle.
- Image-guided navigation: AI integrates preoperative imaging with real-time data to guide surgeons during complex procedures.
- Predictive modeling: AI assists in planning surgeries by simulating outcomes and recommending optimal approaches based on patient-specific anatomy.

4.2.4 Teledermatology

Teledermatology allows for the transmission of images of skin lesions to dermatology specialists for remote diagnosis. AI enhances this process by automating image interpretation and increasing diagnostic consistency. The ways that AI enhances Teledermatology.

- Automated image analysis: Deep learning models, particularly convolutional neural networks (CNNs), analyze dermoscopic images to detect melanoma, psoriasis, eczema, and other skin conditions with accuracy comparable to expert dermatologists.
- Triage and prioritization: AI helps prioritize urgent cases by analyzing severity indicators in uploaded images, ensuring faster response times for critical conditions.
- Mobile-based diagnosis: Patients can upload photos *via* smartphone apps, and AI models provide preliminary assessments that assist dermatologists in making faster decisions.

4.2.5 Patient education and treatment follow-up

AI-enhanced digital communication tools facilitate patient education and treatment follow-up by delivering personalized content and tracking adherence to prescribed therapies.

- Personalized educational content: AI tailors educational materials based on a patient's condition, literacy level, and preferences, increasing engagement and understanding.
- Intelligent reminders and notifications: Chatbots and mobile apps remind patients to take medications, attend appointments, and adhere to lifestyle recommendations.
- Treatment adherence tracking: AI analyzes self-reported symptoms and sensor data to assess how well patients are following treatment plans and alerts providers if deviations occur.

Table 3 details the AI techniques that have contributed to enhancing telemedicine services, along with their beneficial impacts.

By augmenting remote consultation, monitoring, diagnostics, surgical capabilities, and patient engagement, AI not only improves efficiency but also ensures more equitable access to quality care. As these technologies continue to evolve, they will play a central role in shaping the future of global healthcare—particularly in underserved and resource-limited settings.

4.3 The necessity of integrating telemedicine and AI in healthcare

By examining existing telemedicine systems worldwide and analyzing the patient-to-physician communication pipeline over long distances, it becomes evident that

Service	Core AI technologies	Key benefits
Remote consultation	NLP, LLMs, decision support systems	Faster triage, reduced workload, improved access
Remote monitoring	Wearables, predictive analytics, real-time alert systems	Early detection, personalized care, reduced hospitalizations
Teledermatology	Deep learning, CNNs, image recognition	Accurate diagnosis, scalability, rapid assessment
Remote surgery	Robotic systems, computer vision, simulation algorithms	Enhanced precision, expanded access to specialized care
Patient education and follow-Up	Chatbots, adaptive learning, behavioral analytics	Improved adherence, better patient engagement, and continuous support

Table 3.
AI services, technologies, and benefits in telemedicine.

there are numerous challenges in the acquisition and analysis of clinical patient data. These challenges encompass a wide range of issues, including effective communication with patients, accurate presentation of patient history, and proper understanding of this information by physicians. However, these difficulties are not limited to these aspects alone.

Therefore, there is a pressing need for a tool or solution capable of verifying data accuracy, analyzing large volumes of data within seconds, and providing recommendations and suggestions. This tool is none other than AI and AI-enabled technologies, which, when employed by physicians or clinicians, can serve as a valuable resource offering extensive benefits to all stakeholders involved.

The synergy and integration between AI tools and telemedicine have the potential to significantly enhance healthcare services. The following points elaborate on the rationale for employing AI alongside telemedicine systems:

4.3.1 Accurate and rapid analysis of medical data in telemedicine platforms

AI tools can analyze vast amounts of medical data, including radiology images, CT scans, MRIs, electrocardiograms, and patients' biometric data—with high precision and at speeds far exceeding human capability. When these analyses are conducted within telemedicine frameworks, physicians gain access to accurate results anytime and anywhere, enabling timely, data-driven clinical decisions.

4.3.2 Clinical decision support and personalized diagnosis

AI, through Clinical Decision Support Systems (CDSS), assists telemedicine practitioners by providing rapid access to relevant patient information, thereby facilitating optimal treatment choices. Furthermore, machine learning models can offer personalized, real-time recommendations based on the patient's medical history and current condition.

4.3.3 Continuous monitoring and real-time alerts

AI-powered systems analyze real-time data collected *via* wearable devices and sensors to continuously monitor patient health status. In the event of detecting

warning signs, these systems promptly alert healthcare teams. This capability enables proactive and preventive care in telemedicine, reducing the risk of sudden medical emergencies.

4.3.4 Automation of administrative and communication processes

In telemedicine, AI can automate repetitive tasks such as record keeping, answering frequently asked patient questions, medication reminders, and appointment scheduling. This automation alleviates the workload of healthcare providers, allowing them to focus more on specialized care.

4.3.5 Enhancing accessibility and equity in healthcare

The combination of AI and telemedicine broadens access to specialized medical services in remote and underserved areas with limited access to expert physicians. These technologies help bridge geographical and economic gaps, promoting greater equity in healthcare delivery.

4.3.6 Increasing diagnostic accuracy and reducing medical errors

AI can detect subtle features in medical images or clinical data that might be overlooked by human practitioners, thereby improving diagnostic accuracy. This is particularly crucial in telemedicine settings where physical examinations are limited.

4.3.7 Improving patient experience and active engagement

AI-driven virtual assistants in telemedicine provide 24/7 responses to patient inquiries, health education, and treatment follow-up. This fosters greater patient engagement in managing their own health and enhances overall patient satisfaction.

To summarize, the integration and synergy between AI tools and telemedicine enable the provision of healthcare services that are more precise, faster, accessible, and personalized. This combination not only elevates the quality of care but also reduces costs and optimizes resource utilization, thereby increasing the efficiency of healthcare systems [12, 17–21].

4.4 The evolving landscape of healthcare and digital transformation

The global healthcare landscape is undergoing a profound transformation driven by rapid advancements in digital technologies and the demographic shift toward aging populations with increasing burdens of chronic diseases. These factors have placed unprecedented pressure on healthcare systems worldwide, exposing systemic vulnerabilities such as workforce shortages, rising operational costs, fragmented care delivery, and the growing demand for continuous, patient-centered care.

In response to these challenges, digital health innovations, particularly telemedicine and AI, have emerged as critical enablers of a more efficient, scalable, and personalized healthcare paradigm. Telemedicine has expanded access to medical services, especially in underserved and rural areas, by bridging geographical barriers through real-time consultations, remote monitoring, and asynchronous communication. Simultaneously, AI-powered tools are revolutionizing diagnostics, treatment

planning, predictive analytics, and administrative workflows by processing vast amounts of clinical and nonclinical data with speed and precision beyond human capability.

The onset of the COVID-19 pandemic served as a catalyst for the widespread adoption of digital health solutions. As in-person visits became restricted, healthcare providers rapidly scaled virtual care platforms to ensure continuity of services while minimizing exposure risks. This period not only validated the feasibility of large-scale telehealth implementation but also demonstrated its effectiveness in managing both acute and chronic conditions remotely. Moreover, AI played a pivotal role in pandemic response through contact tracing, drug discovery, resource allocation modeling, and predicting outbreak trajectories.

Looking ahead, the integration of digital technologies into mainstream healthcare delivery promises to redefine traditional models of care. With the continued development of wearable sensors, mobile health applications, cloud-based electronic health records (EHRs), and interoperable health information systems, the future of healthcare is increasingly becoming decentralized, proactive, and data-driven. However, realizing the full potential of this digital transformation requires addressing key challenges, including regulatory alignment, equitable access, data privacy, and clinician buy-in.

Ultimately, the convergence of technological innovation and evolving patient needs is shaping a new era in healthcare—one that prioritizes value over volume, prevention over intervention, and personalized care over one-size-fits-all approaches [22, 31].

4.5 The importance of integrating artificial intelligence with telemedicine

The integration of AI with telemedicine extends far beyond simple video consultations. AI can analyze vast and diverse patient data, monitor vital signs in real-time, perform preliminary diagnoses, and even function as a virtual assistant in treatment management and patient communication. This combination personalizes, optimizes, and broadens access to healthcare services. The fusion of AI with telemedicine represents one of the major transformations shaping the future of healthcare systems.

This integration not only enables the provision of healthcare services in remote and underserved areas but also significantly enhances the quality of medical care. Leveraging big data analytics, machine learning, and NLP, AI offers novel capabilities for early disease detection, health pattern recognition, and personalized treatment planning. Concurrently, AI-driven technologies can improve diagnostic processes, strengthen physician-patient relationships, and reduce diagnostic errors.

Integrating these technologies within telemedicine—for instance, in managing chronic diseases such as diabetes or hypertension—facilitates continuous health monitoring and the issuance of preventive alerts. Moreover, AI-powered chatbots and virtual assistants streamline pre-consultation procedures and patient inquiries, alleviating pressure on healthcare systems. This synergy not only reduces healthcare costs but also enhances the speed and efficiency of service delivery [12, 14, 19].

A conceptual model (**Figure 2**) whereby AI tools, alongside clinical specialists, serve as instrumental resources in telemedicine can profoundly enhance the quality of healthcare services.

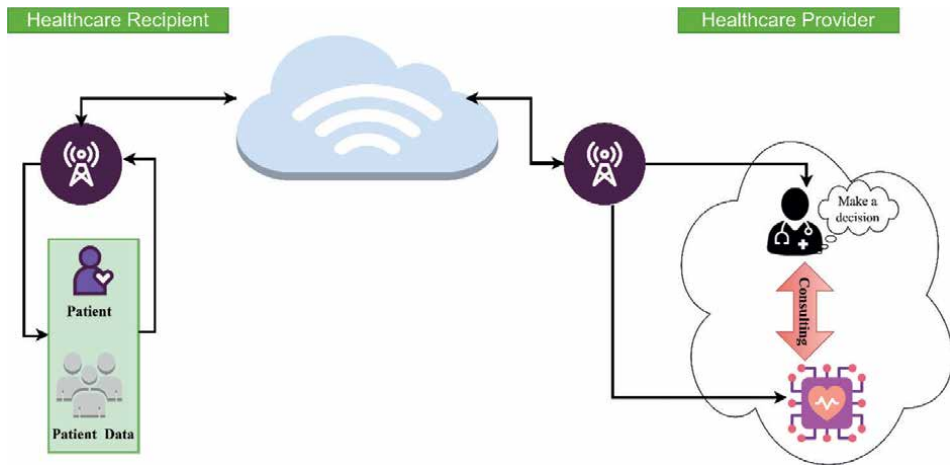


Figure 2.
Role of AI tools as a consultant to reach accurate decision-making.

5. Integrating AI with telemedicine: Enhancing accuracy, efficiency, and access

5.1 Advantages of the synergy between telemedicine and AI for healthcare stakeholders

5.1.1 Enhanced diagnostic accuracy and reduced human error

AI, leveraging advanced machine learning algorithms and neural networks, can analyze vast volumes of medical data—including radiology images, laboratory results, and clinical records—with exceptional speed and precision. Such accurate analyses facilitate early disease detection, identification of subtle symptoms, and reduction of human errors caused by fatigue, distraction, or cognitive limitations. For example, AI in medical imaging has achieved diagnostic accuracy for breast cancer and cardiovascular diseases equal to or even surpassing that of human specialists. This capability ensures that, even in the absence of a physician's physical presence, diagnostic quality is maintained and improved in telemedicine.

5.1.2 Improved efficiency and reduced physician workload

AI can automate many time-consuming and repetitive medical tasks such as data classification, coding of laboratory results, and management of electronic health records. This automation lessens the administrative and cognitive burden on physicians, allowing them to focus more on clinical decision-making and direct patient care. In telemedicine, this translates to the ability to serve more patients with higher quality and greater speed.

5.1.3 Preventive and personalized care

AI, as a powerful analytical tool, can process extensive genetic, clinical, and behavioral patient data to identify predictive patterns for diseases and their progression. This enables physicians to offer highly personalized treatments tailored to each

patient's unique characteristics and to initiate preventive care in a timely manner. For instance, in managing chronic diseases like diabetes or heart failure, AI can continuously monitor patient data to predict and warn of disease exacerbation, thereby reducing unnecessary hospitalizations and improving patients' quality of life.

5.1.4 Expanding access to specialist services in underserved areas

One of the greatest benefits of integrating AI into telemedicine is the promotion of equity in access to specialized medical services. AI can act as a physician's assistant in remote and underserved regions where access to specialists is limited. Through automated diagnostic systems, medical chatbots, and remote data analysis, patients in these areas can receive high-quality specialist care without the need for costly and time-consuming travel, significantly improving public health and reducing treatment disparities [14–16, 23, 24].

5.2 AI-driven innovations in telemedicine: Transforming remote healthcare through intelligent diagnostics, monitoring, and patient engagement

5.2.1 AI-driven innovations in telemedicine

AI has sparked transformative innovation across every field it touches, and telemedicine is no exception. In this rapidly evolving domain, AI-driven advancements have introduced groundbreaking capabilities that are not only reshaping how healthcare is delivered remotely but also promise continuous growth and expansion in the future. These innovations enhance diagnostic accuracy, improve patient monitoring, streamline clinical decision-making, and facilitate seamless communication between patients and providers. As telemedicine continues to integrate AI technologies, the scope and impact of these innovations are expected to broaden significantly, driving more accessible, efficient, and personalized healthcare solutions. Below, we explore some of the key AI-powered innovations that are revolutionizing telemedicine today.

5.2.2 AI in diagnosis and clinical decision support

In telemedicine, diagnosing diseases without the patient's physical presence is challenging. AI, using advanced image analysis algorithms, can accurately interpret remotely transmitted medical images—such as radiology, dermatology, and ophthalmology scans—facilitating faster and more precise diagnoses. This enables the provision of specialist services to patients in remote and hard-to-reach locations. AI-based CDSS in telemedicine assist physicians in selecting optimal treatment options based on patient data and clinical guidelines. By analyzing clinical and medical history data, these systems streamline decision-making and reduce human error, especially when physicians treat patients remotely without in-person consultations.

5.2.3 AI in remote monitoring and wearable devices

Wearable devices and remote monitoring tools continuously collect patients' biometric data. AI analyzes this data to predict heart attacks, exacerbation of chronic diseases, and other critical conditions, issuing real-time alerts to both patients and physicians. This is particularly important in telemedicine, as remote physicians can respond swiftly to changes in patient status. Notable examples include portable

AI-enabled ECG devices capable of automatically detecting arrhythmias and cardiac disorders and transmitting information to remote care teams, thus increasing patient safety and reducing emergency hospitalizations.

5.2.4 Natural language processing and virtual assistants in telemedicine

NLP, a vital branch of AI, has significantly advanced the capabilities of telemedicine by enabling the creation of intelligent virtual assistants and chatbots. These AI-powered tools are designed to understand and process human language, allowing them to interact naturally with patients and healthcare providers. In telemedicine, where face-to-face interactions are limited or unavailable, NLP-driven chatbots serve as the first point of contact by answering patient queries promptly and providing initial medical consultations based on symptom analysis and clinical guidelines.

Beyond answering questions, these virtual assistants guide patients through their treatment journeys by offering personalized health advice, medication reminders, and educational content tailored to individual needs. They facilitate continuous engagement by monitoring patient adherence to prescribed treatments and prompting follow-up actions, which is crucial for managing chronic diseases remotely. This ongoing interaction not only improves patient compliance but also empowers individuals to take a more active role in their health management.

Moreover, NLP-based virtual assistants can triage patient concerns by identifying urgent symptoms that require immediate medical attention, thus optimizing healthcare resource allocation. They also support healthcare providers by automating routine administrative tasks such as appointment scheduling and documentation, allowing clinicians to focus more on direct patient care.

The integration of NLP and virtual assistants in telemedicine enhances communication efficiency, reduces barriers to access, and improves the overall quality of remote healthcare services. As research in AI-driven personalized diagnostics and treatments progresses, these tools are expected to become even more sophisticated, offering deeper insights and more nuanced patient support, ultimately transforming the landscape of telemedicine and telehealth.

5.2.5 AI as a data management and analysis tools

In telemedicine, one of the most critical challenges lies in the effective management and analysis of vast, heterogeneous datasets generated from diverse sources, such as wearable devices, EHRs, laboratory test results, and imaging modalities. These data streams vary widely in format, frequency, and clinical relevance, necessitating advanced data integration frameworks capable of harmonizing and contextualizing information to support clinical decision-making. AI technologies, particularly those leveraging big data analytics, play a transformative role in addressing these complexities. AI-driven platforms employ sophisticated algorithms to aggregate and preprocess raw data, ensuring data quality through noise reduction, normalization, and anomaly detection. This preprocessing is essential to create a unified, longitudinal patient health profile that accurately reflects the dynamic physiological and pathological states of individuals. Predictive analytics, powered by AI, enable telemedicine providers to move beyond traditional episodic care toward proactive, personalized medicine. By analyzing historical and real-time data, machine learning models identify subtle patterns and risk factors that may not be evident through conventional analysis. These insights facilitate the development of tailored treatment regimens that account

for patient-specific variables, such as genetic predispositions, lifestyle factors, and comorbid conditions, thereby optimizing therapeutic efficacy and minimizing adverse effects.

5.2.6 AI as a provider and designer of care models

AI, as a provider and designer of care models, offers healthcare systems advanced capabilities, including automated patient triage based on disease severity and the development of dynamic, personalized treatment plans that adapt in real time to patient data.

In telemedicine, intelligent triage systems powered by machine learning algorithms can receive and analyze patients' initial symptoms and data *via* online platforms. This automated analysis prioritizes patients in real time, optimizing resource allocation. Such systems are especially beneficial during crises or in busy healthcare centers, reducing staff workload and improving response times.

Integrating AI with telemedicine enables the creation of dynamic treatment plans that are updated based on real-time data from wearables, health apps, and patient reports. These plans automatically adjust treatments, medications, and lifestyle recommendations to ensure fully personalized and optimized care.

5.2.7 AI as a telemedicine consultant

In telemedicine systems, AI analyzes remotely transmitted medical images, laboratory data, and clinical symptoms to provide accurate preliminary diagnoses. These tools can assist physicians in diagnosing chronic or acute diseases and refer patients for in-person visits when necessary.

AI, through chatbots and virtual assistants, enables fast and accurate responses to patient inquiries. These technologies reduce waiting times, increase patient satisfaction, and improve the quality of telemedicine interactions. They can also automate appointment scheduling, medication reminders, and patient follow-up.

5.2.8 AI as an extractor of information and knowledge from EHRs

Intelligent data extraction and analysis for identifying treatment needs and preventing errors: AI, when integrated with EHR systems, serves as a powerful tool for synthesizing and interpreting vast amounts of clinical data that are often fragmented, heterogeneous, and unstructured. These data originate from diverse sources, including wearable devices, physician notes, laboratory results, radiology reports, patient-reported outcomes, and longitudinal treatment histories. Through advanced NLP, machine learning algorithms, and real-time analytics, AI transforms this complex information into actionable insights.

This intelligent integration enables a more accurate and timely identification of individual patient needs by uncovering hidden patterns, predicting disease progression, and personalizing therapeutic strategies. Furthermore, AI-driven analysis significantly reduces the likelihood of medical errors, such as medication mismatches, diagnostic oversights, or procedural inconsistencies, by flagging anomalies, cross-referencing patient data, and providing evidence-based alerts at the point of care.

In the context of telemedicine and remote patient monitoring, AI-enhanced EHR systems support continuous evaluation of patient health status, allowing clinicians to intervene proactively and coordinate care more effectively across multidisciplinary

teams and care settings. Ultimately, the synergy between AI and EHR not only enhances clinical decision-making but also contributes to safer, more efficient, and patient-centered healthcare delivery [18, 20, 23, 25–31].

5.3 The impact of AI on telemedicine and the influence of integrating in healthcare delivery

The integration of AI and telemedicine represents a fundamental transformation in healthcare delivery. This synergy not only improves access to medical services but also enhances clinical outcomes, reduces costs, and optimizes workflows in healthcare. In this section, the multifaceted impact of AI on telemedicine can be explored, and the interplay of telemedicine for the development and application of AI can be explored, using resources such as equity, efficiency, and participation, among others.

5.3.1 Improving access and equity

Reducing geographical and economic disparities in access to specialized services: The integration of AI with telemedicine enables the provision of specialized medical services to remote and underserved areas. Intelligent algorithms can analyze data collected from patients in these regions, allowing for initial diagnoses and expert assessments without the physical presence of a physician. These technologies help to reduce geographical and economic inequalities and facilitate access to specialized care for low-income populations and residents of rural areas.

5.3.2 Enhancing clinical outcomes

Early diagnosis and timely treatment of diseases: By utilizing AI within telemedicine platforms, continuous monitoring and real-time analysis of patient symptoms become possible. These systems can identify early signs of diseases and send immediate alerts to physicians and patients, leading to early diagnosis and prompt initiation of treatment. This process significantly contributes to slowing disease progression and improving clinical outcomes.

5.3.3 Cost savings

Reducing unnecessary in-person visits and hospitalizations: AI in telemedicine, through remote initial assessments and patient triage, decreases the need for unnecessary in-person visits. Furthermore, by continuously monitoring chronic patients and predicting critical situations, emergency hospitalizations and related costs are reduced. This reduction in visits and hospitalizations results in substantial savings for the healthcare system.

5.3.4 Optimizing healthcare workflows

Streamlining processes and reducing operational burdens: AI-driven telemedicine streamlines healthcare workflows by conducting remote preliminary assessments and triage, thereby reducing unnecessary in-person appointments. Continuous monitoring of chronic patients and forecasting acute events further diminishes emergency admissions and associated expenses. Collectively, these efficiencies contribute to significant cost reductions and improved resource allocation within healthcare systems.

5.3.5 Engagement and satisfaction

Enhancing interaction, education, and treatment adherence through intelligent tools: AI, in the form of virtual assistants, chatbots, and interactive health applications, enables continuous patient education regarding diseases and treatments. These tools, through intelligent reminders, health status tracking, and responsive communication, foster active patient participation in the treatment process. As a result, treatment adherence improves, and patient satisfaction with telemedicine services is markedly enhanced.

5.3.6 Comparison of AI applications in telemedicine services

The diverse applications of AI within telemedicine platforms facilitate the provision of a wide array of services, many of which emerge following the identification of needs in consultation, treatment planning, surgical procedures, follow-up, and counseling, and subsequently undergo further development. AI, with its capacity to analyze large datasets, identify complex patterns, and provide personalized recommendations, plays a pivotal role in enhancing clinical decision-making and reducing medical errors. Conversely, telemedicine enables the delivery of healthcare services remotely, ensuring patient access to specialized care at any time and place, thereby reducing costs and promoting health equity.

However, to better understand the strengths, limitations, and synergistic opportunities of these two domains, a structured comparison of their features, applications, challenges, and future trends is essential. The following table aims to provide a comprehensive overview by comparing various aspects of AI and telemedicine, as well as their points of intersection and synergy. This comparison can serve as a roadmap for researchers, policy-makers, and healthcare administrators in planning and developing innovative solutions [18, 23, 31–34]. **Table 4** presents a detailed comparison between AI and telemedicine.

Feature/ dimension	Artificial intelligence	Telemedicine	Synergy points (AI in telemedicine)
Definition	The development of algorithms and systems capable of performing tasks similar to human intelligence	The provision of healthcare services remotely using information and communication technologies	The integration of intelligent algorithms to enhance remote healthcare delivery
Types/subfields	Machine learning, deep learning, generative AI, large language models, expert systems	Remote consultation, monitoring, teledermatology, remote surgery, health education	Clinical Decision Support Systems (CDSS), intelligent patient monitoring, medical chatbots, automated image interpretation
Applications	Disease diagnosis, prediction, NLP, data analytics, process automation	Remote medical consultation, patient monitoring, remote treatment, patient education and follow-up	Automated diagnosis, real-time alerts, personalized therapeutic recommendations, optimized physician-patient interaction
Advantages	Increased accuracy, speed, personalization, error reduction, and analysis of big data	Improved access, reduced costs and time, enhanced health equity, decreased need for in-person visits	More precise and rapid care delivery, improved patient satisfaction, and better resource management

Feature/ dimension	Artificial intelligence	Telemedicine	Synergy points (AI in telemedicine)
Challenges	Data quality, algorithmic bias, transparency, security, ethical and legal considerations	Data security, communication quality, infrastructure limitations, acceptance by patients and providers	Combined challenges: Security, privacy, trust, legal responsibility, user training
Key technologies	Neural networks, machine learning algorithms, language models (GPT, BERT), generative adversarial network (GAN)	Video consultation apps, online consultation platforms, wearable devices, health sensors	Health chatbots, intelligent alert systems, automated image interpretation, clinical decision support
Standards and regulations	General Data Protection Regulation (GDPR), Health Insurance Portability and Accountability Act (HIPAA), AI ethics principles, data safety standards	HIPAA, GDPR, digital health regulations, telemedicine licensing	Need for compliance with both sets of regulations and development of new frameworks for integrated applications
Social impact	Transformation of jobs, increased productivity, issues of equity, and bias	Improved health equity, reduction of geographical and economic disparities	Enhanced health equity, reduced inequalities, and provision of specialized services to underserved areas
Future trends	Explainable AI, federated learning, generative AI, human-AI collaboration	Integration with Internet of things (IoT), augmented/virtual reality, data-driven care	Intelligent care, self-learning systems, integration with Internet of Medical Things (IoMT), and use of blockchain for data security
Case studies	AI-based cancer diagnosis, health chatbots, automated image analysis	Teledermatology in India, remote robotic surgery, and remote cardiac monitoring in the US	Babylon Health (UK), Dexcom diabetes monitoring, Da Vinci surgical robot with AI support

Table 4.
Comparative analysis of key dimensions of AI, telemedicine, and their synergy in healthcare.

6. Challenges and ethical considerations of AI in telemedicine

With the rapid expansion of AI applications in the field of telemedicine, numerous challenges and ethical considerations have emerged alongside the abundant opportunities and benefits. These include safeguarding patient privacy and the security of sensitive data, addressing potential biases and inequalities within algorithms, overcoming legal and regulatory barriers, resolving technical issues related to system integration and interoperability, and recognizing the inherent limitations of AI in clinical settings. Addressing these issues is not only vital for ensuring the quality and safety of healthcare services but also plays a key role in building patient trust and promoting equity and transparency in healthcare delivery. This section provides a comprehensive examination of these challenges and ethical considerations.

6.1 Privacy and data security

Protecting sensitive patient data is one of the most critical challenges in integrating AI with telemedicine. Medical data—including personal information, medical

history, test results, and real-time data from wearable devices—if disclosed without authorization, can lead to abuses such as identity theft and privacy violations. Therefore, AI systems must be designed and implemented in compliance with international standards such as GDPR and HIPAA to ensure data security. Moreover, the use of advanced encryption technologies and stringent access control mechanisms is essential to safeguard data. Additionally, educating users and healthcare personnel about the importance of data security and strategies to counter cyber threats constitutes a key component of these efforts.

6.2 Bias and fairness in AI algorithms

A fundamental ethical challenge in AI is the presence of bias in algorithms, which can result in discrimination in the delivery of medical services. It is imperative to train AI models on diverse and representative datasets encompassing various populations to prevent racial, gender, economic, and geographic biases. This issue is particularly significant in telemedicine, where patients from different backgrounds and with varying levels of access to healthcare are connected. Neglecting this aspect may lead to inequalities in diagnosis and treatment. Furthermore, transparency in algorithm design and the continuous review and correction of biases are essential to uphold fairness.

6.3 Legal and regulatory barriers

The integration of AI in telemedicine faces numerous legal and regulatory challenges. The absence of comprehensive and up-to-date legal frameworks that ensure accountability, safety, and quality of AI services constitutes a major obstacle. Existing laws are often designed for traditional technologies and require revision and updating to address emerging technologies adequately. Additionally, determining liability in cases of errors or harm resulting from AI-driven decisions is a complex issue that must be clearly defined within legal statutes. Coordination among regulatory bodies, healthcare providers, and technology developers is essential to establish clear and coherent legal frameworks.

6.4 System integration and interoperability

A significant technical challenge lies in achieving coordination and interoperability among various digital health systems. AI and telemedicine platforms must seamlessly communicate with EHRs, diverse platforms, and medical devices. The lack of common standards and differences in data formats complicate information exchange and reduce system efficiency. Moreover, integrating new technologies with traditional workflows requires time, resources, and appropriate training. Addressing these challenges necessitates the development of international standards, the adoption of API-based technologies, and close collaboration between technology developers and healthcare institutions.

6.5 Limitations of AI in clinical settings

AI in telemedicine should be regarded as an assistive tool for physicians and healthcare professionals rather than a substitute for human decision-making. Limitations such as the inability to fully comprehend clinical context, lack of empathy and emotional understanding, and the possibility of unforeseen errors mean that final decisions must remain

under human authority. Furthermore, AI systems are often specialized and domain-specific and cannot replace the comprehensive and holistic judgment of a physician. Therefore, the role of human oversight in reviewing and validating AI outputs is vital to maintain the quality and safety of medical care [1, 35–38].

7. Future directions and innovations

7.1 Emerging technologies

7.1.1 Federated learning for privacy preservation and enhanced data security in training AI models for telemedicine

Federated learning, as an advanced technology, enables the training of AI models on distributed patient data across different healthcare centers without the need to transfer or share data. This approach preserves the privacy and security of sensitive medical data while allowing for the development of accurate and generalizable models in telemedicine environments. Leading projects such as Google Health and NVIDIA Clara have leveraged this technology to develop highly accurate diagnostic and predictive models while fully adhering to data protection principles [39].

7.1.2 Explainable AI for increased transparency, trust, and acceptance in telemedicine services

Explainable AI models are capable of articulating their decision-making processes in a manner understandable to physicians and patients. This capability is especially vital in telemedicine, where direct and in-person communication is limited, and plays a crucial role in building user trust. Technologies like the IBM Watson Explainability Toolkit and Google Explainable AI are developing algorithms that not only deliver precise results but also provide the rationale and evidence behind decisions, thereby enabling specialists to evaluate and refine the models [40].

7.2 The potential of AI in global telemedicine

7.2.1 Delivering intelligent specialized services to underserved regions and developing countries via AI-based telemedicine platforms

AI, with its ability to analyze medical data and provide preliminary diagnoses, enables access to specialized services for disadvantaged populations and residents of remote geographic areas. Projects such as Babylon Health and Project Extension for Community Healthcare Outcomes (ECHO), utilizing intelligent algorithms and telemedicine platforms, have delivered health monitoring and consultation services to these regions at lower costs and with satisfactory quality. These technologies play a significant role in reducing health disparities and promoting equity in access to specialized care [22].

7.2.2 Personalizing telemedicine care by adapting AI algorithms to local, cultural, and demographic data

To enhance the effectiveness of telemedicine services in developing countries, AI models must be tailored to demographic, cultural, and local environmental

characteristics. Such personalization ensures that diagnoses and treatment recommendations are more accurate and better aligned with patients' real needs, thereby increasing the acceptance of new technologies in these communities [22].

7.3 The role of AI in pandemic response and preparedness

7.3.1 Real-time surveillance and prediction of infectious disease outbreaks through multisource and large-scale data analysis

AI systems can collect and analyze real-time data from diverse sources, such as medical reports, social networks, travel data, and environmental sensors, to forecast the spread of infectious diseases and identify critical points. Successful projects like BlueDot and HealthMap played a key role in early warning and crisis management during the COVID-19 pandemic.

7.3.2 Optimizing resource management and strategic decision-making in health crises with AI models

By analyzing extensive data and modeling various scenarios, AI assists health managers in optimally allocating limited resources such as hospital beds, medical equipment, and human resources. This leads to a more efficient pandemic response and reduces the burden on healthcare systems [22].

7.4 Collaborative care models: Integrating AI and human expertise

7.4.1 Developing intelligent decision support systems for effective collaboration between physicians and AI in clinical processes

Telemedicine platforms equipped with AI act as clinical assistants, providing precise analyses, data-driven predictions, and treatment suggestions to support physicians in clinical decision-making. This synergistic collaboration increases diagnostic accuracy, reduces medical errors, and improves treatment outcomes.

7.4.2 Maintaining human aspects, empathy, and effective communication in telemedicine supported by smart technology

Despite advances in AI, human aspects such as empathy, emotional understanding, and effective patient communication remain essential. Collaborative care models that combine human expertise with intelligent capabilities ensure comprehensive, empathetic, and patient-centered care [22, 41].

7.5 Policy and strategic recommendations

7.5.1 Establishing legal, ethical, and technical standards to ensure security, equity, and accountability in AI applications

The development of policies and regulations governing the use of AI in telemedicine and protecting patient rights is of paramount importance. These frameworks should encompass principles of transparency, accountability, privacy protection, and mitigation of algorithmic bias.

7.5.2 Investing in health IT infrastructure development and training specialized human resources

Optimal utilization of AI in telemedicine requires advanced IT infrastructure, high-speed internet, and smart medical equipment. Continuous training of physicians, nurses, and other healthcare personnel in the use of intelligent technologies and medical data analysis is also essential for improving service quality [42].

7.6 Operational use cases

The integration of AI and telemedicine is one of the most transformative trends in contemporary healthcare systems. This technological synergy has not only enabled the delivery of specialized medical services to remote and underserved areas but has also significantly enhanced the quality, speed, and accuracy of healthcare. AI, with its capacity for big data analysis, complex pattern recognition, and personalized recommendations, assists both physicians and patients in making optimal treatment decisions. Conversely, telemedicine removes geographical barriers, making healthcare accessible to all segments of society. Below are real-world, successful examples from around the globe where AI and telemedicine have been implemented simultaneously and interactively:

7.6.1 Babylon health (UK)

Babylon Health is a comprehensive digital health platform that combines AI and telemedicine to provide medical consultations to millions of users. Users initially interact with an AI-based chatbot, inputting their symptoms. The chatbot analyzes the medical history and symptoms to assess the likelihood of various diseases and offers initial recommendations. If necessary, the patient is referred to a human physician for a video consultation. The system continuously improves its performance using big data and machine learning algorithms and can even issue public health alerts based on population trends.

7.6.2 Dexcom G6 and Livongo (USA)

Dexcom G6 is a continuous glucose monitoring system that collects real-time blood glucose data from diabetic patients and transmits it to a cloud platform *via* the internet. Livongo analyzes data from wearable devices and sensors using AI algorithms to identify and predict blood glucose trends. When dangerous changes or abnormal patterns are detected, the system automatically sends alerts to the patient and care team and even provides personalized recommendations for dietary or medication adjustments. This model makes chronic disease management intelligent, preventive, and personalized.

7.6.3 Aidoc (Israel)

Aidoc is an advanced medical imaging analysis platform that uses deep learning to automatically and rapidly analyze CT, MRI, and radiology images. Especially in emergency situations, the system receives patient images remotely and reports critical findings (such as cerebral hemorrhage or pulmonary embolism) to the physician within minutes. By integrating with telemedicine platforms,

Aidoc enables rapid diagnosis and reduces waiting times for patients in remote areas, playing a significant role in enhancing the accuracy and speed of clinical decision-making.

7.6.4 Ping an good doctor (China)

This Chinese platform, with over 300 million users, utilizes AI for initial screening and medical history collection. Patients enter their symptoms, and the system analyzes the data to assess disease probabilities and suggest appropriate treatment pathways. The patient is then connected to an online physician for specialized consultation. Ping An Good Doctor accelerates and optimizes triage processes using AI, facilitating access to healthcare for China's vast population.

7.6.5 Tytocare (Israel-USA)

Tytocare is a smart home medical kit that allows patients to collect clinical data such as heart and lung sounds, images of the ear and throat, and body temperature. This data is sent to the physician *via* the internet. AI pre-analyzes the data (e.g., detecting abnormal lung or heart sounds) and reports key findings to the physician. This tool enables virtual physical examinations and faster diagnoses within telemedicine frameworks.

7.6.6 Qure.ai (India)

Qure.ai has developed deep learning algorithms for interpreting radiology images, CT scans, and X-rays. Images from remote areas are sent online and analyzed by AI, with results quickly provided to local physicians to facilitate treatment decisions. This technology has been especially effective in screening for tuberculosis and COVID-19 in underserved regions of India.

Da Vinci Surgical Robot (USA and Europe)—The Da Vinci is an advanced surgical robot supported by AI, enabling complex surgeries to be performed remotely (See **Figure 3**). The surgeon controls the robot *via* a console, while AI analyzes real-time images and vital data, suggesting optimal surgical pathways. This technology is particularly useful for precise, minimally invasive surgeries and enables the provision of specialized services to patients in remote areas.

7.6.7 Cardiac patient monitoring systems (Europe and USA)

Smart wearable devices such as the Apple Watch and remote cardiac monitoring systems collect vital patient data and analyze it using AI algorithms. If arrhythmias or signs of heart attack are detected, the system automatically sends immediate alerts to the patient and care team. This model plays a vital role in preventing acute complications and managing cardiac patients.

7.6.8 TeleICU and eICU (USA)

In these systems, intensive care unit (ICU) patients are remotely monitored by medical teams. AI continuously analyzes patients' vital data and issues necessary alerts in case of dangerous changes. This model enables continuous care and rapid response to patient status changes, even in small hospitals or remote areas.



Figure 3.
Da Vinci surgical system (courtesy of intuitive surgical).

These examples demonstrate that the integration of AI and telemedicine is being utilized across a wide range of healthcare services, from consultation and monitoring to diagnosis and surgery, shaping a future for global healthcare that is intelligent, precise, and accessible.

8. Conclusion

In conclusion, this chapter has shown that the integration of AI and telemedicine has brought about a fundamental transformation in contemporary healthcare systems. This synergy not only enables more equitable access to medical services for patients in remote and underserved areas but also significantly enhances the quality, speed, and accuracy of healthcare delivery. AI, through big data analysis, complex pattern recognition, and personalized recommendations, plays a key role in improving clinical decision-making and reducing medical errors. Meanwhile, telemedicine, by eliminating geographical and temporal barriers, provides opportunities for continuous and preventive care to all segments of society. Although challenges such as ethical issues, data security, and user acceptance of technology remain, emerging trends such as explainable AI and federated learning are opening new horizons for the future of this field. Overall, the convergence of AI and telemedicine promises a smarter, more efficient, and more human-centered future for global healthcare systems.

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Edited by Charles R. Doarn

This book, structured into three sections, contains 14 chapters that make an outstanding contribution to the growing field of telemedicine and the application and integration of Artificial Intelligence (AI). The contributing authors provide extensive knowledge from their experience. While many of you who read this book and utilize it as a ready reference may already have a firm foundation with which to work. This book will serve as a tool to reinforce change. For those new to the field, this book can be an invaluable addition to their library and work. Regardless of its application, we know that technology, especially with AI, will continue to push the boundaries and perhaps provide healthcare and knowledge to the more than 8 billion inhabitants of this place we call home!

Robert Koprowski, Biomedical Engineering Series Editor

Published in London, UK

© 2026 IntechOpen
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IntechOpen

ISSN 2631-5343

ISBN 978-1-83635-317-1

