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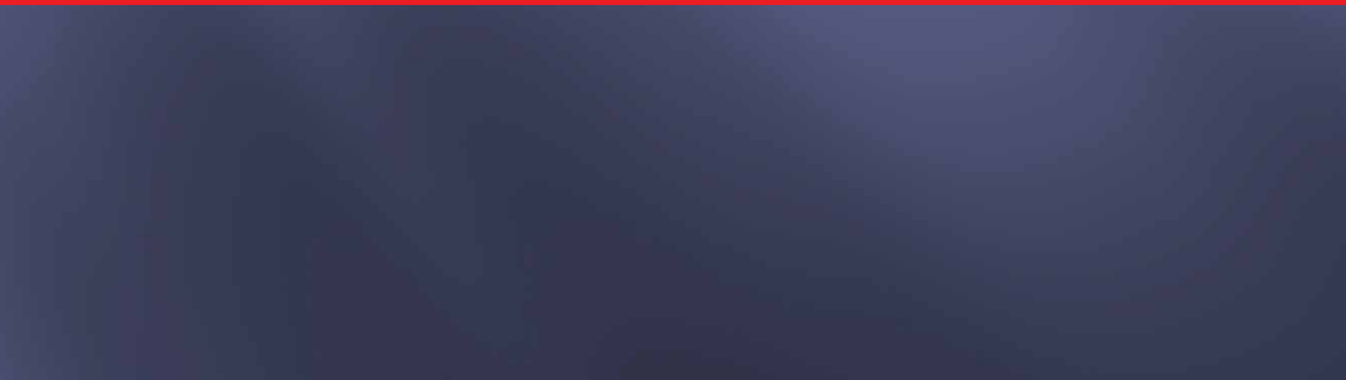
Human Teeth
The Intersection of Science, Disease, and Clinical Practice

Edited by Manal A. Ablal
and Adejumoke Adeola Adeyemi



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Aims and Scope of the Series

This book series will offer a comprehensive overview of recent research trends as well as clinical applications within different specialties of dentistry. Topics will include overviews of the health of the oral cavity, from prevention and care to different treatments for the rehabilitation of problems that may affect the organs and/or tissues present. The different areas of dentistry will be explored, with the aim of disseminating knowledge and providing readers with new tools for the comprehensive treatment of their patients with greater safety and with current techniques. Ongoing issues, recent advances, and future diagnostic approaches and therapeutic strategies will also be discussed. This series of books will focus on various aspects of the properties and results obtained by the various treatments available, whether preventive or curative.

Meet the Series Editor

Dr. Sergio Alexandre Gehrke is a doctorate holder in two fields. The first is a Ph.D. in Cellular and Molecular Biology from the Pontificia Catholic University, Porto Alegre, Brazil, in 2010 and the other is an International Ph.D. in Bioengineering from the Universidad Miguel Hernandez, Elche/Alicante, Spain, obtained in 2020. In 2018, he completed a postdoctoral fellowship in Materials Engineering in the NUCLEMAT of the Pontificia Catholic University, Porto Alegre, Brazil. He is currently the Director of the Postgraduate Program in Implantology of the Bioface/UCAM/PgO (Montevideo, Uruguay), Director of the Cathedra of Biotechnology of the Catholic University of Murcia (Murcia, Spain), an Extraordinary Full Professor of the Catholic University of Murcia (Murcia, Spain) as well as the Director of the private center of research Biotecnos – Technology and Science (Montevideo, Uruguay). Applied biomaterials, cellular and molecular biology, and dental implants are among his research interests. He has published several original papers in renowned journals. In addition, he is also a Collaborating Professor in several Postgraduate programs at different universities all over the world.

Meet the Volume Editors

Manal A. Ablal is a Senior Clinical Lecturer in Restorative Dentistry at the School of Dentistry, University of Liverpool, UK. She holds a Master of Dental Science and a Ph.D. focused on tooth wear and related research. Actively engaged in both undergraduate and postgraduate dental education, her interests include curriculum innovation, preventive oral health, and the use of digital tools and reflective learning in clinical teaching. She has contributed to numerous academic publications and conference presentations, sharing her expertise through articles and book chapters on restorative dentistry and dental education.

Adejumoke Adeola Adeyemi is a Senior Clinical Lecturer and Honorary Consultant in Periodontology at the School of Dentistry, University of Liverpool, UK. She also serves as Adjunct Visiting Professor of Periodontology at the University of Benin Dental School in Nigeria. She has been involved in undergraduate and postgraduate dental education since 2006 and has led periodontics teaching at the University since 2015. She has a membership in Periodontics from the Royal College of Surgeons of Edinburgh and is on the GDC specialist register for Periodontics. She has authored book chapters and presented and published her work nationally and internationally.

Contents

Preface

Human Teeth – The Intersection of Science, Disease, and Clinical Practice brings together a timely and multidisciplinary oral health examination from various clinical, public health, and technological perspectives. This edited volume aims to inform professionals and curious readers about the essential role of teeth as anatomical structures and indicators of health, disease, and innovation in modern medicine.

The volume begins with the Introductory Chapter.

Chapter 2, *Smile for a Lifetime: Education in Oral Health, Cavity Prevention, and Early Diagnosis from Childhood*, emphasizes the significance of early intervention and lifelong oral hygiene habits. The chapter discusses the role of caregivers, healthcare providers, and education systems in shaping oral health outcomes from infancy through adolescence.

In Chapter 3, *Global Trends and Projection of Caries of Permanent Teeth Incidence from 1990 to 2030: A Modeling Study*, the discussion shifts to an international scale. This data-driven chapter reveals persistent and rising global trends in dental caries, linking oral disease to socioeconomic disparities and offering important projections to inform future public health efforts.

Chapter 4, *Endodontic Challenges Arising from Root Canal Morphology* focuses on clinical complexity, presenting detailed insights into the anatomical variations that make root canal therapy among the most challenging dental procedures. The chapter highlights the importance of precision and expertise in modern endodontic care through clinical classification and diagnostic strategies.

The final contribution, Chapter 5, *Additive Manufacturing in Operative and Restorative Dentistry Techniques, Clinical Applications, and Future Outlooks*, examines how digital design and 3D printing transform restorative practices. This chapter discusses current applications and future directions, emphasizing how these technologies enhance personalization, efficiency, and innovation in dental care.

While concise in scope, this five-chapter volume was designed with intentional breadth and depth. Each chapter addresses a distinct yet complementary facet of oral health, enabling the book to deliver both clarity and impact without compromising academic rigor.

Together, these chapters illustrate the vital convergence of science, clinical application, and public policy in contemporary dental medicine. The volume aims to support clinicians, researchers, educators, and students in deepening their understanding of the interconnected dimensions of oral health. The editors would like to sincerely thank the chapter authors for their valuable contributions and the reviewers, assistants, and colleagues who supported the development of this volume. Special appreciation goes to [insert names of individuals or institutions to be acknowledged] for their editorial assistance and guidance throughout the publication process.

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Chapter 1

Introductory Chapter: Understanding Human Teeth – From Biology to Clinical Practice

Manal A. Ablal

1. Introduction

1.1 Why teeth matter

Human teeth are among the most vital structures in the human body. They are essential for basic functions such as eating and speaking, yet their role extends far beyond mere physical utility. Teeth serve as markers of our identity, influencing self-esteem and social interactions. Their durability also speaks to the evolutionary history of humans, reflecting adaptations to diet, environment, and lifestyle. Today, understanding human teeth is not only the domain of dentistry but intersects with broader fields such as biology, medicine, and technology, offering profound insights into human health and disease [1, 2].

This chapter will explore the multifaceted role of human teeth in health, disease, and clinical practice. It will highlight how advances in dental science, materials, and technology are shaping modern dental care. Additionally, it will examine how teeth offer a lens through which we can better understand broader medical conditions and systemic health. Ultimately, this chapter serves as a foundation for understanding the importance of teeth in human health, setting the stage for a deeper dive into the various facets of dental care, from evolutionary biology to cutting-edge restorative technologies.

2. The role of teeth in human health

Teeth are not only critical for basic functions like chewing and speaking; they are essential to our overall health and well-being. Beyond their primary role in mastication, teeth contribute to facial esthetics, speech, and social identity. The condition of a person's teeth can significantly affect their quality of life, impacting everything from their ability to eat to their self-esteem. The loss or deterioration of teeth can lead to profound psychological and social consequences, highlighting the importance of maintaining oral health [3, 4].

From a medical perspective, teeth offer unique insight into overall health. Oral diseases, such as dental caries and gum disease, are prevalent worldwide and often serve as early indicators of systemic conditions. For example, poor oral health has been linked to cardiovascular disease, diabetes, and other chronic conditions [5, 6].

As a result, the study of teeth has grown beyond traditional dental care, influencing broader fields like medicine and public health.

The health of human teeth is therefore not an isolated issue but is deeply intertwined with a person's overall health. Recognizing this connection, modern dental practice emphasizes a holistic approach, where treatment goes beyond addressing symptoms to consider the patient's broader health needs. As research continues to uncover the link between oral health and general well-being, the role of dentists has expanded to include preventive measures and interdisciplinary collaboration with other healthcare providers.

3. The evolution of dental science and technology

The study of human teeth offers a unique perspective on the evolution of our species. Through the analysis of teeth, researchers can gain insights into the dietary habits, social behaviors, and environmental conditions of past human populations. Over time, human teeth have adapted to changes in diet and lifestyle, providing a window into the cultural and environmental forces that have shaped human development.

Alongside this evolutionary perspective, dental science has undergone significant transformations in recent centuries. From the rudimentary tools of early dentistry to the advanced materials and technologies used today, the field has evolved in response to new scientific discoveries. Innovations such as digital imaging, 3D printing, and new biomaterials have revolutionized dental care, improving diagnostic accuracy and treatment outcomes [7].

Technological advancements have made dental procedures more precise, efficient, and personalized. 3D printing, for example, is increasingly being used to create custom restorations, offering new possibilities in restorative dentistry. These innovations not only enhance the quality of care but also enable more personalized and patient-specific treatments. However, they also introduce new challenges, such as ensuring the long-term safety, effectiveness, and biocompatibility of these new technologies.

As the field of dental science continues to evolve, it is essential for dental professionals to stay informed and adaptable, integrating new technologies responsibly to improve patient care while maintaining high standards of practice.

4. Current challenges and future directions

Despite the progress made in dental care, numerous challenges remain. Dental diseases such as caries and periodontitis are still widespread, particularly in underserved populations. Limited access to dental care, economic disparities, and a lack of public awareness contribute to these persistent challenges. While preventive care has made significant strides, there is still a substantial burden of oral disease, especially in regions with limited access to care [3].

Another emerging challenge is the increasing complexity and variety of materials used in dental restorations. While innovations in materials science have led to more durable and esthetically pleasing restorations, concerns about the biocompatibility of certain materials and their long-term effects on health have arisen [8]. This requires ongoing research and careful consideration of material selection in clinical practice.

Furthermore, as new technologies like 3D printing become more prevalent in restorative dentistry, questions about their long-term safety, efficacy, and integration into clinical workflows continue to emerge. While additive manufacturing holds promise for more precise and efficient treatments, it also presents challenges related to the mechanical strength, dimensional accuracy, and durability of printed restorations—factors that are critical to clinical reliability.

5. A holistic approach to dentistry

The complexities of human teeth and the challenges of modern dentistry necessitate a more integrated approach to patient care. A holistic perspective in dental practice involves not only treating oral diseases but also considering the broader implications of oral health on overall well-being [9]. This approach recognizes the interconnection between oral health, systemic health, and the social determinants that affect both.

Dentists must consider the patient as a whole, acknowledging the interplay between oral conditions and overall health. By incorporating the latest research, evidence-based practices, and patient-centered care, dental professionals can improve patient outcomes while addressing the broader societal challenges of oral health [10, 11]. This integrated approach is essential for tackling the current challenges in dentistry and preparing for the future, ensuring that dental care remains accessible, effective, and patient-focused.

This chapter introduces the multifaceted role of human teeth in health, disease, and clinical practice, emphasizing the need for an integrated approach that includes technological innovation, research, and patient-centered care. As the field of dentistry continues to evolve, the intersection of science, disease, and clinical practice will shape the future of dental care, ensuring that it meets the challenges of tomorrow while improving the quality of life for all patients.

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Chapter 2

Smile for a Lifetime: Education in Oral Health, Cavity Prevention, and Early Diagnosis from Childhood

Segundo Orlando Parra Chiza and Constanza Sánchez Dávila

Abstract

This chapter analyzes the importance of dental hygiene in preventing early childhood caries, starting with proper care during pregnancy. During pregnancy, the main oral health problems in children are addressed, highlighting the need for education and prevention strategies along with adequate hygiene and feeding techniques. In addition, the relevance of a multidisciplinary approach is highlighted, where parents and health professionals, such as pediatricians, psychologists, and speech therapists, work together to promote optimal oral health from an early age. This comprehensive approach is essential to ensuring healthy oral development and a future full of smiles. Success in maintaining pediatric oral health depends on comprehensive education and prevention strategies, including proper hygiene, which plays a crucial role in promoting general well-being, considering that health enters through the mouth.

Keywords: teeth, enamel, caries, prevention, education, oral hygiene

1. Introduction

Oral health is essential for children's well-being, and its care begins before birth. During pregnancy, the mother should be concerned about the future health of the baby, receiving guidance, and making biannual visits to the pediatric dentist for preventive and specific care (**Figure 1**). Once the child is born and the first teeth begin to appear, we ensure their well-being (**Figure 2**).

This chapter analyzes that dental hygiene habits are necessary to keep children free of caries, emphasizing education and prevention of when and how to brush the teeth to prevent the formation of bacterial plaque. White staining of teeth is a major warning sign of enamel demineralization. In addition, the application and benefits of dental sealants, an effective tool to prevent caries on occlusal surfaces, will be explored.

In pediatric dentistry, overall wellness is crucial for the proper development of children. Dental disorders can affect a child's ability to speak, eat, and interact with others, potentially leading to long-term consequences. This chapter will examine

Figure 1.
Care of a pregnant mother, carrying out her dental checkups. All images in this review are unpublished and were taken at the Pediatric Dental Center of Dr. Constanza Sánchez Dávila in collaboration with Dr. Orlando Parra. Each image is used with patient consent and the author's permission. These images illustrate key concepts and enhance the understanding of the text. Source: Photograph courtesy Dr. Constanza Sánchez Dávila.

Figure 2.
A child's clinical check-up is shown. Source: Photograph courtesy Dr. Constanza Sánchez Dávila.

various types of pediatric dental conditions, including caries, gingivitis, enamel hypoplasia, and supernumerary teeth, with a focus on preventive measures and their potential outcomes. It will also cover less common but significant phenomena, such as natal and neonatal teeth, which require special attention to prevent complications. Furthermore, strategies for preventing baby bottle tooth decay, a serious condition impacting infant dental health, will be discussed.

Finally, this chapter aims to provide essential information and tools based on our extensive professional experience in pediatric dentistry. It is supported by research focused on the collection and analysis of data from real dental cases, as well as the implementation of proven practices for children's dental care. Through this work, we have gathered and presented concrete evidence to support the maintenance of healthy, cavity-free smiles in children. Establishing good dental hygiene habits and proper nutrition from an early age not only prevents future problems but also creates a solid foundation for optimal oral health. This chapter aims to serve as a reliable and valuable guide for parents and caregivers dedicated to promoting children's dental health.

2. Pediatric dental diseases

This section of the chapter will emphasize the importance of maintaining a healthy smile throughout life, highlighting that good hygiene habits and proper nutrition are essential to prevent long-term complications. Dental caries is a prevalent worldwide disease, so its prevention is a fundamental aspect. To begin with, it is important to understand the concept of a healthy patient.

A caries-free patient has no active carious lesions on their teeth. This condition is the result of a combination of factors, including a diet low in sugars, regular use of fluoride, and routine dental visits every 6 months for checkups and cleanings (**Figure 3**). Additionally, such patients demonstrate effective preventive education and a consistent commitment to maintaining their oral health.

2.1 Dental caries

Dental caries is an infectious disease of microbial origin located in dental hard tissues. This process begins with the demineralization of enamel, resulting from the action of organic acids produced by specific bacteria that metabolize carbohydrates present in the diet, as well as factors such as insufficient saliva, genetic predisposition, and prolonged use of baby bottles (**Figure 4**). Globally, it's estimated that dental caries affects between 60 and 90% of the school and adult population; however, it is particularly prevalent in deciduous dentition, representing the most relevant disease in this group since 2015 [1]. Patients may experience sensitivity and pain due to the formation of cavities in the teeth, which can be observed clinically [1].

Figure 3.
The figure shows a caries-free patient in all his teeth of approximately 4–5 years old. Source: Photograph courtesy Dr. Constanza Sánchez Dávila.

Figure 4.
Early childhood caries age approximately 5–6 years, complete comprehensive rehabilitation treatment. Source: Photograph courtesy Dr. Constanza Sánchez Dávila.

2.1.1 Signs and symptoms

- White spots
- Sensitivity to heat, cold, or sweet foods
- Pain
- Infection
- Functional wear and tear
- Reduced quality of life [2]

2.1.2 Consequences

- Dental abscesses and infections
- Difficulty in eating and speaking
- Development of malocclusions and malposition of teeth
- Loss of anterior teeth, which affects speech development.
- Affection of the permanent dentition
- Psychosocial repercussions, including low self-esteem
- Malnutrition [3]

2.2 Early childhood caries

It is essential to understand the concept of "early childhood caries" (ECC), as defined by the American Association of Pediatric Dentistry. Early childhood caries is the presence of one or more decayed surfaces (with or without cavitary lesions),

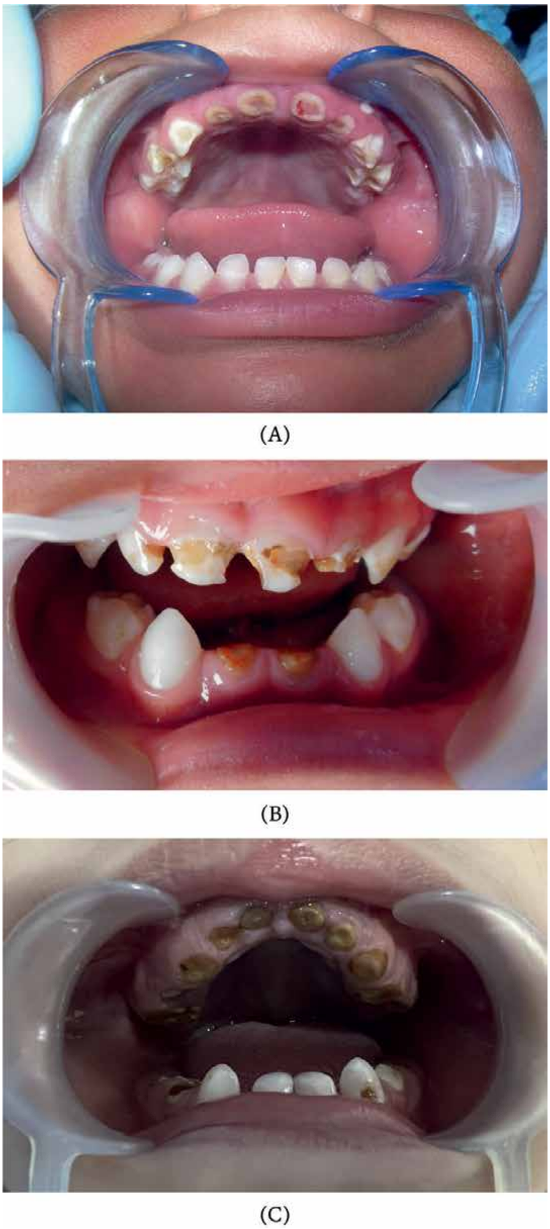

Figure 5.
A. Early childhood caries, associated with high sugar consumption, approximate age 4–5 years. B. Early childhood caries associated with poor oral hygiene, approximate age 1–2 years. C. Early childhood caries, malnutrition due to not chewing food, approximate age 4–5 years. These three patients require mandatory dental treatment. Source: Photograph courtesy Dr. Constanza Sánchez Dávila.

missing surfaces (due to caries), or filled surfaces in any deciduous tooth of a child between birth and 71 months of age (**Figure 5**) [4].

3. Gingivitis

Gingivitis is an inflammation of the gingival tissues caused by food retention. Clinically, it presents with reddened, swollen, and bleeding gums, along with halitosis. Initially, the inflamed tissues may become fibrotic over time. Normally, sharp gingival margins may become irregular, and the interdental papillae may appear enlarged and bulbous. Without treatment, true periodontal pockets can develop, potentially leading to significant gingival hyperplasia or hypertrophy (**Figure 6**). It is important to note that all these clinical signs are reversible once the underlying cause, such as plaque accumulation, is addressed. If left untreated, gingivitis can progress to periodontitis, increasing the risk of tooth loss due to loss of attachment and bone resorption [5].

3.1 Streptococcal gingivitis

Streptococcal gingivitis is an infection characterized by enlarged papillae, gingival abscesses, and painful, erythematous gums that bleed easily. Microbiological cultures usually show a predominance of hemolytic streptococci. While often considered an acute condition, there is limited recognition of chronic forms due to the complexity of diagnosis without extensive laboratory testing. This type of infection may be more prevalent than previously thought [6].

Broad-spectrum antibiotics are recommended when the infection is suspected to be bacterial. In addition, improving oral hygiene is crucial to the treatment of the infection. For any acute microbial infection in the oral cavity, the use of 0.2% chlorhexidine mouth rinses is appropriate [6].

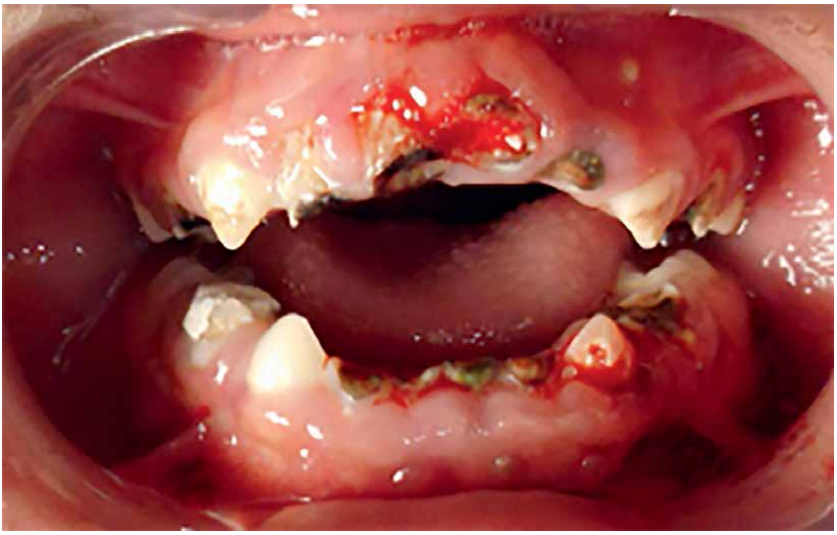

Figure 6.
Gingivitis, child approximately 5–6 years old, complete comprehensive rehabilitation.

3.2 Gingival disease associated with asthma in pediatric patients

Gingival disease associated with pediatric asthmatic patients may influence the development of gingivitis primarily through changes in immune response and breathing patterns. This leads to a systemic inflammatory response that can be exacerbated during asthmatic attacks, affecting gingival health. During these episodes, mouth breathing and oral mucosal dehydration can create an environment prone to bacterial growth and gingival inflammation [5].

In addition, asthmatic patients have been observed to have elevated levels of certain enzymes and inflammatory markers, such as myeloperoxidase, as well as a higher concentration of IgE in the gingival tissues. These factors contribute to periodontal tissue destruction by increasing the local inflammatory response and compromising the body's ability to fight bacterial infections in the mouth. Therefore, it is crucial in the dental care of asthmatic patients to emphasize the importance of good oral hygiene and to perform regular dental cleanings to prevent problems such as gingivitis and cavities [5].

3.3 Acute ulcerative necrotizing gingivitis (AUNG)

Necrotizing ulcerative gingivitis is a painful acute infection caused by bacteria such as *Treponema*, *Prevotella intermediate*, and *Fusobacterium*. It occurs occasionally in children between 6 and 12 years of age and is more common in young adults. Clinical manifestations of this disease include necrosis of the interproximal papillae, bleeding gums, bad odor, a temperature of 40°C, and poor appetite (**Figure 7**) [6].

The disease responds dramatically within 24–48 hours to subgingival curettage, debridement, and the use of mild oxidizing solutions. If the gingival tissues are acutely

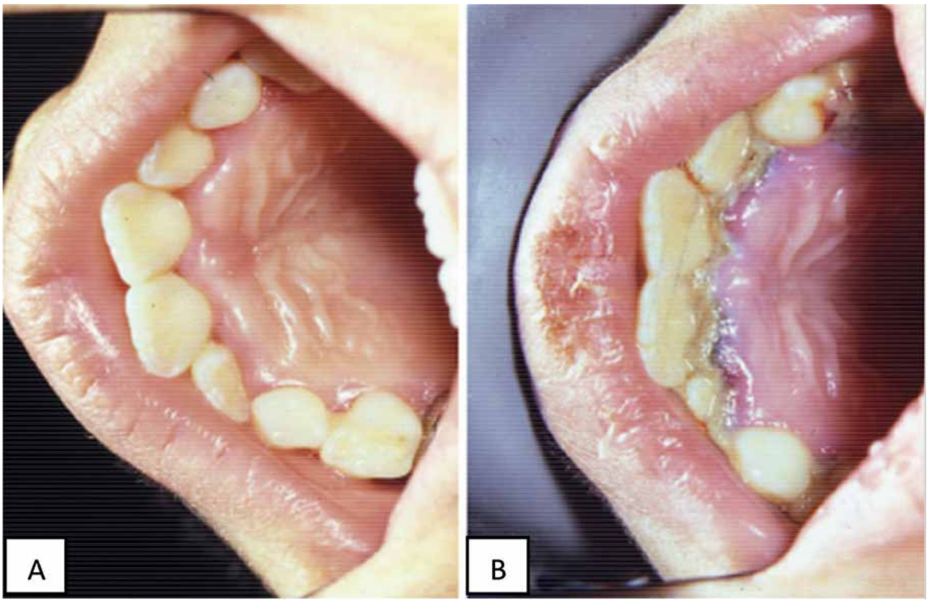

Figure 7.
A. A rare example of necrotizing ulcerative gingivitis in an 8-year-old boy. B. Local treatment and improved oral hygiene produced a dramatic recovery from the infection. All images in this review were published in the journal ScienceDirect, in the book "Dentistry for Children and Adolescents" by McDonald and Avery, and are the authorship of Vanchit John, James A. Weddell, Daniel E. Shin, and James E. Jones. Each image is used with the explicit consent of the authors. These images illustrate key concepts and enhance the understanding of the text.

and extensively inflamed when the patient is first seen, antibiotic therapy is indicated [6]. Three percent (3%) hydrogen peroxide has been used as a mouthwash for debridement of necrotic areas. Its effect is thought to be due to the release of oxygen and the effect on anaerobic bacteria. Mouthwash with chlorhexidine (0.12%) twice daily may be helpful when mechanical brushing is not possible but should only be considered as an adjunct to mechanical debridement and good personal plaque control [7].

Metronidazole is the antibiotic of choice, as it is more effective than oxidative antiseptics (e.g., hydrogen peroxide) and has no local side effects. It is as effective as penicillin, has a shorter course of action, produces no known hypersensitivity or allergic reactions, has had fewer problems with the development of resistant species, and has a narrower spectrum, so has less effect on commensal bacteria compared to penicillin [7].

3.4 Hereditary gingival disorders

3.4.1 Acute herpetic gingivostomatitis

Caused by the herpes simplex virus type 1, a characteristic oral finding in acute primary disease is the presence of yellow or white fluid-filled vesicles. Within a few days, the vesicles rupture and form painful ulcers, 1–3 mm in diameter, that are covered by a whitish-gray membrane and have a circumscribed area of inflammation. Ulcers may be seen on any area of the mucous membrane, including the buccal mucosa, tongue, lips, hard and soft palate, and tonsillar areas (**Figure 8**). Patients may present with malaise, irritability, headache, and pain provoked by the ingestion of acidic foods or liquids [6].

Treatment of herpetic gingivostomatitis lasts 10–14 days and should include specific antiviral medication and measures to relieve acute symptoms so that fluid and nutrient intake can be maintained. Application of a mild topical anesthetic, such as dyclone hydrochloride (0.5%), before mealtime temporarily relieves pain. Antiviral

Figure 8.
Ulcerated stage of primary herpes in a young adult. Notice the circumscribed confluent areas of inflammation. All images in this review were published in the journal ScienceDirect, in the book "Dentistry for Children and Adolescents" by McDonald and Avery, and are the authorship of Vanchit John, James A. Weddell, Daniel E. Shin, and James E. Jones. Each image is used with the explicit consent of the authors. These images illustrate key concepts and enhance the understanding of the text.

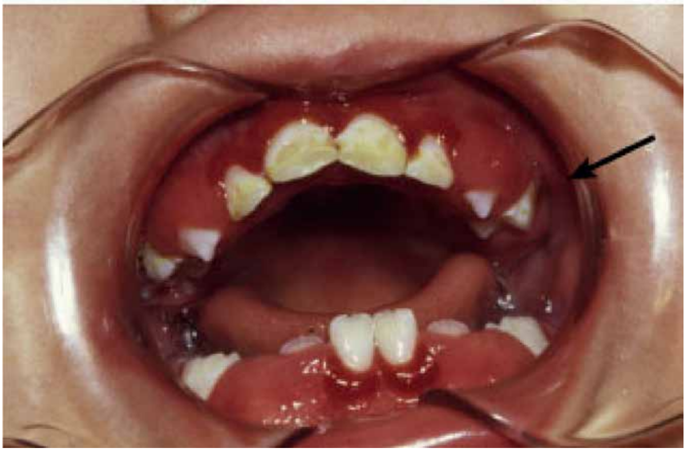

Figure 9.
Mild inflammation (arrow) is evident in the tissue partially covering the crown of the erupting first permanent molar. All images in this review were published in the journal ScienceDirect, in the book "Dentistry for Children and Adolescents" by McDonald and Avery, and are the authorship of Vanchit John, James A. Weddell, Daniel E. Shin, and James E. Jones. Each image is used with the explicit consent of the authors. These images illustrate key concepts and enhance the understanding of the text.

drugs currently available include acyclovir, famciclovir, and valacyclovir. These drugs inhibit viral replication in cells infected with the virus [6].

3.4.2 Hereditary gingival fibromatosis (HGF)

Clinically, the condition is normal in color, firm in consistency, and without signs of bleeding. Clinical examination reveals that it is usually asymptomatic. This is a benign disease characterized by excessive growth of the gums that may partially or completely cover the teeth. Treatment of HGF usually requires surgical treatment to remove the excess tissue [8].

3.4.3 Eruptive gingivitis

Eruptive gingivitis is a gingival inflammation that occurs during the eruption of primary and permanent teeth. The main signs include redness and swelling of the gums around the emerging tooth. Common symptoms are pain, sensitivity, and sometimes bleeding during brushing (**Figure 9**). Management typically involves maintaining optimal oral hygiene with the supplementary use of antibacterial mouthwashes to help reduce inflammation [6].

4. Gingivitis associated with systemic diseases

4.1 Pubertal gingivitis

During puberty, hormonal changes can make the gums more susceptible to inflammation, even in the presence of minimal plaque. This condition is characterized by bleeding gums, redness, and swelling. Prevention and treatment include maintaining proper oral hygiene, routine professional cleanings, and, in some cases, the use of antimicrobial mouthwashes that can reduce inflammation [6].

4.2 Diabetes

Children with diabetes are at increased risk of developing periodontal disease because of their compromised immune response to infections. This increased susceptibility is often the result of the body's reduced ability to handle and respond to bacterial infections in the gums [6].

4.3 Leukemia

In children, leukemia can manifest as severe gingivitis, characterized by painful, bleeding, and markedly swollen gums, which may be one of the initial signs of the disease. This condition can also lead to gingivitis and periodontitis due to a compromised immune response and the increased proliferation of abnormal white blood cells. These factors impair and hinder the body's ability to fight infections and maintain healthy gingival tissue, like the effects seen in children with diabetes (**Figure 6**) [6].

5. Enamel defects

5.1 Enamel hypoplasia

Enamel hypoplasia refers to the inadequate and incomplete formation of the organic structure of enamel. This condition can be due to systemic, local, and hereditary factors; therefore, it can affect both temporary teeth (baby teeth) and permanent teeth [9].

5.1.1 Clinical manifestations

- It often manifests as pits, grooves, pits, lines, or smooth, flat areas on the tooth surface.

- In affected teeth, the enamel is thinner than normal or absent in some areas. This results in irregular and rough surfaces and often an uneven appearance of the teeth.

- Teeth affected by enamel hypoplasia may have white, yellowish, or brownish spots due to exposure of the underlying dentin or pigment buildup (**Figure 10**).

- Enamel hypoplasia increases the risk of caries and can lead to esthetic problems, potentially affecting self-esteem [9].

5.1.2 Preventive measures

- *Prenatal care*: Maternal health is closely linked to the baby's health, so maintaining good oral health before, during, and after pregnancy is essential to prevent future risks. Expectant mothers should have regular checkups to ensure optimal oral health, gain important knowledge for the baby's birth, and ensure timely, multidisciplinary care from specialists [10].

Figure 10.
Enamel hypoplasia, 1-year-old patient, showing reduced enamel, rough, irregular surfaces, and yellowish or brown spots. Defects are usually localized and may be present in any tooth. Source: Photograph courtesy Dr. Constanza Sánchez Dávila.

5.1.3 Preventive measures can include

- *Regular checkups:* Schedule dental checkups every 6 months for both children and adults to maintain optimal oral health [10].

- *Diet:* Establish healthy eating habits and make sure to eat a diet rich in vitamins and minerals. Tooth decay is mainly caused by high sugar intake and poor oral hygiene. It is important to remember: "If a baby doesn't taste sugar, he doesn't know it exists." Introducing low-sugar options early on helps develop a palate that favors healthier options [10].

- *Fluoride application:* Periodic fluoride applications, conducted under the supervision of a pediatric dentist or dentist, are crucial for dental prevention. Various types of fluoride treatments should be administered exclusively by these specialists. The frequency and type of application depend on the patient's age, as well as their dietary habits and oral hygiene practices. Fluoride concentrations vary according to age, the formulation of toothpaste, and professional guidelines [11].

- All patients need to begin fluoride use with the emergence of their first teeth. For this reason, baby clinics are conducted from pregnancy onward, allowing mothers to implement early preventive measures that help prevent the onset of dental diseases [11]. Baby clinics, conducted from pregnancy onward, play a key role in implementing early preventive measures to help prevent the onset of dental diseases [11].

Figure 11.
A. Presence of MIH in tooth 36. B. The presence of MIH is observed in tooth 21, while tooth 11 does not present this defect. Source: Photograph courtesy Dr. Constanza Sánchez Dávila.

- *Dental sealants:* Modern dental sealants use advanced materials that can release Fl when applied. These sealants protect vulnerable areas of the teeth and help prevent cavities by forming a protective barrier on the chewing surfaces [9].

5.2 Hypomineralization of incisors and molars (MIH)

Molar Incisor Hypomineralization (MIH) is a clinically relevant condition with an etiology that remains unknown. However, it has been suggested that it may be associated with the indiscriminate use of antibiotics, excessive fluoride, and episodes of high fever during the first 2 years of life, a critical period for the formation of the germs of permanent teeth. These factors have been potentially linked to enamel defects. Further studies and research are needed to precisely determine the cause. As its name indicates, it affects permanent incisors and molars, but it can affect only one, two, or all of the incisors and molars, as we mentioned (**Figure 11**) [12].

5.2.1 Clinical manifestations

- Stains on teeth affected by MIH are creamy white, yellow, or brown and vary in extent and severity; they are commonly seen on permanent first molars and incisors.

- The enamel surface is porous and fragile, susceptible to wear and fracture.

- Increased tooth sensitivity to different stimuli.

- Increased risk of caries due to plaque retention in compromised enamel [12].

6. Sealants and fluoride application

Pit and fissure sealants are essential for protecting the chewing surfaces of molars, which have grooves and depressions that are difficult to clean with regular brushing. These areas tend to trap food particles and bacteria, which can lead to dental

Figure 12.
Sealant on the occlusal surface of the first permanent molar 36. Source: Photograph courtesy Dr. Constanza Sánchez Dávila.

problems. Applying sealants creates a protective layer over these hard-to-reach areas, preventing the buildup of food and bacteria. This effective barrier provides significant protection for both permanent and primary teeth (**Figure 12**) [13].

Several clinical studies have shown that fissure sealants are effective in controlling caries development compared to other interventions such as fluoride varnishes or fluoride rinses. However, there is also research suggesting that more high-quality evidence is still needed to confirm their definitive efficacy compared to other preventive methods. Therefore, it is important to evaluate and compare the results of different studies to obtain more accurate conclusions about their effectiveness [14].

The benefit of sealants increases when they are indicated for patients at risk of caries and healthy occlusal surfaces with macromorphology that promotes greater accumulation or difficulty in removing bacterial plaque. This benefit also increases for patients who already have incipient caries lesions, that is, those who already have caries activity. The placement of sealants on minimal enamel lesions inhibits the progression of the disease [14].

The importance of fissure sealants lies in their ability to provide additional protection to the teeth, especially in those areas most prone to caries, thus contributing to maintaining better long-term dental health [15].

7. Fluoride topical

Fluoride has been one of the most important agents in therapeutic and preventive dental care. Its primary mechanism of action is topical, as it integrates into the dental enamel, forming fluorapatite crystals. This process increases the enamel's resistance to acid attacks. Fluoride also promotes the remineralization of early carious lesions and inhibits the demineralization of dental hard tissues, making it a fundamental component in cavity prevention [16].

8. Malocclusion problems

Malocclusion refers to the improper positioning of the teeth, both upper and lower, which causes difficulties in speaking, chewing, and aesthetics. This type of malocclusion can be triggered by hereditary factors or harmful habits such as thumb sucking, premature loss of primary teeth, or excessive use of pacifiers and bottles. There are different types of malocclusions [17].

9. Vertical plane malocclusions

9.1 Overbite

This occurs when the upper teeth significantly overlap the mandibular teeth. In this situation, an increased overbite is present, with the maxillary teeth extending further than the lower teeth. This condition is associated with alignment issues, difficulties in speech development, and dental wear [18].

9.2 Open bite

This facial alteration is characterized by the absence of contact between anterior and posterior teeth. This prevents the patient from correctly performing the functions of mastication and pronunciation, resulting in decreased overbite and overjet (**Figure 13**) [19].

Figure 13.
Patient of approximately 7–8 years of age with harmful habits of sucking his thumb and using a pacifier, causing an open bite and deformation of the jaw. Source: Photograph courtesy Dr. Constanza Sánchez Dávila.

10. Transverse plane malocclusions

These are alterations in the malocclusion of the palatal cusps of the molars and premolars in both the upper jaw and the fossae of the lower molars and premolars [17].

10.1 Crossbite

This condition occurs when the upper jaw is significantly smaller and positioned inside the lower arch, resulting in a narrow jaw. A crossbite can lead to several consequences, including abnormal tooth wear, temporomandibular joint (TMJ) issues, and facial asymmetry [20].

10.2 Scissor bite

The scissor bite is a type of dental misalignment where the upper and lower teeth do not align correctly when the mouth is closed. Specifically, in a scissor bite, the cusps of the upper molars and premolars overlap the cusps of the lower molars and premolars in a way that creates a cutting effect, similar to a pair of scissors. This misalignment can cause difficulties with biting and chewing, as well as problems with the temporomandibular joint (TMJ) [21].

11. Deciduous persistence

Tooth eruption is the process by which a tooth moves from its formation in the jaw to its functional position in the mouth. This continuous process involves the replacement of deciduous teeth with permanent teeth. The eruption patterns of both primary and permanent teeth vary with age and may be influenced by some factors like genetics, gender, environment, and individual characteristics (**Figure 14**) [22].

Deciduous persistence refers to the condition in which a deciduous tooth does not fall out within the expected period and remains in the mouth longer than it should. A persistent deciduous tooth remains in place long after the permanent tooth should

Figure 14.
Deciduous persistence of temporary lower central incisors, teeth 71 and 81. Source: Photograph courtesy Dr. Constanza Sánchez Dávila.

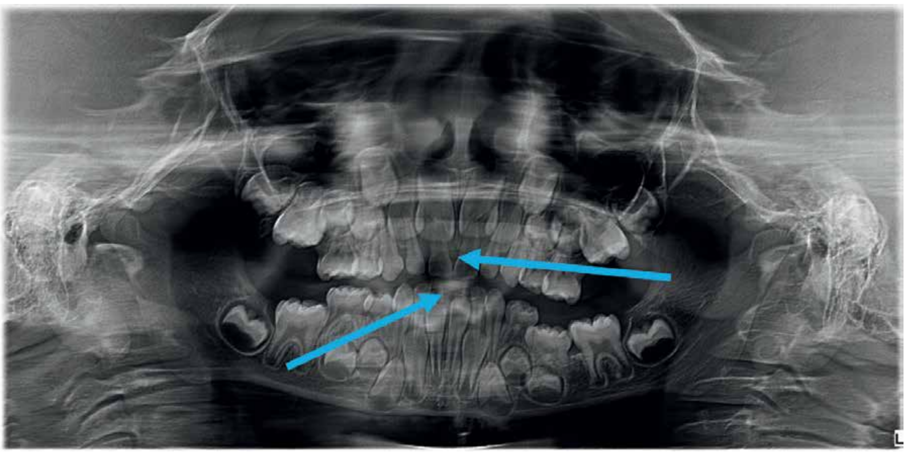

Figure 15.
A chronological delay can be observed in temporary teeth 51-61-71-81; age approximately 5–6 years. Source: Photograph courtesy Dr. Constanza Sánchez Dávila.

have emerged, usually more than a year after the expected time. This can occur due to several reasons, such as the congenital absence of the permanent tooth, obstruction of the permanent tooth, or the presence of anomalies such as cysts or tumors, as well as the existence of physical barriers and liquefied diets (**Figure 15**) [22].

12. Other conditions associated with missing teeth

12.1 Dental agenesis

Dental agenesis is the congenital absence of one or more teeth. It is one of the most prevalent dental anomalies and can affect both primary and permanent teeth. Agenesis of the third molars (wisdom teeth) is the most common, followed by the absence of the upper lateral incisors and lower second premolars. The causes are usually genetic and are often associated with various genetic syndromes and conditions [23].

12.2 Anodontia

Anodontia is an extremely rare condition in which all teeth are absent. It is usually part of a broader genetic syndrome such as ectodermal dysplasia. Individuals with anodontia require dentures from an early age to maintain proper chewing and phonetic function [24].

12.3 Hypodontia

Hypodontia refers to the absence of one to six teeth, excluding the third molars. It is a relatively common issue that can have a hereditary component, such as in Down syndrome. Missing teeth can lead to esthetic and functional problems and typically require orthodontic or prosthetic treatment for correction. Addressing hypodontia usually involves a multidisciplinary approach to ensure optimal oral health and prevent long-term complications [23].

12.4 Supernumerary teeth

Supernumerary teeth are extra teeth that develop in addition to the normal dentition. In primary dentition, their prevalence ranges from 0.1 to 0.8%, while in permanent dentition, it ranges from 0.1 to 3.8%. These additional teeth often appear in the anterior region of the upper jaw and can disrupt the normal eruption path of the permanent teeth (**Figure 16**). Supernumerary teeth are generally hereditary and can be associated with syndromes such as cleidocranial dysostosis and Gardner's syndrome. They are more common in males than females, with a male-to-female ratio of approximately 2:1. [25].

The management of these teeth depends on their position and the possible complications observed both clinically and radiographically. No consensus has been established on the optimal time for extraction of supernumerary teeth; however, immediate extraction is recommended if there is inhibition or retraction of eruption, displacement of adjacent teeth, interference by appliance, or crowding (**Figure 17**) [25].

Figure 16.
Patient of approximately 8 years of age who has supernumerary canines in both upper arches, teeth 53 and 63. Source: Photograph courtesy Dr. Constanza Sánchez Dávila.

Figure 17.
A patient of approximately 4–5 years old presents supernumerary between permanent central incisors teeth 11 and 21. Source: Photograph courtesy Dr. Constanza Sánchez Dávila.

13. Education, prevention, and control habits

The fundamental approach to prevention has become increasingly apparent, as caries rates worldwide have remained high and have not shown significant decreases. This underscores the ongoing need for effective educational strategies and preventive measures.

Educational and preventive clinical behaviors to avoid early childhood caries:

13.1 Oral hygiene and dietary habits

This chapter has explored strategies to help patients maintain caries-free teeth. Proper oral hygiene from an early age is essential for preventing early childhood caries. Additionally, the oral health habits established by the mother will significantly impact the baby's health from birth. Therefore, starting from the seventh month of pregnancy, mothers should receive guidance on their child's health care, focusing on breastfeeding, the use of nipples, oral hygiene, and fluoride application. Effective caries prevention includes maintaining good oral hygiene practices, providing education, offering dietary advice, and avoiding prolonged exposure to dairy, sweets, and sugary drinks [26].

The pediatric dentist must discuss with the parents about children's oral health from an early age. It is essential to introduce oral hygiene habits before the first teeth appear. Parents can do this by gently massaging the gingivae and cleaning the mouth to encourage healthy oral microbiota. Manual removal of food debris, which often accumulates in the corners of the mouth and other areas of the mouth, can be done using a special finger toothbrush, soft brushes, or clean cloths wrapped around the index finger. This practice is ideally at night, after the last feeding, and only once a day since the immunoglobulins in breast milk protect the oral mucosa from infections [27].

It's beneficial to establish an oral hygiene routine that the child can associate with other hygiene habits, such as bath time or bedtime. As the first baby teeth erupt, a toothbrush can be introduced, which will help to create a healthy oral hygiene pattern from the beginning and encourage effective plaque removal [27].

13.2 Prevention

13.2.1 Modified bass brushing technique

The modified bass technique, also known as the horizontal brushing technique, is highly recommended for effective cleaning of the gums and teeth. This technique involves placing the toothbrush at a 45-degree angle to the gum line and making gentle back-and-forth strokes. Brushing teeth three times a day, especially after meals, helps remove plaque and prevent the formation of cavities and periodontal disease [28].

13.2.2 Use of fluoride toothpaste

Fluoride remains one of the most effective tools for caries prevention in dentistry, and adequate fluoride exposure is critical to initiating early preventive interventions. A recent study shows that the use of fluoride toothpaste and the application of fluoride varnish at dental visits are effective methods for preventing the onset of caries in young children [26].

The best practice for preventing caries from early childhood is to begin using fluoride toothpaste daily as soon as a child's first tooth appears. However, there is concern about the possibility of fluorosis if young children ingest too much fluoride. For this reason, the American Academy of Pediatric Dentistry (AAPD) recommends using an amount of fluoride toothpaste no larger than a grain of rice for children 3 years of age or younger, helping to protect against cavities [26].

13.2.3 Reducing sugar consumption

Reduced consumption of sugary foods and beverages is crucial for preventing tooth decay. Sugar serves as a primary food source for cariogenic bacteria, which produce acids as they metabolize sugar. These acids then lead to the demineralization of tooth enamel. Encouraging a balanced diet that includes plenty of fruits, vegetables, and dairy products can support both oral and overall health in children [29].

13.2.4 Pediatric dentist visits

Regular visits to the pediatric dentist, recommended every 6 months, are crucial for maintaining children's oral health. During these visits, the pediatric dentist performs oral cleanings, applies fluoride treatments, places sealants, and assesses the growth and development of the teeth and jaws. Early detection of dental issues allows for prompt intervention and prevents more serious complications. According to the literature, semiannual checkups are recommended to ensure optimal oral health in children [30].

13.2.5 Feeding during the first year of life

Breastfeeding is crucial for the healthy growth and development of infants. Research has demonstrated that breast milk not only reduces mortality rates but also lowers the risk of leukemia and otitis media. Therefore, it is recommended to breastfeed on demand until the baby is 6 months old. Breast milk, being free of sugars and additives, does not contribute to tooth decay.

It is important to start dental hygiene practices as early as 4 months, even before teeth have erupted. This practice helps stimulate the gums and can alleviate discomfort associated with the dental eruption. The American Academy of Pediatrics (AAP) recommends exclusive breastfeeding until 6 months of age to ensure optimal health and development.

13.2.6 Breastfeeding and bottle-feeding

Breastfeeding is essential for promoting health and preventing various diseases. It plays a critical role in the proper development of the maxillofacial structures, as it encourages optimal lip sealing, jaw function, and the correct positioning of the tongue against the palate. This natural feeding process requires the infant to actively extract milk from the breast through the coordinated efforts of the tongue and facial muscles, which supports proper oral development [31].

In contrast, bottle-feeding, although suitable until the age of 1 year, involves less effort from the infant to suckle milk. This reduced effort does not adequately stimulate the functional development of the oral structures and may contribute to the development of malocclusions such as posterior crossbite, anterior open bite, increased protrusion, and class II molar and canine relationships [31].

Additionally, baby bottles are often made from less flexible materials, which can put pressure on the oral cavity, potentially leading to misaligned teeth and a narrow palate. Children who use pacifiers are also more likely to develop these dental malocclusions, which can further affect oral health and development [31].

13.2.7 Pacifier use

Non-nutritive sucking habits are repetitive behaviors that can cause defects in tooth structure. Although they do not have a nutritional function, their impact depends on the nature, onset, and duration of the habits. They are abnormal disorders in newborns, and their persistence can lead to long-term problems in the stomatognathic system like jaw deformation and sudden death [32].

Common malocclusions associated with these habits include open bite, deep bite, and crossbite, with prevalence ranging from 20–93%, depending on age. The interaction of genetic and environmental factors influences the occurrence of these malocclusions. Therefore, interdisciplinary collaboration between speech therapists, pediatricians, otolaryngologists, and orthodontists is crucial for the success of the treatment and its long-term stability [32].

A 2016 systematic review highlighted the risks of non-nutritive sucking in the development of malocclusions and stressed the importance of educating parents about these habits in children. It is vital to understand the etiology of malocclusions to properly treat patients and advise parents on how to prevent them [32].

14. Natal and neonatal teeth

Natal teeth are those with which the child is born, while neonatal teeth appear in the first 30 days of life. These can cause various problems, such as breastfeeding difficulties due to pain during sucking, ulcerated nipples, and nutritional deficiencies that can lead to growth retardation. Additionally, friction of the tongue with the teeth can cause an injury called Riga-Fede, and aspiration of the tooth by the newborn can occur, which can lead to lung damage or asphyxia (**Figure 18**) [33].

Early detection is essential, as it allows for appropriate care and helps preserve the health and well-being of both mother and child. If excessive mobility of the tooth is

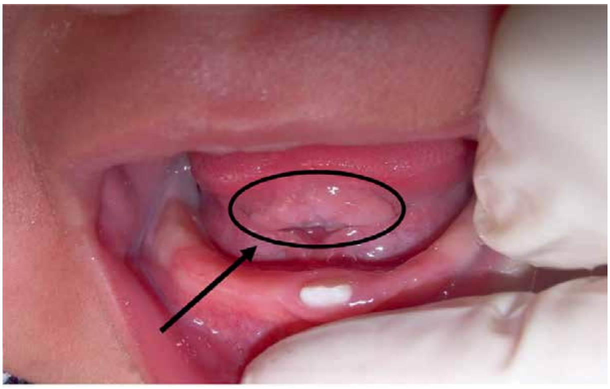

Figure 18.
Riga-Fede ulcer in a newborn. Source: Photograph courtesy Dr. Constanza Sánchez Dávila.

Figure 19.
A. Natal teeth are those teeth with which the child is born. B. Neonatal teeth are observed in the first 30 days after birth. Source: Photograph courtesy Dr. Constanza Sánchez Dávila.

observed, pediatric dentists should inform the parents and consider extraction. The surgery should be scheduled with caution, especially since the patient is a newborn and minimizing radiation exposure is crucial. It is advisable to wait at least 10 days before performing the extraction to ensure that the baby has adequate levels of vitamin K in the blood, which helps prevent hemorrhagic complications (**Figure 19**) [33].

15. Tongue and lip frenulum

It is crucial to identify lingual and labial frenulum issues at birth to facilitate successful breastfeeding and, later, to ensure proper feeding and speech development. Early detection can prevent the need for complex surgical procedures requiring anesthesia and sutures, often limited to a simple frenotomy that heals naturally with breastfeeding. These congenital conditions are characterized by unusually short, thick, or tight oral frenula, which restricted natural movement in the oral cavity (**Figure 20**). In recent years, they have become more recognized due to their impact on breastfeeding, phonetics, abnormal swallowing habits, and associated emotional stress [34].

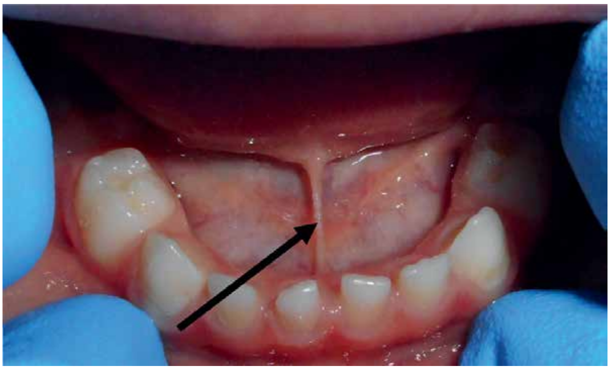

Figure 20.
Age approximately 1.5 years, with the presence of lingual frenulum. Source: Photograph courtesy Dr. Constanza Sánchez Dávila.

16. Conclusion

Ensuring optimal health from infancy requires a proactive approach that includes education, prevention, and management of pediatric dental diseases. This chapter highlights the significance of instilling proper dental hygiene and dietary habits early on, with a particular emphasis on providing comprehensive guidance to mothers throughout pregnancy. We have reviewed common dental conditions affecting children, such as early childhood caries, gingivitis, enamel defects, malocclusions, and the presence of extra teeth. Additionally, the importance of identifying and addressing issues like natal and neonatal teeth and lingual frenulum to prevent long-term complications has been discussed.

Achieving comprehensive oral health involves a collaborative, multidisciplinary approach with all healthcare professionals. By working together, we lay the foundation for excellent oral health and foster a world of bright smiles. Just as medicine integrates with overall patient care, dentistry must be seamlessly included, recognizing that health truly begins with oral well-being.

Implementing healthy eating and hygiene practices from an early age is crucial not only for preventing dental issues but also for supporting the overall development of the jaws and the entire system. By following the recommendations and preventive measures outlined in this chapter, we can ensure that children enjoy a superior quality of life and maintain a healthy smile. Ultimately, the cornerstone of keeping our patient's cavity-free and supporting a long, healthy life lies in proper education and a steadfast commitment to oral health.

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I extend my gratitude to the parents and patients who have trusted the Pediatric Dental Centre and whose experiences have significantly influenced the recommendations offered here. Their commitment to their children's oral health has been a continuous source of inspiration.

Additionally, I appreciate the reviewers and editors whose valuable feedback and suggestions have greatly improved this chapter. Their expertise has been vital in refining the accuracy and relevance of the content.

Notes

Importance of continuing education: Pediatric dentistry is a constantly evolving field. Practitioners are encouraged to stay current with the latest research and advances to provide the best possible care for their patients.

Interdisciplinary collaboration: Children's oral health benefits greatly from a collaborative approach that includes pediatricians, psychologists, speech therapists, and other health care professionals.

Statements

This chapter has been prepared with the purpose of providing evidence-based information and practical recommendations for the prevention and management of dental disease in the pediatric population. All data and studies cited have been obtained from reliable sources, and every effort has been made to ensure the accuracy and currency of the information.

Any errors or omissions are the sole responsibility of the author. This work would not have been possible without the dedication and continued effort in the field of pediatric dentistry, and I hope that it will contribute to improving the oral health and quality of life of children worldwide.

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Chapter 3

Global Trends and Projection of Caries of Permanent Teeth Incidence from 1990 to 2030: A Modeling Study

Fatemeh Shabazi

Abstract

The aims of this research were to examine the temporal trends in Caries of permanent teeth incidence at the global level from 1990 to 2021 and to forecast caries experience to 2030. Data on permanent tooth decay (PTD) were extracted from the Global Burden of Disease (GBD) 2019 study. Generalized additive model was used to predict permanent tooth caries incidence until 2030. Additionally, the average annual percentage change (AAPC) index that computed in Joinpoint Regression Software was used to evaluate the temporal trends of PTD age-adjusted incidence rates during 1990–2021 and 2022–2030. Worldwide, the PTD age-adjusted incidence rate increased from 28,154 per 100,000 populations in 1990 to 29,896 per 100,000 in 2021. The PTD age-standardized incidence rate is predicted to increase slightly to 30,414 per 100,000 (95% credible interval (CrI): 126177 to 34,651). We predicted that the incidence of PTD in women and men will increase to 30,488 and 30,288 cases per 100,000 populations in 2030, respectively. The PTD incidence rate is predicted to increase in the next decade. Due to the extent of this problem in all subgroups of age, gender and countries, public health policies to prevent this health consequence should be expanded in all subgroups and societies.

Keywords: dental caries, forecasting, trend, incidence, temporal trends, global

1. Introduction

Tooth decay is a chronic infectious condition characterized by the presence of cariogenic bacteria in the mouth, particularly *Streptococcus mutants*, which leads to the formation of cavities in the teeth [1, 2]. This condition is a major public health problem at the global level and is the most common non-communicable disease [3–5]. According to the Global Burden of Diseases (GBD) study in 2019, the prevalence of permanent teeth decay worldwide affected 2.0 billion people, making it the most common disease in global super regions [6–8]. The age standardized prevalence of untreated caries in the world decreased by approximately 3.6% between 1990 and 2019 [9]. Worldwide, 64.6 million cases of caries in permanent teeth are attributed to socio-demographic inequality between countries [7].

Several studies have shown that factors such as physical disabilities, low socioeconomic status, dementia, and difficulties in performing oral hygiene activities such as brushing, increase the risk of tooth decay. Recurrent caries, often occurring at the sites of existing restorations, further contribute to the problem [10–15]. On the other hand, regular and daily use of dental floss, fluoride toothpaste, professional dental care, fluoride mouth rinses, and varnish, especially for high-risk individuals, reduces the risk of tooth decay [16].

Although numerous studies have examined the prevalence of permanent tooth decay (PTD), along with its risk and protective factors at both global and regional levels, there is currently no research predicting the future incidence rates of this condition [16]. Consequently, forecasting the future quantity of this issue can better equip health system planners and policymakers to address its complications. It also provides a general framework for determining the necessary resources and the level of intervention required to control this disease effectively. In other words, predictive models help assess the future impact of health consequences, enabling more effective preparation. Furthermore, predicting future incidence rates by geographic area lays the groundwork for reducing inequalities, and highlights which regions are likely to experience higher incidences of PTD in the future and will therefore require greater attention from health policymakers [17–19].

To achieve these objectives, we used a generalized additive model (GAM) on PTD incidence at both global and nation levels from 1990 to 2021 to forecast incidence rates through 2030. These predictions are crucial for reallocating limited medical resources and updating prevention strategies for PTD.

2. Material and methods

2.1 Data source

PTD data: In this cross-sectional and ecological study, the researchers extracted the data related to the age-adjusted incidence rates from PTD between 1990 and 2021 by sex, age, country, World Health Organization regions, and grouping countries based on the sociodemographic index (SDI) from the Global Burden of Disease result tools that are openly available from: https://vizhub.healthdata.org/gbd-results/. The SDI is a composite indicator that encompasses per capita income, educational attainment, and fertility rates. The value of this index ranges from zero to one. An SDI closer to zero indicates a less favorable social and economic situation, while a value closer to one signifies a more favorable condition. The Global Burden of Disease categorizes 204 countries worldwide into five groups based on their SDI levels, including low SDI, low-middle SDI, middle SDI, high-middle SDI, and high SDI.

2.2 Statistical analysis

GAM was used to predict the PTD age-adjusted incidence rates until 2030. The GAM is written as follows:

$$\ln(numbers) = s\left[\ln(pnum)\right] + s(c) + s(year) + s(e) + r \tag{1}$$

Where numbers referring to the count of PTD cases, pnum is the population; c denotes the median age in each age group; year represents the calendar year; and e is the calendar year minus mid value of age group; r is the intercept; and the s is a smoothing spline function. The smoothness of each function is determined by the smoothing regularization parameter known λ . In our study λ was varies from 0.10 to 0.90. We obtained the predicted values until 2030 and the corresponding 95% credible interval (CrI) using the bootstrap method. It should be noted that selecting 2030 as the endpoint for the forecasts is connected to the Sustainable Development Goals (SDGs). These goals were adopted in September 2015 by heads of state, high-level representatives from United Nations (UN) specialized agencies, and civil society and were endorsed by the UN General Assembly, aiming for achievement by 2030. The primary objective of this document is to tackle poverty in all its forms around the globe; as a result, most public health and medical studies have designated 2030 as the endpoint for their projections. All statistical analyses were run using R version 4.1.2. It should be mentioned that the GAM was implemented using “gam” package in R software.

2.3 Quantifying the PTD incidence trends

After predicting the age-adjusted incidence rates of PTD until 2030 using GAMs, the temporal trends of incidence rates were described by calculating the average annual percent changes (AAPC). This quantitative measure evaluates the average annual variation in incidence rates over specific periods, which in our study include 1990–2021 and 2022–2030. The negative value of AAPC indicates a decreasing trend, while positive values of this measure indicate an increasing trend in the incidence rate during the study period. To calculate the Average Annual Percent Change, we analyzed the natural logarithm of time variables in relation to their corresponding PTD incidence rates. Essentially, we established a connection between the natural logarithm (ln) of age-adjusted incidence rates and time through the following equation: $y = b_0 + \beta x + \varepsilon$. In this equation, (y) represents the natural logarithm of age-adjusted incidence rates, (x) stands for the calendar year, b_0 is the intercept, (ε) is the error term, and (β) indicates the trend’s direction (positive or negative) in the chosen age-adjusted mortality rate. We then computed the AAPC using the ((exponential [β]-1) *100) formula.

3. Results

3.1 Permanent tooth decay age-adjusted incidence rates, 1990–2021

Globally, the PTD incidence rates increased from 28,154 per 100,000 in 1990 to 29,896 per 100,000 in 2021 (AAPC = 0.06, 95% confidence interval (CI): 0.05–0.07). This means that on average we are seeing a 0.06% annual increase in the age-adjusted incidence rate from PTD (**Table 1** and **Figure 2**). Both genders experienced an increasing trend in the age-adjusted incidence rate. During the study period, the PTD age-adjusted incidence rate in men and women increased from 27,893 to 29,771 per

	ASR (×100,000)		AAPC ‡ (95% CI) of ASR
	1990 (95% CI)	**2021 (95% CI)**	**1990–2021**
Sex			
Both	28,154 (27,998 to 28,309)	29,896 (29,741–30,052)	0.06 (0.05–0.07)
Male	27,893 (27,762–28,023)	29,771 (29,641–29,901)	0.07 (0.06–0.08)
Female	28,427 (28,246–28,609)	30,022 (29,841–30,204)	0.06 (0.05–0.07)
Age groups[a, b]			
5–14 years	25,393 (25,168–25,618)	26,020 (25,795–26,245)	0.02 (0.01–0.03)
15–24 years	44,815 (44,560–45,071)	50,516 (50,260–50,771)	0.13 (0.12–0.14)
25–34 years	42,008 (41,726–42,289)	45,306 (45,025–45,588)	0.08 (0.07–0.09)
35–44 years	32,451 (32,297–32,606)	34,742 (34,587–34,896)	0.07 (0.06–0.08)
45–54 years	25,848 (25,684–26,013)	26,195 (26,031–26,359)	0.01 (0.00–0.02)
55–64 years	20,026 (19,974–20,077)	19,987 (19,936–20,039)	−0.01 (−0.02–0.00)
65–74 years	21,036 (20,914–21,159)	21,055 (20,933–21,177)	0.00 (−0.01–0.01)
≥ 75 years	14,492 (14,424–14,559)	13,236 (13,168–13,304)	−0.09 (−0.10–−0.08)
WHO Regions			
Western Pacific Region	21,289 (20,631–21,947)	25,806 (25,148–26,464)	0.21 (0.20–0.22)
African Region	28,371 (28,318–28,424)	28,451 (28,398–28,505)	0.00 (−0.01–0.01)
South-East Asia Region	31,657 (31,387–31,927)	32,519 (32,249–32,789)	0.03 (0.02–0.04)
Eastern Mediterranean Region	31,804 (31,749–31,859)	31,702 (31,648–31,757)	−0.01 (−0.02–0.00)
Region of the Americas	32,203 (32,106–32,300)	31,952 (31,855–32,049)	−0.01 (−0.02–0.00)
European Region	31,336 (31,299–31,373)	31,539 (31,502–31,576)	0.01 (0.00–0.02)
Grouping countries base on the sociodemographic index (SDI)			
High-SDI	30,272 (30,177–30,367)	29,947 (29,852–30,043)	−0.01 (−0.02–0.00)
High-Middle SDI	26,147 (25,759–26,536)	28,151 (27,763–28,540)	0.08 (0.07–0.09)
Middle SDI	26,500 (26,205–26,795)	30,121 (29,826–30,415)	0.14 (0.13–0.15)
Low-Middle SDI	30,982 (30,816–31,147)	31,426 (31,261–31,591)	0.02 (0.01–0.03)
Low-SDI	29,404 (29,322–29,486)	29,507 (29,425–29,589)	0.01 (0.00–0.02)

$P < 0.05$.‡Average Annual Percent Change (AAPC).

[a] *The 95% CIs of AAPC was calculated by using the Joinpoint Regression model.*

[b] *The incidence rates for age groups have not been standardized by age.*

Table 1.

The age-adjusted incidence rate of caries of permanent teeth (CPT) in 1990 and 2021, by sex, age groups, grouping country based on the SDI and WHO regions.

100,000 (AAPC = 0.07, 95% CI: 0.06–0.08) and from 28,427 to 30,022 per 100,000 (AAPC = 0.06, 95% CI: 0.05–0.07), respectively. On the other hand, the age-adjusted incidence rate was higher in women than in men between 1990 and 2021. Except for the age groups older than 75 years and also 55–64 years, the incidence rates of PTD in other age subgroups were increasing between 1990 and 2021 (**Table 1** and **Figure 2**). Among all age subgroups, the highest increase in the PTD age-adjusted incidence rate was related to the age group 15–24 years (AAPC in this age group was 0.13 95% CI: 0.12 to 0.14). Among World Health Organization (WHO) regions, the region of the Americas had the highest age-adjusted incidence rate of PTD. The PTD age-adjusted incidence rate in the Americas region decreased from 32,203 per 100,000 in 1990 to 31,952 per 100,000 in 2021. Also, the PTD age-adjusted incidence rate in the Eastern Mediterranean Region (EMRO) decreased from 31,804 per 100,000 in 1990 to 31,702 per 100,000 in 2021. In terms of grouping countries based on the sustainable development index (SDI), the highest PTD age-adjusted incidence rate was observed in the low-middle SDI nations. In these countries, the PTD incidence rate increased from 30,982 per 100,000 to 31,426 per 100,000. Only high-SDI countries had a downward trend in the PTD incidence between 1990 and 2021 (AAPC = −0.01, 95% CI: −0.02 to 0.00). More details about the PTD age-adjusted incidence rates by sex, age groups, WHO regions, and grouping countries based on the SDI are presented in **Table 1**. Regional and country analyses indicated that in 1990, the countries with the highest incidence of PTD included the United States and Ecuador in the Americas, South Africa, Botswana, Congo, Somalia, Sudan, Chad, Burkina Faso, Sierra Leone, and Liberia in Africa, as well as Italy, Finland, and Russia in Europe. In Asia, Thailand, Nepal, Bangladesh, Kazakhstan, and Tajikistan also reported high incidence rates. The age-standardized incidence rate in all of these countries exceeded 32,075.85 cases per 100,000 people (**Figure 2A**). Based on the estimates from the GAM in 2021, the following countries had the highest incidence rates: in the Americas, the United States, Venezuela, Ecuador, and Nicaragua; in Africa, Southern Africa, Tanzania, Somalia, Ethiopia, Sudan, Chad, the Central African Republic, the Congo, Guinea, Sierra Leone, and Liberia; in Europe, Portugal, Italy, and Russia; in Asia, Kazakhstan, Tajikistan, Nepal, and Bangladesh; and finally, in Oceania, New Zealand. In these regions, the incidence rate exceeded 32,075.85 cases per 100,000 populations (**Figure 2D**). **Figure 2A**–**D** provide more details on the incidence of PTD by country for the years 1990, 2000, 2010, and 2021.

3.2 Permanent tooth decay age-adjusted incidence rates, 2022–2030

Between 2022 and 2030, the PTD age-standardized incidence rate increased from 29,948 per 100,000 to 30,414 per 100,000. Men and women will experience a 0.02% and 0.01% annual increase in PTD age-adjusted incidence rate, respectively. In other words, it is forecasted that in the next decade, the PTD age-adjusted incidence rate in men and women will increase from 29,832 and 30,064 per 100,000 in 2022 to 30,288 and 30,488 per 100,000 in 2030, respectively (AAPC in males were 0.02 and in females were 0.01) (**Table 2** and **Figure 1**). It is forecasted that the PTD age-adjusted incidence rate increased in all age groups except for those older than 75 years. GAM predictions showed that the age group of 15–24 years will have the highest incidence in 2030 (age-adjusted incidence rate in this age group in 2030 will be 51,996). It should mention that, except for the region of the Americas and Eastern Mediterranean region, the PTD age-adjusted incidence rates are predicted to increase for other WHO regions (**Table 2** and **Figure 2**). Among the six regions of the World Health Organization, the largest increase until 2030 will be in the Western Pacific region (the age-standardized incidence rate in this region in 2030 is predicted to be 25,011 per 100,000 (95% credible interval (CrI): 13649 to 36,374 and the AAPC = 0.21%). Among the grouping of countries based on the sociodemographic index, the trend of PTD until 2030 is predicted to decrease in high-middle SDI countries (AAPC = −0.02%, 95% CrI: −0.03 to −0.01), increase in low SDI (AAPC = 0.02%, 95% CrI: 0.01 to 0.03) and middle SDI countries (AAPC = 0.01%, 95% CrI: 0.00 to 0.02), and remain stable in high SDI and low-middle-SDI countries (AAPC = 0%).

	ASR (×100,000)		**AAPC ‡ (95% CI) of ASR**
	2022 (95% CrI)	**2030 (95% CrI)**	**2022–2030**
Sex			
Both	29,948 (29,932–29,963)	30,414 (26,177–34,651)	0.02 (0.01–0.03)
Male	29,832 (29,820–29,843)	30,288 (26,284–34,292)	0.02 (0.01–0.03)
Female	30,064 (30,049–30,080)	30,488 (25,811–35,166)	0.01 (0.00–0.02)
Age groups[a, b]			
5–14 years	26,083 (26,069–26,097)	26,827 (23,205–30,449)	0.03 (0.02–0.04)
15–24 years	50,667 (50,649–50,685)	51,996 (48,716–55,275)	0.03 (0.02–0.04)
25–34 years	45,367 (45,350–45,383)	46,057 (40,406–51,708)	0.02 (0.01–0.03)
35–44 years	34,829 (34,811–34,846)	35,539 (31,047–40,031)	0.02 (0.01–0.03)
45–54 years	26,203 (26,193–26,214)	26,197 (22,468–29,926)	0.00 (−0.01–0.01)
55–64 years	19,990 (19,979–20,001)	20,006 (17,587–22,425)	0.00 (−0.01–0.01)
65–74 years	21,052 (21,014–21,090)	21,036 (20,942–21,129)	0.00 (−0.01–0.01)
≥ 75 years	13,169 (13,161–13,177)	12,580 (10,737–14,422)	−0.04 (−0.05–−0.03)
WHO Regions			
Western Pacific Region	25,639 (25,627–25,651)	25,011 (13,649–36,374)	−0.02 (−0.03–−0.01)
African Region	28,456 (28,441–28,471)	28,538 (26,232–30,844)	0.01 (0.00–0.02)
South-East Asia Region	31,056 (29,676–32,435)	31,056 (29,676–32,435)	0.00 (−0.01–0.01)
Eastern Mediterranean Region	31,702 (31,649–31,756)	31,703 (31,554–31,852)	0.00 (−0.01–0.01)
Region of the Americas	31,971 (31,965–31,977)	31,965 (31,804–32,127)	−0.01 (−0.02–0.00)
European Region	31,569 (31,552–31,586)	31,770 (28,579–34,960)	0.01 (0.00–0.02)
Grouping countries base on the sociodemographic index (SDI)			
High-SDI	29,948 (29,798–30,098)	29,952 (29,539–30,364)	0.00 (−0.01–0.01)
High-Middle SDI	28,054 (28,039–28,068)	27,354 (20,714–33,994)	−0.02 (−0.03–−0.01)
Middle SDI	30,134 (30,120–30,149)	30,333 (24,419–36,246)	0.01 (0.00–0.02)
Low-Middle SDI	30,574 (29,698–31,450)	30,574 (29,698–31,450)	0.00 (−0.01–0.01)
Low-SDI	29,567 (29,551–29,584)	30,125 (25,877–34,373)	0.02 (0.01–0.03)

$P < 0.05$.‡Average Annual Percent Change (AAPC).
[a] *The 95% CIs of AAPC was calculated by using the Joinpoint Regression model.*
[b] *The incidence rates for age groups have not been standardized by age.*

Table 2.
The predictive age-adjusted incidence rates of caries of permanent teeth (CPT) in 2022 and 2030, by sex, age groups, grouping country based on the SDI and WHO regions.

It is predicted that by 2030, the countries of America, Nicaragua, Venezuela, Ecuador, and Paraguay will experience the highest incidence of PTD in the Americas. In contrast, Chile is expected to have the lowest incidence, with an ASIR of less than 24,854.75 per 100,000 people. In Africa, the countries with the highest incidence rates are projected to be Botswana, Madagascar, Tanzania, Ethiopia, Sudan, Chad, the Central African Republic, Congo, Guinea, and Sierra Leone, while South Sudan

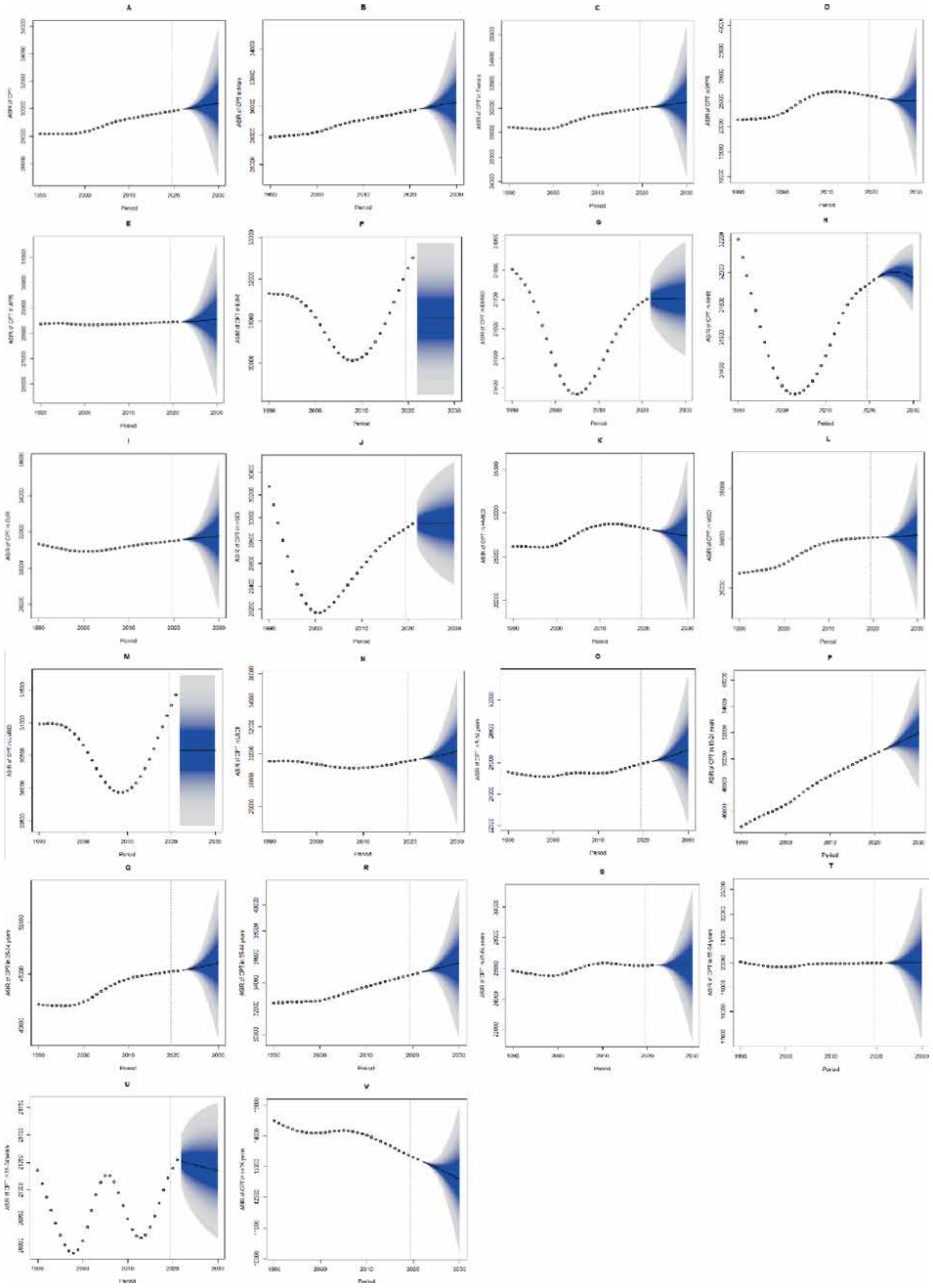

Figure 1.
(A–V) The temporal trends of ASRs (per 100,000) of CPT between 1990 and 2021 and their projections up to 2030 at the global level. Incidence rates for the eight age groups are crude, not age-standardized. The open dots represent the observed values, and the fan shape denotes the predictive distribution between the 2.5 and 97.5% quintiles. The predictive mean value is shown as a solid line. The vertical dashed line indicates where the prediction starts. (AMR: Americas region, AFR, African region, EUR: Europe region, WPR: West Pacific region, SEAR: South-East Asia region, EMRO: Eastern Mediterranean region, LSDI: low socio-demographic index countries, LMSDI: low-middle socio-demographic index countries, MSDI: middle socio-demographic index countries, HMSDI: high-middle socio-demographic index countries, HSDI: high socio-demographic index countries).

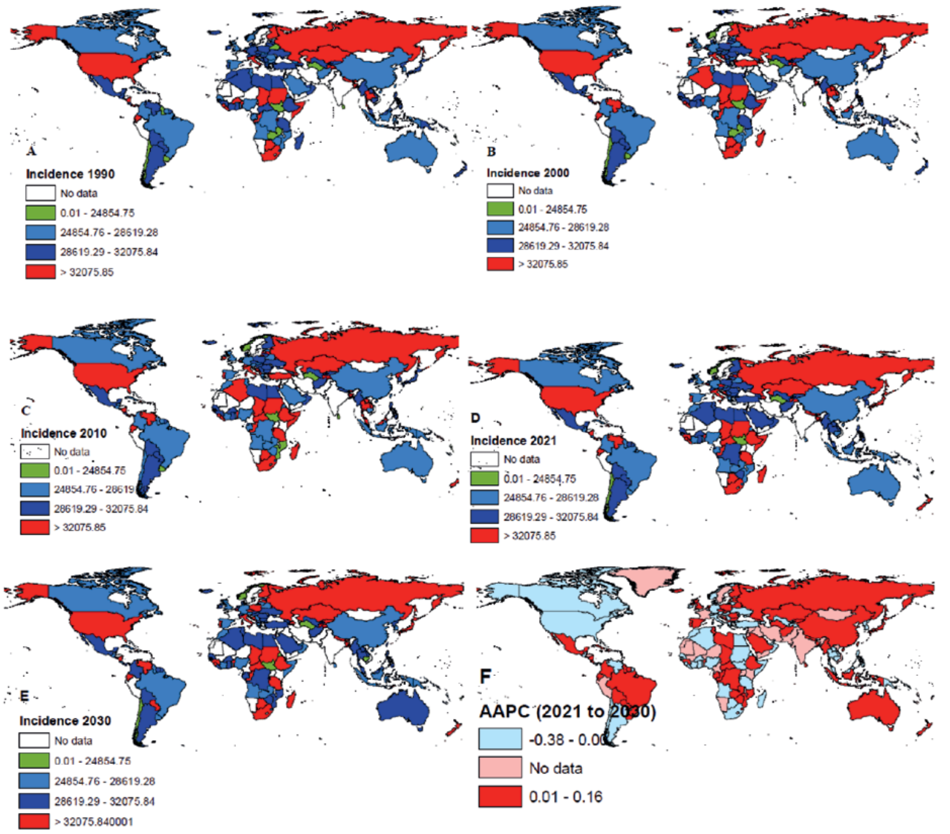

Figure 2.
The global distribution and the average annual percentage changes (AAPCs) in age-standardized incidence rates (ASIRs per 100,000) of permanent dental caries at the global level. (A) ASIR of permanent dental caries in 1990; (B) ASIR of permanent dental caries in 2000; (C) ASIR of permanent dental caries in 2010; (D) ASIR of permanent dental caries in 2021; (E) ASIR of permanent dental caries in 2030; and (F) AAPC of permanent dental caries ASIR between 2021 and 2030.

will have the lowest incidence rate. In Europe, Asia, and the Pacific, countries such as Portugal, Italy, Poland, the Czech Republic, Lithuania, Finland, Latvia, Russia, Kazakhstan, Kyrgyzstan, Tajikistan, Nepal, Bangladesh, Japan, and New Zealand are expected to have PTD incidence rates exceeding 32,075.85 per 100,000 people by 2030 (**Figure 2E**). Generally, the most pronounced decrease between 2022 and 2030 is expected to be in Canada, America, Venezuela, Argentina, Chile, Morocco, Algeria, Egypt, Sudan, Uganda, Somalia, Madagascar, Botswana and other countries marked in blue in **Figure 2F** (AAPC = −0.38 to 0). In contrast, countries such as Mexico, Nicaragua, Colombia, Ecuador, Bolivia, Brazil, Paraguay, Uruguay, Russia, China, Kazakhstan, and others marked in red will experience a rising trend in the incidence of PTD during the same period (AAPC = 0.01 to 0.16) (**Figure 2F**).

4. Discussion

In the present study, we examined the temporal trends of PTD incidence rates at the global level from 1990 to 2021 and made predictions for age-adjusted incidence rates leading up to 2030. Our findings showed a significant increase in age-adjusted PTD incidence rates over the past thirty-two years. This increasing trend was observed across both genders, all age groups, and all country classifications according to the WHO and the sociodemographic index, except for individuals aged 55–64, those over 75, high SDI countries, and regions in the Eastern Mediterranean and the Americas. Similar to the patterns observed over the last three decades, we anticipate that PTD incidence rates will continue to rise by 2030. This increasing trend was present in women, men, all age subgroups except ≥75 years, all regions of the World Health Organization except the Western Pacific region and region of the Americas, and all grouping counties based on the SDI except high-middle SDI countries.

The current findings indicate that the incidence rate of PTD is highest among individuals aged 15–24, consistent with previous research. This trend can be attributed to the fact that dental care is often sought based on symptoms, resulting in delays until individuals experience pain. Since cavities develop slowly, it may take years for lesions in newly erupted permanent teeth to become advanced enough to cause discomfort. This is further evidenced by the declining prevalence of untreated carious lesions in those 15–24 years, who tend to seek dental care more consistently. Additionally, because the DMFT index only accounts for decayed teeth and not those at risk for decay, younger individuals typically have lower decay teeth (DT) scores. This is because they usually have fewer permanent teeth that have been exposed long enough to factors that promote cavities, like sugary foods [20–23]. On the other hand, after the age of 24, the incidence of permanent dental caries decreases in a dose–response relationship with increasing age. The decreasing trend in the incidence of caries in permanent teeth with age is attributed to the increase in missing teeth compared to decayed and filled teeth. In other words, when comparing different age groups, DT and missed teeth (MT) were higher in older age groups compared with middle-aged or younger old age groups, while filled teeth (FT) were lower in the older population. This suggests there may be differences in disease patterns and/or access to dental care between younger and older adults [24].

Furthermore, the findings reveal that the age-standardized incidence rate of PTD is higher in women compared to men. This gender difference may arise a contribution of biological, genetic, social, and behavioral factors. Biologically, differences such as the earlier eruption of teeth in girls and prolonged exposure to cariogenic environments, variations in salivary composition and flow rates, hormonal changes, pregnancy, differences in oral microbiota, and variations in tooth enamel quality may all play a role. From a genetic standpoint, factors influencing enamel formation could contribute to a higher prevalence in females. Additionally, genetic variations that result in a deficiency of the enamel-forming protein Amelogenin can disrupt the formation of the enamel matrix, increasing the risk of PTD. Behavioral factors involve eating habits, women's access to food, and the tendency to snack frequently, particularly while preparing meals. During the agricultural revolution, the division of labor meant that women were responsible for gathering food, while men were more focused on consuming meat. As a result, men were less exposed to high sugar content in their diets. Social factors, particularly in underprivileged cultural areas, may lead to male children receiving more healthcare and better nutrition. Additionally, the misconception that restricting one's diet during pregnancy can lead to an easier childbirth can contribute to nutritional imbalances, ultimately increasing the risk of cavities in females [25–27].

The current global and regional patterns of PTD reflect distinct risk profiles across countries, influenced by living conditions, lifestyles, and the effectiveness of preventive oral health systems [28]. Countries experiencing an increasing trend in the incidence of permanent tooth decay by 2030 may be facing factors such as increased sugar consumption and inadequate fluoride exposure. Consequently, public health policies can play a crucial role in prevention before negative outcomes arise [29]. In contrast, the reduction of caries in other countries by 2030 is the result of various public health measures, including the effective use of fluoride, along with improvements in living conditions, lifestyle changes, and enhanced care practices [30]. It is recommended that the aforementioned measures, which are effective in preventing dental caries, be prioritized by all countries, especially those with a high incidence rate or those predicted to experience an increasing trend in the next decade. The analysis of this study indicated that some countries such as Scandinavian countries had a decreasing trend. In these countries, organized public health services and oral health care are provided to children and underprivileged population groups, and the presence of these interventions is the reason for the observed decrease [31–33].

Our analysis indicates that the PTD incidence rate is higher in low SDI countries compared to high SDI countries. This finding can be attributed to the limited access of deprived countries to timely diagnostic services and subsequently their less access to new and more effective treatment methods. Also, the high prevalence of PTD in developing countries can be attributed to the fact that oral and dental health services are primarily offered in regional or central hospitals located in urban areas, with insufficient emphasis placed on preventive or restorative dental care [34]. Additionally, many countries in Africa, Asia, and Latin America face a shortage of oral health personnel, and the capacity of these healthcare systems is generally limited to pain relief and emergency care. In Africa, the dentist-to-population ratio is approximately 1: 150,000, in stark contrast to about 1: 2000 in most industrialized nations [35]. As a result, many adults suffering from severe tooth decay often have their teeth left untreated, or they undergo extraction solely to alleviate pain or discomfort.

5. Conclusion

In conclusion, our projections indicate that the incidence rate of PTD is expected to rise over the next decade. The most significant increases are anticipated among men, individuals younger than 24 years, those of African descent, and regions with low SDI. These findings highlight the urgent need for targeted prevention efforts aimed at these high-risk subgroups, which are likely to continue experiencing upward trends until 2030. Effective preventive measures, including public health initiatives and access to dental care, are essential to mitigate the incidence of PTD in these vulnerable populations, ultimately improving overall oral health outcomes.

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Chapter 4

Endodontic Challenges Arising from Root Canal Morphology

Aida Dzankovic, Samra Korac, Irmina Tahmiscija and Naida Hadziabdic

Abstract

Endodontic challenges relating to root canal morphology are critical problems in everyday dental practice. The complexity and variability of the root canal system present significant difficulties in effective cleaning, shaping, and obturation. Variations in canal anatomy, such as accessory canals, bifurcations, and intricate curvatures, complicate the debridement process and may leave infected tissue or debris behind. Moreover, these anatomical irregularities can lead to procedural errors during instrumentation. Advanced imaging techniques, such as cone-beam computed tomography, have enhanced the detection of complex canal morphologies, allowing for more precise treatment planning. However, the clinician's ability and experience remain critical in addressing these anatomical obstacles. The development and application of flexible nickel-titanium instruments have greatly improved the ability to navigate and shape complex canal systems. Despite these advances, the unpredictability of root canal morphology remains the most important factor influencing the success rate of endodontic treatments. The following chapter provides guidelines for addressing the challenges that morphology presents to the clinician.

Keywords: endodontic challenges, root canal morphology, complex canal systems, anatomical variations, treatment guidelines

1. Introduction

Root canal treatment is a set of procedures intended to restore a severely damaged tooth caused by caries or trauma. The three fundamental steps of root canal treatment are cleaning, shaping, and obturation. The complexity of root canal anatomy has a direct impact on the obstacles encountered throughout each step of root canal treatment. False assumptions about root and canal anatomy might lead to insufficient debridement and obturation, resulting in endodontic failure. Knowledge of root canal morphology is the foundational basis for effective endodontic therapy. As a result, it is vital to understand what the root canals look like and what makes them unique.

1.1 Root canal complexities and their impact on endodontic treatment

Root canals are anatomical spaces within the root that extend from the pulp chamber floor to the tooth's apical area. Their shape is conical, with the largest diameter at the orifice and the smallest at the apex, where dentin and cementum meet. However, root canals are rarely as simple, especially in the posterior teeth. The main root canal can divide along its path and create small branches such as lateral canals, intercanal communications, and apical deltas (**Figure 1**).

Lateral canals are tiny branches that extend from the main canal at a sharp angle and terminate in the periodontal ligament area. Their most frequent location is the apical region, particularly in posterior teeth [1]. The pulp and the periodontal ligament communicate primarily through the apical foramen, but lateral canals may also play a significant role in the etiopathogenesis of pulp-periodontal disease. The presence of lateral canals does not indicate endodontic treatment failure, although it may cause or prolong periapical inflammation [2].

Intercanal communication (isthmus and transversal anastomoses) refers to a small pathway that connects two root canals. Unlike lateral canals, intercanal communication does not reach the outer surface of the tooth but contains bacterial biofilms and dentine debris formed during root canal instrumentation [3].

Apical delta is a morphological feature where the main root canal breaks into three or more branches in the apical area, resulting in a loss of main canal continuity. Instrumentation and disinfection are difficult to achieve within the ramifications and may have a negative impact on the long-term outcome of root canal therapy [4].

These ramifications substantially impact a clinical setting as they create an environment that allows bacteria to grow and prevent effective infection control. Root canal cleaning and irrigation are hard to achieve, resulting in the continued presence of bacteria [5].

1.2 Apical root canal morphology

The apical third of the root canal is the most morphologically complex due to variations in the position of the apical constriction, the increased frequency of lateral canals, and the potential presence of an apical delta [6]. The anatomical features of

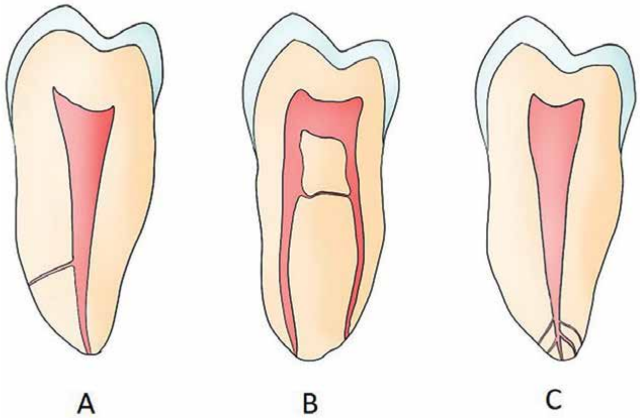

Figure 1.
Root canal ramification: (A) lateral canal, (B) intercanal communication, (C) apical delta.

this area are altered when apical periodontitis occurs [7]. Furthermore, the so-called open apexes can arise when pulp tissue necrosis happens before the completion of root growth. In these situations, the root canal is wider apically than at the orifice [8]. The aforementioned morphological complexities affect all aspects of clinical work and the very prognosis of dental treatment [9, 10].

The apical part of the root exhibits several distinct morphological landmarks: anatomic apex, radiographic apex, apical foramen, apical constriction, and cemento-dentinal junction (**Figure 2**). The anatomic apex of the tooth represents a morphologically determined tip or end of the root. The radiographic apex is the radiographically identified tip or end of the root. The apical foramen is an exit opening on the root's outer surface. It can be positioned at the root's anatomic apex or 0.5–1 mm mesially, distally, lingually, or labially [11, 12]. The position of the apical foramen varies with age and more intensive cement deposition, as well as the type of tooth [13]. A higher frequency of deviations was seen on the posterior teeth and may be explained by increased cement deposition in response to occlusal stress and enamel wear [14]. Branching of the main root canal in the apical third into two or more accessory canals results in the same number of apical foramina.

The apical foramen could be round, oval, semilunar, flat, or irregular in shape [15]. In immature teeth, the apical foramen is funnel-shaped, with a wider portion on the root's outer surface. At this stage, it is filled with periodontal tissue, which will be replaced by dentin and cementum. As the root develops, the apical foramen narrows and moves away from the apex [16]. The apical constriction is the region of the root canal with the lowest diameter, which is typically located 0.5–1 mm from the apical foramen inside the root canal. It is most commonly found in the dentin, then in the cemento-dentinal junction, and lastly in the cementum [17]. The apical constriction has great clinical significance because it represents the apical reference point when determining the working length and therefore indicates the root canal's instrumentation and obturation limits. If the apical constriction is destroyed by instrumentation, postoperative sensitivity occurs more often, the obturation procedure is difficult, and the healing process can be jeopardized. The apical constriction can also be destroyed by a pathological process [18]. Dummer et al. classified apical constriction into four different forms: single (traditional), tapering, multiconstricted, and parallel constriction [19] (**Figure 3**). The results of a micro-computed tomography (micro-CT)

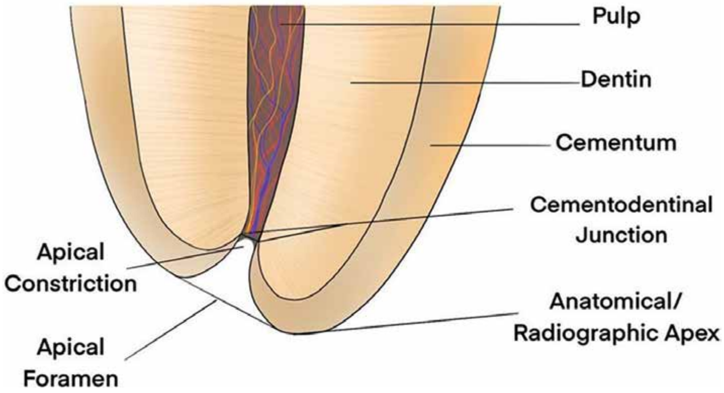

Figure 2.
Landmarks of apical root canal morphology.

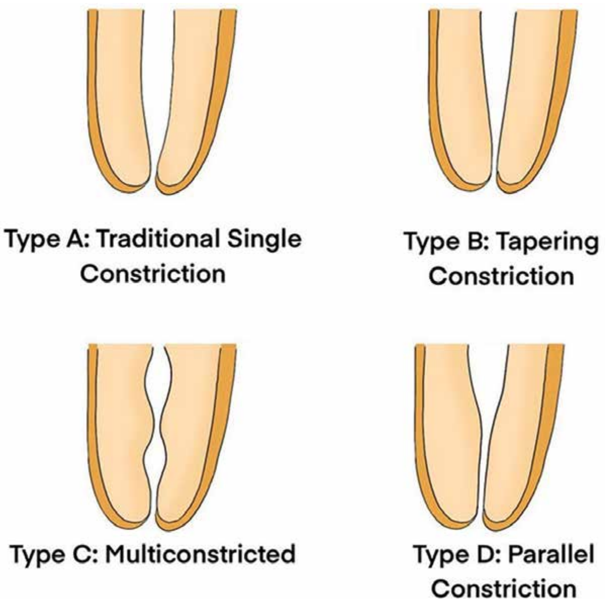

Figure 3.
Different shapes of apical constrictions.

of the maxillary molar's palatal roots revealed that apical constriction is not always present. In the same study, the same research group considered apical constriction in cases of single or tapering morphology. However, roots with flaring, parallel, or delta shapes were assumed to have no constriction [20].

The interface line between cementum and dentin is known as the cemento-dentinal junction. In theory, the cemento-dentinal junction would be the optimum location to complete root canal instrumentation and obturation. This would prevent microbes from penetrating the periapical tissue and fluid from entering the canal. Nevertheless, this zone cannot be clinically identified and represents only a histological landmark [21].

1.3 The factors affecting root canal morphology

Root canal appearance varies with age, gender, ethnicity, and race. With increasing age, the size of the pulp chamber, the diameter of the root canal, and the tubular lumen gradually decrease due to the slow rate of secondary dentine deposition. The physiological aging of the root canal system, as a result of secondary dentine formation, begins when the tooth erupts and enters the occlusion [22]. Continuous dentin deposition over time makes it difficult to identify root canals orifices and perform debridement (**Figure 4**).

Gender differences in root canal morphology can be observed in a variety of aspects, including the configuration and complexity of the root canals, their length and curvature, tooth size, and pulp chamber dimensions. Although a certain number of studies support the view that there are no significant gender differences in the morphology of root canals [23–25]. Other studies have shown that males have a more complex root canal system, with higher frequencies of additional and lateral canals, as well as more complex canal configurations [26–28]. Previous studies have revealed

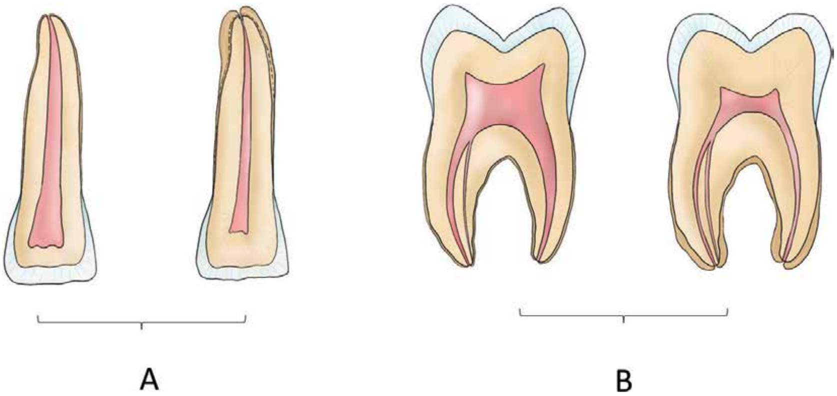

Figure 4.
Changes in endodontic space dimensions and cement apposition with aging on incisors (A) and molars (B).

a higher prevalence of roots in males for maxillary premolars and mandibular molars [26–28]. Males have a higher incidence of three-rooted maxillary premolars [29–31]. Similarly, males had a higher rate of additional root canals [32–34]. Type I of the root canal morphology, according to Vertucci, the simplest for endodontic treatment, is more common in women [35, 36]. Root canal size and curvature are essential dental parameters in endodontic treatment. Several studies have found that males had longer teeth [37, 38], although there is minimal and inconsistent evidence of gender differences in root canal curvature. While some studies suggest sex-related differences in pulp chamber size [39, 40], further extensive research is necessary to confirm these findings.

Root canal morphology differs by race and ethnicity in terms of canal number and configuration, as well as anatomical complexity. For example, East Asian populations have a higher frequency of C-shaped mandibular second molars than other ethnic groups [41], whereas Africans have a higher frequency of additional canals in mandibular premolars than Europeans [42].

1.4 The classification of root canal morphology

Different root canal classifications have been developed to assist clinicians in better understanding the teeth's internal anatomy. Vertucci's classification has been used to describe variations in root morphology ever since it was published in 1984 [43]. The endodontic literature widely accepts this classification, which divides root canals into eight types based on their spatial arrangement and number of canals (**Figure 5**). For example, it is generally known that Vertucci's type I root canals are most common in maxillary incisors in various populations. In this manner, Vertucci's classification serves as a universal language for endodontists, allowing them to comprehend one another.

Advancements in root canal morphology analysis have highlighted the limitations of the Vertucci classification leading to the introduction of alternative classification systems. Recently, attempts have been made to address the challenges posed by Vertucci's classification and others through the development of an entirely new classification system. Ahmed et al.'s classification may serve as a better alternative for future research [44].

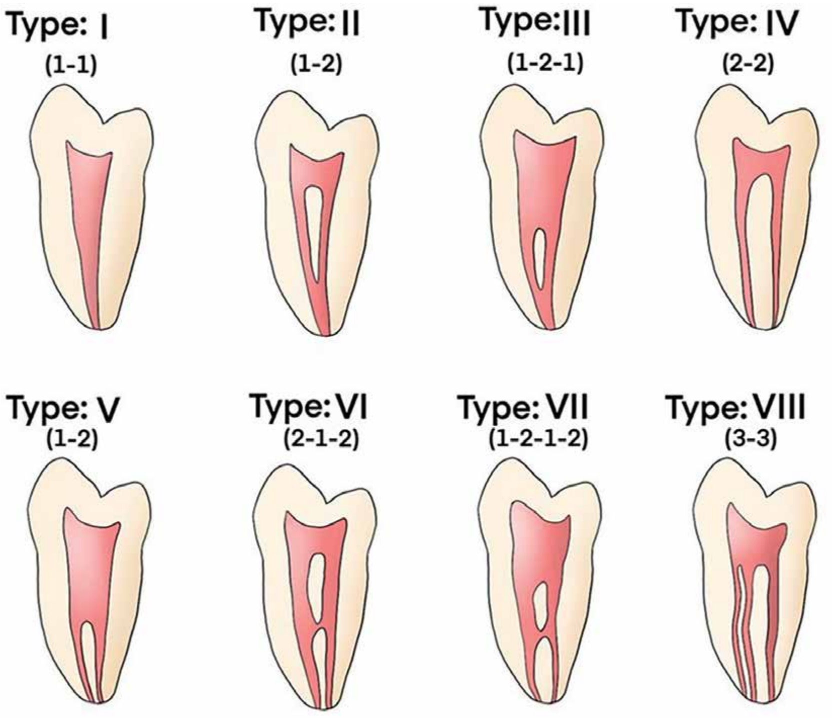

Figure 5.
Vertucci's classification of the root canal morphology.

2. Root canal morphology and clinical considerations for maxillary teeth

2.1 Maxillary central incisor

The maxillary central incisor is most often of simple morphology with one root and one canal [13, 45–48] (**Figure 6A**). However, in rare cases, this tooth may have an additional root [49–52] or multiple root canals [51, 53–57].

In elderly patients, the roof of the pulp chamber is often located at the level of the tooth cervix, which requires moving the access cavity incisally to allow straight-line access to endodontic instruments [58]. In contrast, younger patients with high pulp horns require a larger access cavity with an external triangular form and an incisal base orientation. Relocating the access cavity entry point to the incisal edge improves the incisor's fracture resistance [59].

The pulp chamber of this tooth can be completely or partially obliterated due to irritation-induced dentin formation. The use of cone beam computed tomography (CBCT) scans and optical aids is essential in the endodontic treatment of obliterated teeth [60].

Maxillary central incisors may also exhibit developmental anomalies. Although the palatogingival groove is more common on the maxillary lateral incisor, it can also develop on the maxillary central incisor, requiring endodontic and periodontal therapy [61]. Dens invaginatus is another developmental anomaly that can rarely be diagnosed on this tooth. The presence of this developmental anomaly complicates endodontic treatment and often implies modification of the access cavity preparation with the use

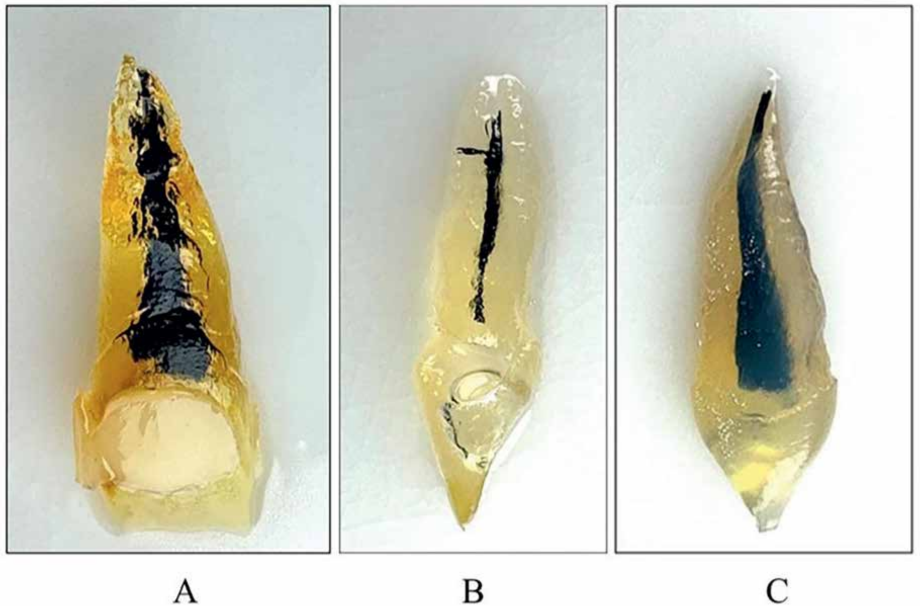

Figure 6.
A common root canal morphology of maxillary anterior teeth with a single root and one root canal: (A) the central incisor; (B) the lateral incisor, with lateral canal in the apical region; (C) the canine.

of the dental operating microscope, passive ultrasound irrigation, and negative apical pressure irrigation system, as well as a combination of obturation techniques [62].

Key point: The shape and position of the access cavity on the maxillary central incisors are influenced by the patient's age and endodontic space dimensions.

2.2 Maxillary lateral incisor

The maxillary lateral incisor is characterized by a single root and one canal [63, 64] (**Figure 6B**). Generally, the canal is straight, although it may exhibit a slight curvature at the apex, which is typically disto-palatal-oriented [65–67]. This tooth is smaller in all dimensions than the central one, except for root length. On a radiograph, it may seem shorter than it is due to root bending. Additionally, the pulp chamber is relatively small, and the root canal is narrow, especially in the apical third [68]. In some cases, this tooth may present with additional canals [69, 70] and supernumerary roots [71].

Morphological variations in both crown and root can lead to challenges in diagnosis and endodontic treatment of maxillary lateral incisors. Developmental anomalies, such as dens invaginatus and palatogingival groove, often affect these teeth, manifesting a complex internal morphology [72, 73]. Therefore, the use of three-dimensional imaging is recommended for the assessment and treatment planning for such anomalies [74–76].

Key point: A narrow and sometimes curved canal can make instrumentation and cleaning difficult. An abscess frequently produces swelling on the palate due to the curvature of the root.

2.3 Maxillary canine

The maxillary canines are the longest teeth in the permanent dentition [77]. The average length of these teeth is 26.4–26.5 mm [78–80] although the data vary depending on the studied population. Additionally, these teeth have the most obvious gender dimorphism compared to all other teeth, with males having longer maxillary canines than females [80]. The maxillary canines are single-rooted (**Figure 6C**), and this appears to be constant regardless of research location [80]. The most common root canal type is type I, while other root canal types are sporadic.

Maxillary canines present several unique challenges in endodontic therapy due to their root canal morphology. Direct access to the root canal can only be achieved by removing the lingual shoulder from the palatal surface. Electronic apex locators are less precise in longer teeth than in shorter ones, and determining the working length may be challenging [78]. If the apex locator produces inconsistent readings, radiographic control of the working length can be considered. Typically, longer endodontic files, such as 31 mm, are required rather than the standard 25 mm-long files. The canine root canals are oval rather than spherical, so it is important to clean the oral and vestibular walls during instrumentation.

Key point: The length of the maxillary canines is the primary characteristic that stands out for root canal therapy. Root canal therapy can be modified by using longer endodontic files, different canal instrumentation, and obturation techniques.

2.4 Maxillary first premolar

Maxillary first premolars usually have two roots (buccal and palatal) that might be separated or partially fused [81]. Typically, these teeth have two canals, with type IV root canal configuration as the most prevalent (**Figure 7A**), followed by types II and I [81]. The anatomic variations of the root and canal number are rare and most commonly include three roots with three canals (two buccal and one palatal). Asians are more likely to have one canal than other ethnic groups, indicating an ethnicity-related morphological trait in maxillary first premolars [81].

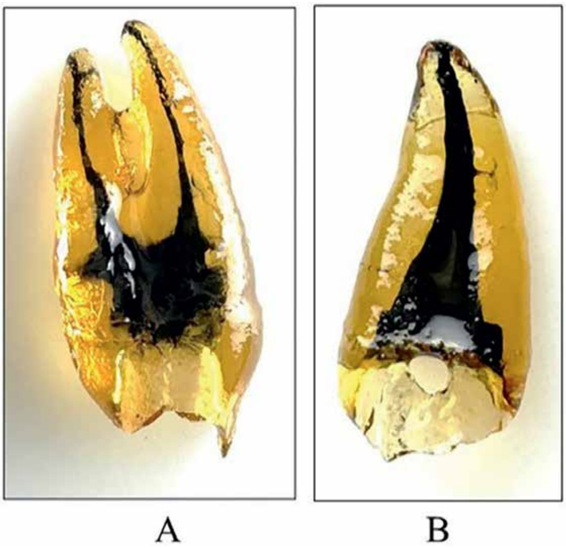

Figure 7.
Maxillary premolars: (A) the first premolar with type IV root canals; (B) the second premolar with type I root canal.

Maxillary premolars are frequently candidates for root canal therapy, comprising 15.8–21.5% of all teeth [81]. In two-rooted maxillary first premolars, the position where roots split modifies the course of root canal therapy [82]. The bifurcation point may occur in the coronal, middle, or within two-thirds of the roots. The roots can separate in the apical region, which is fortunately less frequent compared to the coronal or middle section of the root [82]. If the root splitting occurs in the middle of the roots, the clinician should create a deeper access cavity and expand it in the bucco-palatal direction. This approach provides access to the palatal and buccal root canals for canal instrumentation.

When the crown's mesio-buccal dimension exceeds its bucco-palatal dimension, the presence of extra roots and root canals should be considered [83]. The three-rooted forms of maxillary first premolars need a larger access cavity on the buccal side to facilitate access to buccal canals [82].

A common finding in bifurcated maxillary first premolars are grooves found on the palatal side of the buccal root [84, 85], ranging from 1.1 to 9.0 mm in length [81]. The coronal two-thirds of the buccal root commonly display the grooves, with their prevalence ranging from 62% to 100% [86, 87]. The average dentin thickness at the most prominent groove invagination is only 0.81 mm [87]. This anatomical feature cannot be recognized from periapical radiographs [86]. Over-instrumentation or excessive pressure within the grooves may compromise the root structure, resulting in strip-perforations and vertical root fractures. More dentin removal increases the risk of fracture in endodontically treated teeth, particularly in roots with a narrower mesiodistal diameter than the bucco-palatal, like maxillary premolars [84]. Therefore, Ghoddusi et al. recommended avoiding dowel preparation in the buccal roots of bifurcated maxillary first premolars [88].

Apical morphology of maxillary first premolars is very complex. Data varies among different studies; however, maxillary first premolars had lateral canals in 9–78%, particularly in the apical region [81]. Apical deltas and isthmi were found in 1.8–30.5% and 2.5–34.2% of samples, respectively [81]. These ramifications represent a weak point in root canal treatment since cleaning, shaping, and obturation are rarely achievable. Furthermore, they allow inflammatory substances to spread between the pulp and surrounding tissues. To overcome persistent infections, an extensive irrigation, preferably active, is required to eliminate debris. If a conservative approach fails, surgical removal of the apical 3 mm is one of the therapeutic alternatives.

Key point: The position of root splitting in maxillary first premolars affects root canal therapy, requiring a deeper access cavity. Over-instrumentation within furcation grooves can compromise the root structure, leading to strip-perforations and vertical root fractures.

2.5 Maxillary second premolar

Maxillary second premolars are most commonly single-rooted teeth, with two-rooted forms appearing in a lower percentage [23, 89–91]. It is the only permanent tooth that shows all eight types of root canal described in the Vertucci classification [58].

Maxillary second premolars demonstrate a wide variety of root canal configurations, unlike maxillary first premolars, where type IV is dominant across different age groups, races, and genders. For instance, researchers found that the North American population most frequently had types I (**Figure 7B**), II, and III [43], while the Chinese population had type II, IV, or VI canal configurations [92]. In both the

Turkish and Spanish populations, maxillary second premolars with one root had the most type I canal configuration, while two-rooted forms had the most type IV [23, 91]. In the Saudi Arabian population, the most common canal configuration was type V [93]. This emphasizes the need for the physician to be familiar with the specifics of the root canal morphology in a particular geographic region and different ethnic groups.

Maxillary second premolars are among the most commonly endodontically treated maxillary teeth [94]. As the root canal anatomy becomes more complex, the frequency of technical errors during root canal treatment increases consecutively [95]. When complex root canal morphology is suspected, CBCT is advised. Two-rooted maxillary second premolars have buccal roots that are closer to the maxillary sinus floor than palatal roots. Therefore, odontogenic infections are more prone to spread into the sinus via buccal roots [94].

The roots of maxillary second premolars have longitudinal concavity and apical borders that are difficult to identify in radiographs due to superimposition and distortions [93]. Adjusting the horizontal angle of the X-ray tube could be helpful in visualizing these features, aiding in the assessment of root canal complexity.

Key point: Maxillary second premolars are single-rooted teeth with a high occurrence of two canals. The diversity of the root canal system increases the likelihood of procedural errors.

2.6 Maxillary first molar

The maxillary first molar is the largest tooth in the maxillary dental arch. Usually, it has three roots and three or four root canals [96] (**Figure 8**). The morphology of the root canals is very complex and variable, and it is significantly influenced by race and geographical locations [97].

Palatal and distobuccal roots usually have a simple anatomy, commonly containing a single canal with a type I configuration, according to Vertucci [98]. The mesiobuccal root has a more complex anatomy due to the high frequency of the second mesiobuccal canal (MB2). Type I is the most represented in MB roots, occurring 33.29% of the time. Types II and IV had similar prevalence rates of 27.18% and 26.36%, respectively [99]. Root canal morphology and canal configuration demonstrated bilateral symmetry in 87.37% of maxillary first molars [100].

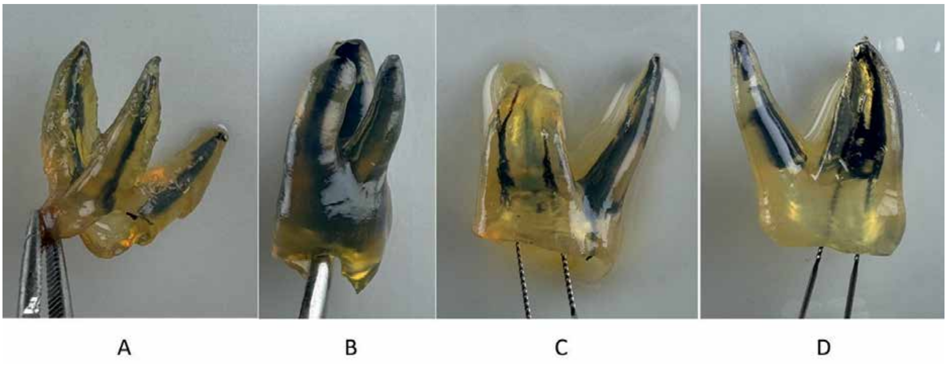

Figure 8.
Maxillary first molars with different root canal morphology. The samples with MB1 canal (A, B) and samples with MB2 canal (C, D).

The frequency of non-recognition MB2 during root canal treatment is high, with rates ranging from 74% to 93% [101]. The mesibuccal root of the maxillary first molar has the highest occurrence of apical periodontitis [102]. Failure to identify the presence of MB2 frequently results in unsuccessful endodontic treatment [103].

The mesial edge of the access cavity outline is defined by an imaginary line connecting the tips of the mesial cusps. For the distal boundary, the oblique ridge serves as a suitable starting point. The buccolingual diameter of the crown is larger than the mesiodistal; hence the pulp chamber is also wider in this direction. Its cervical outline is rhomboid, with rounded edges [104]. The coronal part of the root canals of the first upper molar converges toward the occlusal surface, which can be used when creating the external contours of the access cavity [101]. When creating an access cavity, it is crucial to use a radiograph to determine the distance between the pulp chamber's roof and floor. If the preoperative X-ray indicates a space of less than 1 mm between the roof and the floor of the pulp chamber, the tactile sensation of the bur entering the roof may be less noticeable, especially if the chamber is filled with calcified tissue. In these situations, the use of an operative microscope and coaxial illumination help to visually measure the depth of bur penetration and distinguish the roof from the chamber floor.

Developmental grooves, seen as dark lines on the chamber floor, may serve as useful landmarks to help locate canal orifices [105]. The MB2 canal orifice is typically found along the groove connecting the palatal and mesiobuccal canals, with its position varying relative to the mesiobuccal canal. When searching for the MB2 canal, carefully inspect the groove for a small depression, which may indicate the location of the orifice. This is where the endodontic probe's point may become engaged. The pulp chamber's mesial wall frequently has a dentine shelf that usually covers the underlying MB2 foramen. Ultrasonic tips are useful in removing this dentin shelf [106]. The number of root canal orifices on the pulp chamber floor (**Figure 9**) does not indicate the presence of an MB2 canal [107].

Figure 9.
The pulp chamber floor of a maxillary first molar with four (A) and three root canals (B), cross-section.

For maxillary molars with four canals, the dentin thickness of the mesiobuccal root should be considered. Compared to the first mesiobuccal canal (MB1), the MB2 canals have significantly less dentine thickness in both the mesial (safety zone) and distal (danger zone) aspects of the root. Given the non-tapered shape and the thin dentine walls of the MB2 canal at the furcation level, adjustments to mechanical preparation procedures may be necessary to avoid procedural errors [108].

Key point: The clinician should keep in mind that MB2 occurs frequently and takes time to identify, as an undetected MB2 canal is the most common cause of endodontic treatment failure.

2.7 Maxillary second molar

The maxillary second molar resembles the first, although it is smaller. It typically has three roots that are generally less divergent and positioned closer together, making them harder to distinguish on radiographs. This tooth usually has three canals (one in each root) (**Figure 10**). However, the mesiobuccal root may have two canals, which is less common than in the first molar [109]. The mean prevalence of MB2 in maxillary second molars is 39%, with the highest and lowest prevalence reported in the Brazilian (83.2%) and Chinese (13.4%) sub-populations [110]. Vertucci type I is the most prevalent canal configuration found in all roots of the maxillary second molar [111].

Root fusion is an anatomic variation commonly seen in these teeth, with rates ranging from 5.90% to 42.25%. The most prevalent type of fusion was between the palatal and the mesiobuccal root, followed by the fusion of the mesiobuccal with the distobuccal root. The most uncommon occurrence was the complete fusion of all three roots into a cone-shaped root. As age increased, root canal morphology tended to be more complex [112].

The thickness of the vestibular bone lamella varies near the apex of the buccal roots, which is particularly important to consider during apical surgery. The apex of the distobuccal root is closer to the vestibular lamella compared to the apex of the mesiobuccal root [113]. In terms of proximity to the maxillary sinus, the mesiobuccal root of the second maxillary molar is the closest, followed by the distobuccal root [114]. Due to this proximity, extra caution is advised when performing endodontic treatments and surgery in this region to minimize potential complications [115].

Figure 10.
A typical maxillary second molar's root and canal morphology, showing three roots and three canals.

Key point: The root fusion can lead to deviations from the typical root canal morphology of the maxillary second molar. When performing root canal treatment and apical surgery, it's crucial to be mindful of the potential proximity to the maxillary sinus.

3. Root canal morphology and clinical considerations for mandibular teeth

3.1 Mandibular central incisor

Typically, mandibular central incisors (MCI) have a single root that gradually tapers toward the apex and narrows mesiodistally [116]. The root canal system represents the external anatomy and typically consists of a single root canal (Vertucci's type I) (**Figure 11A**) [117]. However, in a certain percentage (20.4%), there are double canals in the root, lingual and buccal, with the most common configuration being type III [118]. The configuration of the root canals of the left and right lower incisors is symmetrical [117, 119]. The prevalence of the additional canal, which is significantly less common among Asian subpopulations (4.0–11.3%) than among Europeans (24.4–49.3%) [118], may indicate ethnic variability.

Two-dimensional periapical radiographs rarely reveal double root canals in the mandibular incisors [116]. Therefore, to assess the root canal morphology of the mandibular incisors and identify overlapping canals, a periapical radiograph from two projections or CBCT scan analysis is required.

Endodontic treatment of the mandibular central incisor is challenging due to the narrow pulp space and apical root canal curvature [120]. Canals are generally

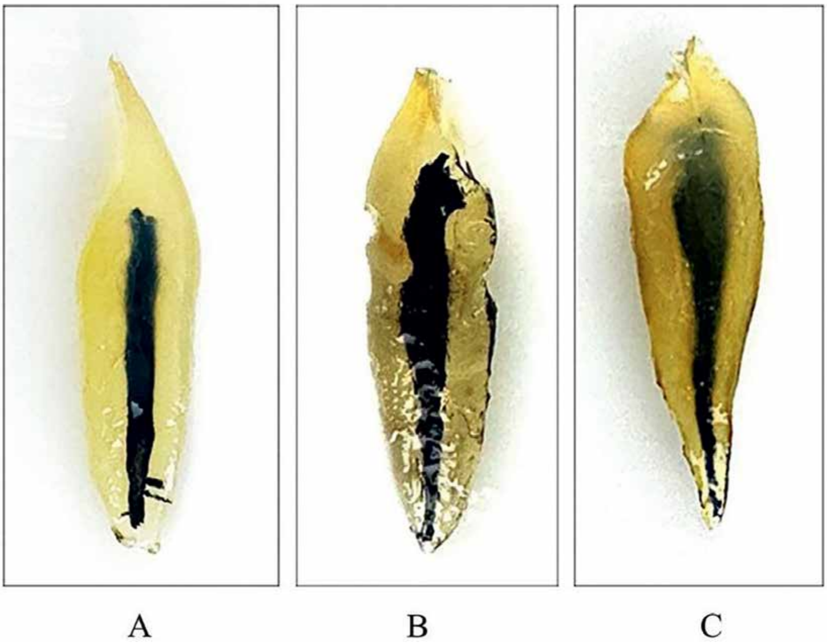

Figure 11.
Common root canal morphology of mandibular anterior teeth, single-root, one root canal: (A) the central incisor with multiple lateral canals in the apical region; (B) the lateral incisor; (C) the canine.

ribbon-shaped or long oval-shaped coronally and become round or oval 1 mm from the apical foramen [116].

The traditional access cavity for the MCI is located lingually above the cingulum, primarily for esthetic reasons. This approach makes localization of the lingual canal more difficult due to the lingual shoulder of the dentine that lies over the entrance. To achieve a direct straight line approach to the apical third and resistance to fracture, it is recommended to move the access opening toward the incisal edge or even to the labial surface [121]. The latter is particularly relevant for patients with extensive incisal edge abrasions.

In the apical third, there is a sudden decrease in dentin thickness, with the thinnest root dentin mostly located mesio-lingually [120]. Due to the mesiodistal compression of the root, the use of instruments with a large taper can lead to procedural errors in the form of root perforation [117]. Thus, the instrumentation should be mainly directed toward the buccal and lingual walls of the root, preferably using flexible instruments [120].

Approximately half of the mandibular incisors revealed lateral canals predominantly located in the apical 2 mm. This ensures the success of endodontic surgery in preserving tooth tissue in case endodontic treatment fails [119].

Key point: Endodontic treatment of the mandibular incisor may have an unfavorable outcome due to the missed second canal, specifically the lingually located.

3.2 Mandibular lateral incisor

The mandibular lateral incisor (MLI) exhibits a root morphology comparable to the central incisor, though it tends to be wider and longer [116, 119].

Similar to central incisors, the most common root canal system configuration is type I (**Figure 11B**), followed by type III [116]. However, studies have shown a higher prevalence (23.7%) of the additional canal in the lateral than in the central incisors [117]. The prevalence of additional root canals for mandibular lateral incisors was observed more frequently in European (27.8–47.2%) than in Asian countries (11.0–23.4%) [118].

Dentists should constantly consider the possibility of two canals in mandibular incisors. Therefore, it is always necessary to determine the existence of superimposed canals in multiple periapical images. In such cases, the access cavity must be modified and extended, and the lingual dentine shelf must be removed.

In younger patients with prominent pulp horns, the dental pulp space of MLI is larger compared to older patients. When working on front teeth, it is important to widen the access cavity in the mesiodistal direction to fully remove the tissue, particularly from the pulp horns. This helps prevent subsequent discoloration of the crown.

Key point: The root canal system of the second mandibular incisor closely replicates the configuration of the adjacent incisor's canal structure.

3.3 Mandibular canine

Mandibular canine most commonly has a single root with one canal (type I) (**Figure 11C**), although two canals can be found in 0–15.1% of cases [122–124]. Single root with Vertucci type II and type III reported as the next most frequent two canal morphologies [123]. The additional root canal in mandibular canine is more common among South Asians and the inhabitants of the Middle East (10.5%), with lower frequencies observed in Europeans (9.2%), and America and Africa (5.2%) [125].

The anatomical variation of double-rooted mandibular canines with two distinct canals is less prevalent, ranging from <1% in Asia and Africa, with a higher frequency among Europeans (3.5%) [125]. Additionally, this variation can be observed in up to 5% of cases and shows a strong preference for females [126, 127]. In over 90% of cases, a high bilateral symmetry is present for the number of roots and canals, as well as the canal configuration [123].

In single-rooted canines, the root canal is wider mesiodistally than buccolingually, with a different cross-sectional appearance throughout the root. The apical third could be round or slightly oval in shape [128]. When a canine has two roots, the roots and canals split in the middle or apical third, creating the lingual and buccal canals, which are about the same length [129].

The presence of a second canal may be considered on a minimum of two diagnostic radiographs taken using different horizontal angulations. Through a careful radiographic examination, it is possible to observe a sudden loss of continuity in the canal or a groove on the external part of the root [127]. Furthermore, the axial view of the CBCT image is very useful for identifying the presence of two root canals.

Modifying the standard access cavity and extending the preparation in a linguo-cervical direction can facilitate localization and instrumentation of the lingual canal.

To locate the lingual canal, the typical oval-shaped access cavity should be modified into a “inverted pear” shape [122]. The localization and mechanical instrumentation of the root canals become more difficult when the division is located apically. This can be facilitated by measuring the distance between the incisal reference point and the bifurcation zone with a periodontal probe or a type K-file. Also, the lingual pericervical dentin should be removed with ultrasonic tips or burs with a long shaft [127].

The major foramen in mandibular canines typically exhibits displacement along the buccal plane of the root, rendering it difficult to observe on the periapical radiograph due to superimposing on the tooth structure. Therefore, the clinicians must be cautious because displacement can result in inaccurate measurement of working length and over-instrumentation [128]. To prevent lateral perforation when there are two canals, it is preferable to adopt a conservative instrumentation approach with an apical size no larger than ISO #35 [127].

Key point: Mandibular canines often have a single canal. A sudden loss of continuity in the canal on the radiograph suggests double canals.

3.4 Mandibular first premolar

Several morphological features make mandibular premolars challenging during endodontic treatment such as root canal variations, a lack of radiographic visibility, narrow mesiodistal dimensions, and apical third trifurcations and deltas [130].

In general, 97.21% of mandibular first premolars have an oval single root, with a low occurrence of two-rooted forms (2.63%) [131]. Most of these teeth have simple canal configuration (type I) (**Figure 12A**). However, there is a surprisingly high prevalence (24.2%) of mandibular first premolars with two or more canals [132], predominantly found in the apical third [133]. Geographic location, ethnicity, race and gender influence the presence of complex root canal morphology in these teeth [131]. The prevalence of two-rooted and two-canal variants of the first premolar has a higher incidence among Indian (50%), Middle Eastern (40%), and Hispanic populations (30%) [131]. Besides morphological variations such as two-rooted and two-canal variants, another feature, called the C-shaped canal, has been observed in

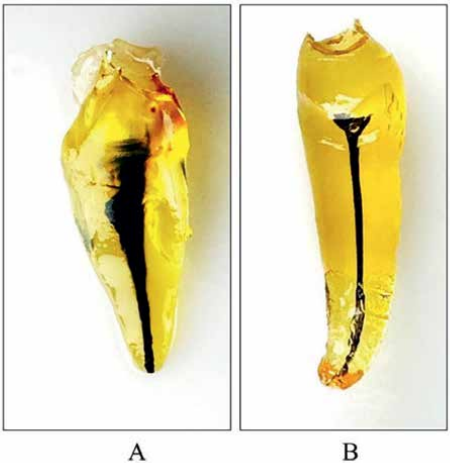

Figure 12.
Mandibular premolars with single root canal: (A) the first premolar; (B) the second premolar.

mandibular first premolars. The prevalence of C-shaped canals varies across different populations, ranging from 10.7% to 18%, with Chinese individuals (24%) having the highest incidence [134].

Understanding complex root canal configurations begins with clinical and radiographic evaluations. A sudden change in the radiographic density of the root canal, or a change in the appearance of the periodontal ligament, indicates the presence of the second canal [130]. A radiological feature of complex internal anatomy is that the cervical portion of the root appears wider than average, with little or no taper [135].

In cases where an additional canal is considered, it is recommended to modify the shape of the access cavity to an oval, wider buccolingually [130]. The pulp chamber's floor is typically located at the enamel-cement junction. However, in the complex canal form, the floor of the pulp chamber is not clinically visible [132]. The buccal canal typically forms a straight line, whereas the lingual canal splits at a sharp angle, resembling a lowercase "h," approximately halfway through the root [130]. Due to this configuration, the wider buccal canal is generally easier to scout and allows for more straightforward linear instrumentation.

A barrier during the initial insertion of scouting files indicates canal division [135]. To detect two canals and bifurcation of the main canal, using a #10K hand file is most helpful [132]. For further instrumentation, straight line access to all canals can be obtained with the dentinal shelf removal using the aid of a Gate-Glidden set of burs at a maximum speed of 1000 rpm [135]. After coronal flaring, repeating of tactile locating of the canals with a precurved #10K file are used [136].

The first mandibular premolars may show an external anatomical feature in the form of radicular developmental grooves, usually located on the proximal mesiolingual portion of the middle root [134]. The groove might indicate the presence of a complex root canal system, such as canal splitting and C-shaped canals [134, 136]. Additionally, excessive dentin removal may result in iatrogenic strip perforation during instrumentation or preparation for a post [130]. Therefore, it is important to use conservative shaping techniques with small instruments and copious irrigation [137].

Key point: In a quarter of cases, there are two canals in one root in the mandibular first premolar. The lingual canal is the one most often overlooked. The preoperative

CBCT scan is the most effective imaging tool for evaluating complex canal anatomy and cases of prior unsuccessful endodontic treatment.

3.5 Mandibular second premolar

The root canal morphology of the second mandibular premolar resembles that of the first premolar. It is commonly described as having a single root and a single canal system (**Figure 12B**) [138]. The single root is typically oval-shaped, with an oval cross-section canal that runs all the way through to the apex [139]. The presence of an extra root, three or more canals, or the C-shaped canal anatomy in mandibular second premolars has been rarely reported [131]. The additional lingual root canal, has a worldwide incidence of 5.3%, with the lowest proportions found among Asians and the highest (>6%) in Europeans and Africans [140].

The endodontic treatment of the second mandibular premolar is less demanding than the adjacent premolar, since the incidence of complex morphology is much less common. It is necessary to carefully assess the pulp chamber floor and integrate radiographic and clinical findings for the eventual aberrant morphology of the root canal.

Compared to other teeth in the lower jaw, the second lower premolar exhibits the closest proximity of its root apex to the mental foramen [141]. On the preoperative radiograph, the clinician can perceive the mental foramen as a periapical pathological process. Therefore, an additional image is needed under different angulations (cone-shift technique) to ascertain the mental foramen relationship with the apex of the tooth. In cases where the mental foramen is in close proximity to the root apex, extra caution is needed to prevent damage to the inferior alveolar nerve. This includes careful confirmation of the working length, as well as irrigation and root canal obturation [141].

Key point: Simple root canal morphology may be responsible for the lower endodontic failure rate of the mandibular second premolar compared to the first premolar.

3.6 Mandibular first molar

The first permanent tooth to erupt is the mandibular first molar. As a result, it is one of the teeth most commonly affected by caries and the most frequently endodontically treated [142].

The mandibular first molar typically has two distinct roots (mesial and distal) and three (61.3%) (**Figure 13A**) to four (35.7%) root canals [143]. A third root could be the radix entomolaris (an extra distolingual root and canal) or the radix paramolaris (an extra mesiobuccal root and canal). This is one of the possible anatomical variations in the internal anatomy. Additionally, an enlarged pulp chamber (taurodontism), C-shaped canal morphology, and canal configurations with 1–7 canals may be present. Apart from variations, endodontic therapy can be complicated by irregular shapes, intra-canal communications, and root canal curvatures that are not visible on radiography [144]. The existence of an additional, third root (in 13%) has been genetically linked to Mongoloid and Chinese populations, Native Americans, and Inuits [144], occurring three times more frequently than in Caucasians and African Americans [143].

The number of canals determines whether the rectangular or trapezoid access cavity is more appropriate for canal access. The initial access is made in the mesial half of the tooth crown. In the mandibular molar with an accessory root, the conventional access cavity should be extended toward the distolingual canal to achieve straight-line access [144]. A close examination of the pulpal floor will reveal the canal entrances

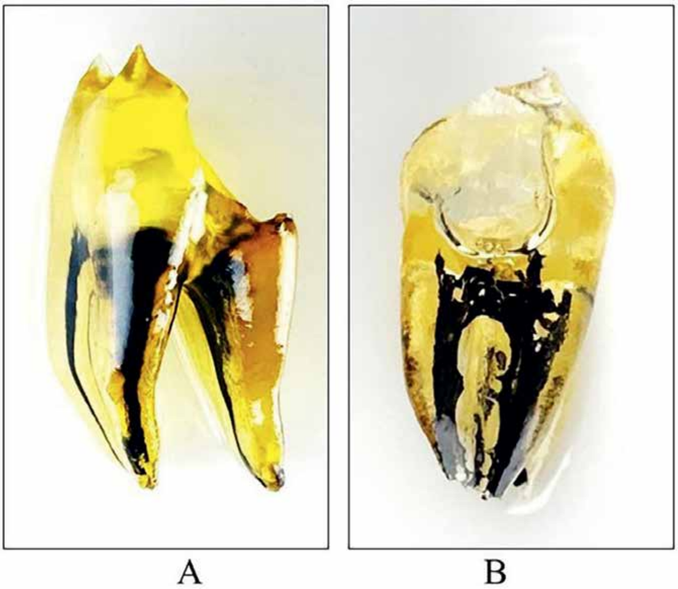

Figure 13.
Mandibular molars: (A) first molar has two distinct roots (mesial and distal) and three canals; (B) mesial root of mandibular second molar with type IV root canals.

after tracking slight color changes in the form of dark developmental lines. To achieve straight-line access, it is essential to refine mesial wall flare.

The distal root is straight, with a single wide, oval canal, or two round canals in the cross-section [143]. Because of its large diameter, the instrumentation does not pose a challenge, particularly in the three-canal molar form. Type I (62.7%) is the most common configuration in the distal root, with type II (14.5%) and type IV (12.4%) appearing less frequently [144]. The most apical 1–2 mm of this canal can curve up to 90 degrees distally; however, this is rarely a clinical issue [145]. To effectively clean the apical portion of the distal canals, at least a #40 file size should be used [142].

Regarding shape and cross-sectional dimensions along the roots, mesial root canals significantly differ from distal [142]. The mesial root is kidney-shaped in a buccolingual direction and contains two root canals. Ribbon-shaped outlines of the root canals in the coronal third were always present. Type IV with mesiobuccal-MB and mesiolingual-ML distinct canals (52.3%), followed by type II (35%), are the most frequent configurations [144]. Intercanal communications and isthmuses are often present in the mesial root (69.6%), mostly in the apical third (44.3%) [146]. Large canals with wide anastomoses are common in young patients, but the frequency decreases after 40 years [144]. The mesial root has mesiodistal curvature [147] that begins right below the canal orifice, then progresses distally along the root canal [145], and is most pronounced in the apical area [148]. In 30% of cases, the canals in the proximal view displayed a secondary curvature in the apical portion [149]. The MB canal exhibit a greater curvature than the ML canal [148]. Because of the off-center position of the mesial canals and the irregular shape of the root, the dentin thickness variesat different levels and in various directions [150]. The thinnest area of dentine, called the "danger" or "risk" zone, is located on the distal wall of the mesial root toward the middle third and below the furcation. However, some researchers have suggested that the danger zone might extend along the furcal aspect of the entire mesial root [142] or anywhere along the furcal aspect of both roots [148]. Caution during instrumentation of the curved mesial canals is necessary, especially at the apical third, to avoid file fracture or iatrogenic canal errors [148]. Coronal flaring [149] could improve access to the apical curve by reducing the cervical curvature [151]. However, the danger zone dictates a restriction on coronal preflaring [152]. The narrow mesiodistal dimension of the mesial root may pose the risk of strip perforations and vertical root fracture under functional loads [153]. Therefore, the dentine thickness of the roots should be preoperatively assessed and appropriate instrument selected. It is advisable to use flexible nickel-titanium (NiTi) rotary instruments with anti-curvature motion against the outer walls [148] to maintain instrumentation centered in the main canal. The best option is to use highly flexible CM-wire-based NiTi instruments due to their conservative preparations, particularly in the cervical section of the canal [151]. High-taper NiTi instruments should be used with caution in the "danger zone" [153], as well as non-flexible instruments due to the risk of root canal transportation [151].

The additional third canal, known as the middle mesial canal (MMC), can occasionally be found in the mesial root of the mandibular molars (1–15%) [145]. This canal is three times more likely to be present in the first molar compared to the second molar [146]. MMC is more easily found in younger patients [145] due to the continuous deposition of secondary dentin and the consequent narrowing of the canal with aging [147].

The difficulty in the instrumentation and disinfection of inaccessible isthmi imposes the need to apply irrigation activation systems during endodontic treatment [143]. It is possible to remove hard tissue debris from the complicated mesial root canal system of mandibular molars using ultrasonically activated irrigation [152]. According to research, for a complete cleaning of the apical portion of the mesial canals, the master apical file in the mesial root canals should be at least an ISO #30. In cases where retrograde endodontic treatment is unsuccessful, a 3.0-mm root-end resection of the mesial and distal roots will remove the bulk of the lateral canals and apical ramifications [142].

Key point: The mesial root of the mandibular first molar is indeed complex, exhibiting several anatomical variations that can complicate endodontic treatment. Flexible NiTi instruments and advanced irrigation methods, such as ultrasonically activated irrigation, can help adequately clean and shape these complex root canal systems.

3.7 Mandibular second molar

The morphology of the mandibular second molar closely resembles that of the first molar, although slightly smaller. There are three distinct external configurations that may be present: two-rooted, C-shaped, and fused-rooted [154], and, as a rare occurrence, an additional, third distolingual root with a separate canal orifice and apex [155].

In the mesial root, two canals were found in 70.4% of cases (type IV) (**Figure 13B**), followed by a single canal in 11.5% of cases. On the other hand, the distal root most commonly presented with a single canal (type I) in 77% of cases [155]. Additionally, researchers have documented a wide variety of canal configurations in the mandibular second molars, including 1–5 canals [155], a C-shaped canal, taurodontism, and a single root with one canal [156]. Overall, the Chinese population showed the most differences, with over 20% of the population falling outside the Vertucci root canal categorization [155].

Fused roots are a common variation in the external morphology of these teeth, with a higher incidence in the mandibular second molar compared to the mandibular first molar. When a single root is present, a shallow or deep radicular groove can be found, in either or in both the buccal and lingual sections of the root [154]. The single-rooted mandibular second molar is more frequent in Asians (55.4%) than in white people (14.3%) [157]. The high prevalence (up to 46.5%) of single-root configurations was characteristic of mandibular second molars in Chinese, Taiwanese, and Korean populations [158]. In the fused root, depending on the depth of the radicular groove, a single wide canal can be present in a low prevalence rate (up to 4.3%) [156] or two root canals that may or may not connect. However, a C-shaped canal is a frequent variant in some fused teeth [155, 159], with a notably higher occurrence among the Asian group (43.3%), compared to the white group [157]. The prevalence of a third root was lower than in the first molars, with 0.8% and 2.6%, respectively, in the Asian and white groups [157].

Compared to the first molars, the volume of the pulp chamber and the entrances to the canals are smaller [159]. The access cavity and coronal flaring should be created following the same guidelines used for the first molar. Over 50% of mandibular second molars have root apices within <1 mm of the inferior alveolar nerve (IAN), and overinstrumentation, extrusion of irrigants, or overfilling during endodontic treatment may cause injury to the inferior alveolar nerve and persistent altered sensation [160].

In preoperative case analysis, a CBCT proved beneficial not only for the study of root canal anatomy, providing accurate information on the buccolingual dimension [156], but also for identifying the precise position of the root apex or apices when a close relationship with the inferior alveolar nerve (IAN) is suspected [160]. Apical surgery on the mandibular second molar often presents the highest number of surgical challenges due to its limited accessibility, the thickness of the alveolar bone, and the potential risk of nerve bundle damage [154].

Key point: The second mandibular molar is more likely to have one canal in the distal root than the first molar.

3.8 Endodontic considerations regarding third molars

Third molars are the most commonly impacted teeth [161], and surgical extraction of these teeth is among the most frequently performed procedures in oral surgery [162]. More than 40% of adult patients still have at least one non-impacted third molar [163] and may require endodontic treatment due to challenges in maintaining proper oral hygiene. A clinician's level of competence and professional background are very important factors in deciding whether to perform endodontic treatment or extraction. Endodontic therapy for properly positioned wisdom teeth is a viable option to preserve natural tooth structures and maintain vertical bone proportions. It should be considered, especially if the permanent first and second molars are lost prematurely. In different systemic disorders, advanced age, and the potential risk of bisphosphonate-related jaw osteonecrosis, root canal treatment should be given preference over surgery.

Maxillary third molars appeared in various root morphologies. Most of them have three roots [164–166] (**Figure 14A–C**), except in the Turkish population, where single-rooted maxillary third molars were identified as the most frequent [167]. Three-rooted maxillary third molars frequently have fused roots, and type VIII is the most prevalent type in this root form [164, 165, 168]. The mesio-buccal roots of maxillary third molars display variations due to the presence of a second canal (MB2), while the palatal and distal roots typically have simple canal morphology [169].

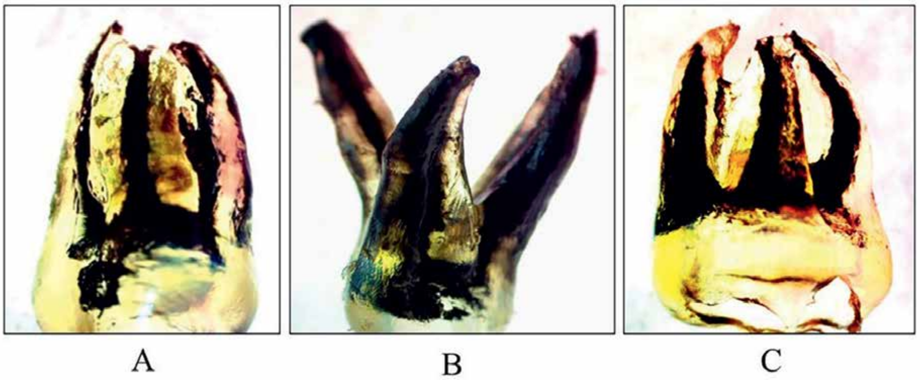

Figure 14.
Different root morphologies of maxillary third molars; (A) three roots, all fused; (B) three roots, all separate; (C) three roots, buccodistal and palatal fused.

Studies on root and canal morphology in various populations revealed that mandibular third molars had two separate roots [165, 170–173]. Single-rooted variants, on the other hand, were more common among the Brazilian [170] and Croatian populations [165]. Types I and IV were the most prevalent in mesial roots and type I in distal roots [165, 172–174].

Before performing endodontic therapy, it is necessary to do a thorough radiographic examination to assess the structure of the root and canal, as well as the positioning of third molars with the surrounding tissue. If the maxillary second molar is absent, the roots of the maxillary third molars may become exposed to the sinus. Mandibular third molar roots, on the other hand, might be located in close proximity of the mandibular canal. Third molars typically incline either mesially or distally, and it is important to align the access cavity preparation with the tooth's longitudinal axis to prevent accidental perforations. Since the overall length of third molars decreases from first to third molars, it is recommended to use a short endodontic file (21 mm) and a contra-angled handpiece with a small head to overcome difficulties in accessibility [169].

Previous research has demonstrated that the root canal morphology of third molars is unpredictable [174] and that extra roots or canals are more common in third molars [175].

Key point: Root canal treatment of third molars should be considered if the benefits exceed the potential risks.

4. Conclusion

Endodontic challenges arising from root canal morphology highlight the complexity of achieving successful outcomes in endodontic therapy. The variability and intricacies of the root canal system require a meticulous and informed approach to treatment. Technological progress has significantly improved endodontic diagnostics and therapy for teeth with complex morphology, reducing procedural errors. Despite that, the skill and expertise of the clinician remain crucial in navigating and addressing the diverse morphological challenges encountered. Every tooth can present a challenge for endodontic treatment. Knowledge of the morphological variations of the root canal system, as well as clinical guidelines for their diagnosis and therapy, is critical to a positive outcome of endodontic therapy. Ultimately, a comprehensive understanding of root canal morphology, combined with the application of advanced techniques and tools, is essential for improving the predictability and success of endodontic treatments.

Conflict of interest

The authors declare no conflict of interest.

Notes/thanks/other declarations

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Apart from **Figures 1**–**5**, all figures in this chapter are courtesy of the authors.

Figures 6–**8** and **10**–**14** show tooth samples that were prepared using a canal staining and clearing procedure.

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Chapter 5

Additive Manufacturing in Operative and Restorative Dentistry Techniques, Clinical Applications, and Future Outlooks

Naghmeh Golriz and Navid Hosseinabadi

Abstract

The focus of operative dentistry lies on treatment of defects with full coverage restorations, which is gradually changing from using CAD/CAM to additive manufacturing (AM) or additive layer manufacturing (ALM) technologies. The advantages are credited to decrease in material waste, unlimited geometric reproducibility, decrease of microcracks in the restoration, lower costs, reduced treatment delays, and custom-made and personalized treatment. AM includes digitally controlled three-dimensional layer depositing toward near-net-shape (NNS) restorations. The virtual restoration design transforms to solid high-quality temporary crowns and bridges with complex geometries, utilizing powder-based precursors, that is, powder mixtures, slurries, and pastes. The routes include layer-wise slurry deposition (LSD) such as stereolithography by custom VAT photo-polymerization using photo-sensitive materials under radiation. The reliability of AM is accredited to high accuracy of 3D-printing through measure of dimensional difference between actual object and printed part (Trueness); dimensional reproducibility and repeatability associated (Precision); and smallest reproducible details (Resolution or anatomical details). Among process and materials, VPP (81%) and zirconia (66%) are among the most commonly used processes and materials in additive manufacturing, with crowns (42%) leading in dental restoration applications, followed by implants and abutments (29%), bridges (17%), and veneers (14%) in applications have most distributions in additive manufacturing of dental restoration.

Keywords: dental restorative prostheses, operative and restorative, additive manufacturing, 3D-printing, clinical applications, durability and reliability

1. Introduction: Dental prosthesis manufacturing process

Dental prosthesis, as intraoral prosthesis; essential for restoring function and esthetics in patients, are categorized into three major types: fixed dental prostheses, removable dental prostheses, and implants. Common applications include crowns, veneers, bridges, dentures, implants, and complete or partial fixed/removable prosthetics (See **Figure 1**). With the increasing number of edentulous patients worldwide, it is estimated that 15–16% of the $55 billion dental restoration market will be dedicated to prostheses, driven by growing demand for implants, abutments, crowns, and bridges, according to Straumann implant supplier (the world-leading brand for confidence in aesthetic dentistry) [1]. The success of these device hinges on the precision and quality of their manufacturing, as these factors influence critical aspects such as functionality, comfort, esthetics, and overall patient satisfaction [2].

Alongside these concerns, mechanical stability (strength and wear resistance), chemical inertness (against hostile environment), biocompatibility, durability (aging), and esthetic compatibility should be addressed in prosthetic manufacturing. Prepared parts can be used in extracoronal or intracoronal treatments with detailed attention to coronal and radicular aggregations.

Different types of dental restorations include composite material custom fillings (Inlays), large covering composite material custom fillings (Onlays) [3], entire tooth surface covering parts (porcelain or ceramic Crown/Caps), attached missing teeth replacement in one or more combinations (Bridges), and removable or partial dentures. Crowns and bridges are the main developed prosthesis in operative dentistry to treat important cases of primary trauma, hypoplastic conditions, tooth wear, and badly broken-down teeth; besides improvement cases such as altering teeth shape/size/inclination, altering occlusion, and appearance. In restorative dentistry, ceramics are the most commonly used materials for crowns and bridges, as they closely mimic natural tooth enamel and dentin. These materials exhibit a hierarchical structure, with properties like hardness, elastic modulus, and translucency varying according to thickness. Traditionally, dental prostheses have been produced through subtractive manufacturing (SM), a process that shapes solid blocks of material by cutting, drilling, or grinding [4]. However, SM has its limitations, including raw material waste, tool wear, and the potential for microcracks, making it less suitable for complex geometries or intricate restorations. This has driven researchers toward exploring

Figure 1.
Dental parts: Areas for application of modern manufacturing methods.

Additive Manufacturing (AM), or 3D printing, which offers a more efficient, customizable, and precise method for creating dental restorations. AM enables the production of complex geometries and intricate designs while minimizing material waste and overcoming many of the limitations associated with SM. As this technology advances, AM has the potential to revolutionize dental care by allowing the creation of restorations with enhanced accuracy, personalization, and material properties, making it a cutting-edge solution for modern prosthesis manufacturing. Looking at a typical SM process, shows the complicated routes for prostheses (a partial framework) fabrication consisting of stages:

- Teeth impression
- Mold manufacturing
- Planning and designing
- Duplicating
- Wax-up creation
- Investment modeling
- Investing the cast
- Melting and casting the partial framework
- De-flasking
- Sandblasting
- Fitting with additional soldering and spot welding if needed
- Polishing

which all steps need specific expertise, tooling, and equipment, which adds up in the cost per part calculation. The processes can be either performed manually or driven by computer numerical control (CNC) with a virtual model designed in Computer-aided design (CAD) software with computer-aided manufacturing (CAM) as input for the fabrication tool [5]. Software simulations are often combined with technician input to indicate the toolpaths of guided cutting tools through part geometry [6]. Through this information, the machine determines how to make necessary cuts, channels, holes, and any other features that require material removal, taking into account the speed of the cutting tool and the feed rate of the material. Basic milling/drilling/diamond disk grinding methods are aided with a combination of more sophisticated routes like laser beam ablation (the thermal or nonthermal process of removing atoms from a solid by irradiating it with an intense continuous wave (CW) or pulsed laser beam), high-frequency vibrations/abrasions, mirror machining using pre-shaped tools with high-frequency mechanical ultrasonic motion (UM). The fabrication of temporary teeth restorations requires multiple processes of molding, curing, and post-finishing, where extensive expertise of dentists is essential. Also, handmade temporary restorations are usually unable to fit the patient's teeth precisely due to the limited formability of dental materials.

Most temporary restorations need further trimming with several iterations in the patient's mouth before cementation. The CAD/CAM systems provide their service *via* three functional components (i) scanning the prepared area either intraorally or extraorally and gathering data about the pertinent region, (ii) planning and developing the restoration in three dimensions on a computer through CAD component, and (iii) manufacturing the virtually prepared restoration. For successfully achieving a final restoration, only 90% of the building blocks are commonly used and 10% is wasted with a small chance for recycling. The trueness of the parts can be calculated with the root-to-mean square (RMS) values between the original model (digital) and manufactured prostheses.

The limitations of SM of dental restoration besides raw materials waste, including high milling tool wear; fine shape formation limitations; and high possibility milling microcracks; have led researchers toward more advanced manufacturing methods. As the most obvious choice, Additive manufacturing (AM) has shown a huge opportunity for manufacturing ceramic restorations with comparable accuracy and mechanical properties to that of SM. One must bear in mind that (i) the high softening temperature, (ii) lack of ductility and brittle nature, and (iii) limited applicable classes have made AM restoration ceramics with high-surface-finish difficult to additively manufacture *via* direct fusion/melting or direct shaping/forming methods. Developing reliable and clinical AM restorations require a comprehensive understanding of important functional parameters of AM technologies for identifying potentials and limitations, and as the most important approach; combining manufacturing methods. These details are discussed in this chapter, starting from introducing widespread categories toward methods more suitable for dental ceramics restorations.

2. Additive manufacturing: A futuristic dental care

Additive manufacturing[1], otherwise commonly known by the moniker of 3D-printing (digital advanced production)[2] [7]; is the industrial production of a computer-controlled process that creates three-dimensional objects by depositing materials, usually in layers (laying successive layers of material on top of each other) [8]. **Figure 2** shows some of additive-manufactured dental parts. This approach focuses on the ALM process that opposes subtractive manufacturing, in which a 3D object is created by cutting away layers of a solid block of material until the final product is completed [9]. Using computer-aided design or 3D object scanning (photogrammetry), additive manufacturing facilitates the creation of objects with precise geometric shapes toward end-use parts. Interface software translates the CAD design into a layer-by-layer framework (2D-plane) for the additive manufacturing machine (*via* slicer modules) and begins creating the object directly. Simultaneous moving on the x, y, and z axes to deposit alternating layers speeds up the manufacturing process of creating 3D objects. Although, the manufacturing period can take several hours to several days, depending

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[1] The American Society for Testing and Materials describes additive manufacturing as "the process of combining materials by layering (adding layer upon layer) to produce objects from computer data of a 3D model, in contrast to subtractive manufacturing methods."

[2] Or rapid prototyping or solid free-forming.

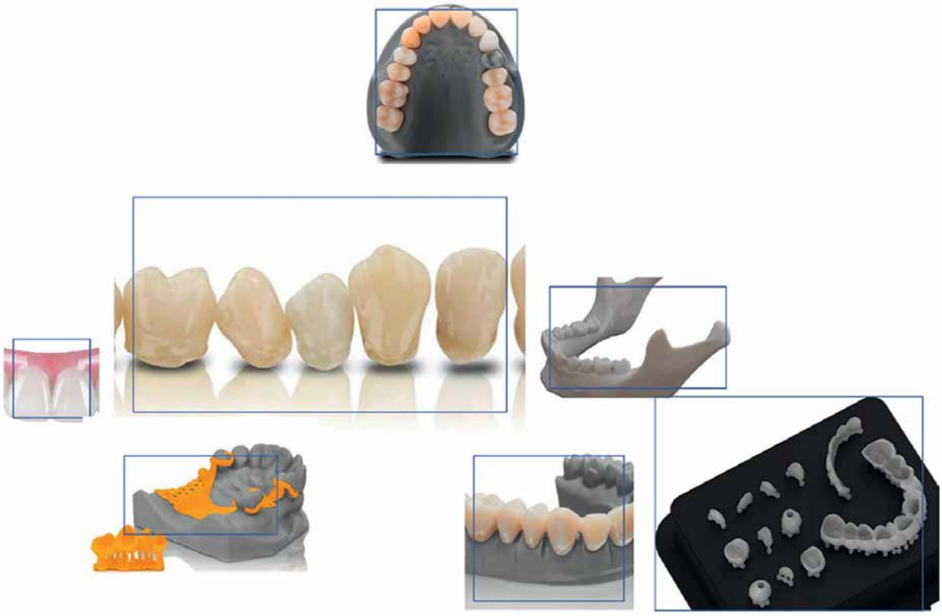

Figure 2.
Some examples of additive-manufactured dental parts.

on the object's size [10]. Overall, *via* additive manufacturing, much of the supply chain's intermediate steps can be removed and localized manufacturing can replace long and costly supply chains[3]. Additive manufacturing makes it possible to create objects with functionally graded materials (innovative materials i.e., ceramics and composite alongside metals and polymers), custom-made specifications versus general properties (customization and personalization) [11], and achieving complex and intricate geometries (such as prosthesis and implants) [12]. These processes can be used to add material to existing components, for repairs, or occasionally to build new parts.

Through constantly developing AM methods by leading universities (MIT, Cornell, Johns Hopkins, Harvard, University of North Carolina, University of Washington, ….) and R&D departments of machinery companies and startups (Ackuretta Denti, Asiga, Dentafab, Dentsply Sirona, EOS GmbH, FormLabs, HeyGears, Keyence, Phrozen, Reajet, Shining, SprintRay, Straumann, Stratasys, Uniz NBEE, Zortrax, and …), endless combinations of 3D-printing technologies are introduced. The applicable systems must fulfill USP Class VI and/or be compatible with ISO 10993 standards. Most of these technologies are based on the main manufacturing methods[4] of.

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[3] "Additive manufacturing provides a way to produce customized and personalized parts with a much more streamlined workflow than traditional manufacturing methods," Professor Hart (lead instructor of MIT - Additive Manufacturing for Innovative Design and Production).

[4] According to ASTM/ISO standardization (ISO/ASTM 52900:2021), AM technologies are categorized into seven main distinct classes of selective laser melting, selective laser sintering, fused deposition modeling, laminated object manufacturing, direct ink writing, and stereolithography (SL). Techniques use similar process to construct parts including printing successive two-dimensional (2D) layers of the starting material on top of each other until the entire 3D part is built.

- Binder Jetting (BJT)
- Material Jetting (MJ)
- Selective laser sintering (SLS)
- Directed Energy Deposition (DED)
- Directed Energy Deposition-Arc (DED-arc)
- DMSL/SLM systems + DMLS/SLM
- Sheet Lamination (SHL)
- Fused deposition modeling
- Powder Bed Fusion (PBF)
- Material Extrusion (MEX)
- VAT Photo Polymerization (VPP)

Selective laser sintering (SLS), as a popular AM technique; consists of sintering thin layers of powdered materials spread over a platform of a printing bed using a laser power source. The SLS fabricates the 3D structures in a layer-by-layer sequence using a CAD model. The thin powder layers should be spread over a platform using a leveling roller (doctor blade) and be selectively sintered by a controlled scanning laser beam (CO_2 laser). The fabrication bed can be dropped down up to the thickness of an additional layer to be built. The process is repeated until the structure with the desired geometry is manufactured.

The fastest additive manufacturing process for the production of functional and highly dense precision parts is *Binder jetting (BJT), or binder jet 3D printing*. This process (also known as inkjet) uses powder materials precursors such as metals, composites, and ceramics. Raw materials should be spread to create a fine powder uniform bed similar to selective laser sintering (SLS). Binder jetting utilizes an industrial printhead to selectively deposit a liquid binding agent onto the powder bed to form successive layers of powder across the build platform. Printhead travels over the bed and selectively releases droplets of binding agent (from natural water/sugar solutions to furan binder, phenolic binder, silicate binder, and aqueous glues) to bond the powder particles together [13]. As binder drops are around 80 μm in diameter (less than the typical diameter of hair), it creates good resolution. Similarly, layers of material are built up based on a CAD file until the desired layer thickness is reached and the final 3D object is complete. Once formed, the green parts need to be cured (polymers like ABS or PLA) or sintered (ceramics and metals (titanium, stainless steel, and copper)) to finalize the part. Through its simplicity, binder jetting can be a cost-effective and low-energy consuming (lack of a laser) method for fabricating parts. The main disadvantage of the process relies on the necessary post-processing step to finish the part, heat treating (sintering for metals and ceramics), infiltrating with a metal melt[5] (for metals) [14], and final finish spraying and curing (for polymers). Powder bed thickness around 100 μm for translucent parts, 100 μm and higher for metallic parts [15], and 100–200 μm for heavy-duty strong yet light parts generally creating durable parts. As the process occurs at room temperature, the distortion of parts associated with thermal effects is minimal. Consequently, the build volumes of parts are among the largest of 3D-printing technologies. Dimension ranges from $2500 \times 1500 \times 1000\ mm^3$ to $50 \times 30 \times 20\ mm^3$ are currently in service. While the powder bed acts as part support, printed parts do not require additional support or the need for removing base supports (powder easily removed by compressed air). Special applications such as dental prosthesis (with internal channels and geometries that are difficult to post-process) require low surface roughness (as low as Ra 2 μm) which can be achieved in binder injecting methods. The main concerns of the process lay on unpredictable accuracy and tolerance related to part shrinkage during post-processing steps, both uniform and nonuniform shrinkage with residual porosity. For instance, 2–3 vol.% shrinkage in metal parts during infiltration, 20–25 vol.% shrinkage in metal parts during sintering, 30–35 vol.% shrinkage in ceramic parts during sintering, and 2–5 vol.% shrinkage in polymer parts during curing of thermosetting resins can be compensated in process design. The residual porosities can be estimated up to 10 vol.% in infiltrated metallic parts, 3–5 vol.% in sintered metallic parts, 2–7 vol.% in sintered ceramic parts, and 1–5 vol.% in cured polymeric parts. Process subcategories may include direct inkjet printing (DIP) and NPJ (nanoparticle jetting).

Material jetting (MJ) manufactures parts similar to two-dimensional inkjet printers. Material is jetted onto a build platform (tray) using either a continuous or Drop on Demand (DOD) approach. After droplets are solidified, the part can be built layer by layer. Normally, the material should be deposited from a nozzle that moves horizontally across the build platform. The injected material layers are cured or hardened using ultraviolet (UV) light [16]. As precursor materials must be deposited in droplets, the available materials are limited to polymers and waxes (due to their viscous nature and ability to form drops) which makes the process suitable for interim dental restorations, smooth and accurate dental and orthodontic models alongside models, surgical guides, and gingiva masks.

Replacing energy sources from UV and laser to plasma arc, focused laser, and electron beam has developed the *Directed Energy Deposition (DED)* 3D printing method. It uses the focused energy source to melt precursor material and simultaneously deposit it through a nozzle [17]. Based on the energy source, methods including Laser Engineered Net Shaping (LENS), Direct Metal Deposition (DMD), Electron Beam Additive Manufacturing (EBAM), Directed Light Fabrication, and 3D Laser Cladding are introduced. The CAD-3D model must be sliced into layers *via* software to create the required layers of the finished workpiece. The deposition of melted material (mostly metals, polymers, or even ceramics) onto a specified tray surface, solidifying, and fusing materials together to form a structure are the necessary stages. The nozzle that is mounted on a multi-axis arm can move in multiple XYZ directions which allows for variable deposition. Typically, the part is in a fixed position while

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[5] A one-step process for making high density composites based on pressure-less, capillary-driven permeation of a molten liquid into porous bodies.

the arm moves to lay precursors. In more developed systems, movements are reversed with the use of a platform that changes position with the stationary arm. The process should be performed within a controlled chamber and reduced oxygen levels, inert shielding gas atmosphere, or vacuum. The heat source melts powder mixture or wire as deposition occurs onto the surface. The powder precursors provide more accuracy in deposition and wires guarantee more efficiency. Layer thicknesses are usually 250–500 μm *via* instant cooling of 1000–5000°C per second. The applications of DED can be categorized as (i) near-net-shape[6] parts, (ii) feature additions, and (iii) repair. Dental metal precursors can include aluminum (dental implants), Inconel (endodontic instruments), niobium (denture bases, dental implants, orthodontic appliances) [18], stainless steel (orthodontic appliances), tantalum (trabecular for endosseous implants) [19], titanium and titanium alloys (prosthetic joints, surgical splints, stents and fasteners, dental implants, dental crowns and partial denture frameworks) [20], and tungsten (focal spot for X-ray). The ability to control the grain structure with the balance between accuracy and speed facilitates high-quality functional parts manufacturing and even repair *via* DED. Furthermore, the process allows for the creation of parts with composition gradients or hybrid structures with multiple precursor materials and differing compositions. The 3D-print onto existing parts and adding additional features to existing parts are other advantages of the process. Wire Arc Additive Manufacturing (also known as Directed Energy Deposition-Arc (DED-arc)) uses arc welding power sources and manipulators to build 3D shapes through arc deposition with wire as a precursor source and a predetermined path to create the desired shape *via* using robotic welding equipment.

Similar to DED, the *Powder bed fusion (PBF)* process begins with the creation of a 3D-CAD model, numerically sliced into several discrete layers. The heat source (e.g., laser) scan path (raster pattern) in each layer should be calculated which defines both the boundary contour and form of the fill sequence. Layers are sequentially bonded on top of each other through the spread of powdered precursor over the formerly joined layer. The manufacturing is discrete rather than continuous and each layer is fully consolidated to adjacent layers. The supplied powder material is spread uniformly over the powder bed build platform area (tray) *via* a roller or doctor blade. The 25 to 100 μm optimal thickness of powder layer spread is usually reported. The electron beam melting (EBM), selective laser melting (SLM), and even selective laser sintering (SLS) are considered as subcategorizes of PBF based on factors such as melting temperature, energy source, energy power, thermal conductivity, room conditions, temperature to be reached, layer thickness, structure orientation, and particles. The SLM technique is considered a variation of SLS with the main difference that SLM completely melts the powdered particles with the powerful CO_2 laser beam to create fully dense metallic models with roughness Ra:12–16 μm. The EBM method produces an object by melting a metal layer by layer using electron beams in a high vacuum chamber or inert gas (typically helium). EBM is suitable to process brittle materials which generally cannot be processed by SLM. Metallic dental restorations, dental implants, orthodontic appliances, and surgical appliances can be manufactured *via* PBF methods. Polymeric dental parts such as polyetherketoneketone (PEKK) implants and prostheses are usefully manufactured by this method [21].

Sheet lamination (SHL) as an AM process can be used for producing multilayered mouthguards. Laminated object manufacturing (LOM) and ultrasonic additive

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[6] Raw restoration part that is very close to its final desired shape or dimensions.

manufacturing (UAM) are the main categories of the SL method. Process involves super-positioning several layers of material composed of foil to manufacture an object shaped *via* cutting of laser ablation. As laminated object manufacturing is suited for creating items with visual or esthetic appeal, it can be useful in dental parts. UAM uses ultrasonic welding to join thin sheets with a low energy consumption at low temperatures. UAM has been used for various metals including aluminum, stainless steel, and titanium. Precursor materials such as metals and even cellulose with thermoplastics and fibers can be used to directly manufacture functional and lightweight technical components.

Material extrusion as an AM technique deposits a continuous filament of composite or thermoplastic material to build 3D parts layer by layer. The filament is commonly fed from a spool through a heated extruding nozzle which heats the material and deposits it onto a build platform. This process is convenient for rapid prototyping and molding. The injected deposits create the first cross-sectional layer of the final object and further layers are added to each layer *via* fusing as a result of temperature control or through the use of chemical agents. The process is capable of creating a printing tolerance of +/− 120 μm (+/− 0.005″), which is perfect for dental applications. The extrusion head is continuously in motion to prevent the deposit from bumping up. While the process is relatively fast and compatible, delamination and other temperature fluctuation-related problems and the need for additional support limit the process.

Fused deposition modeling employs the method of forming layers with melted thermoplastic filaments. FDM creates three-dimensional parts directly from three-dimensional 3D-CAD by layer-by-layer deposition of thermoplastics, extruded by a temperature-controlled nozzle [22]. FDM is also known as fused filament fabrication (FFF) where a thermoplastic filament is fed to a heated nozzle in the FFF process [23]. Fused deposition of ceramics (FDC) defines a modified FDM technique in which ceramic powder is loaded with hot extruded thermoplastics filaments [24]. The melted material is deposited as the nozzle travels the raster layer by layer in the x and y axes along the developing z-axis. Typically, wax, metals, and ceramics are the main precursors of this technique. Dental products include surgical guides for implant insertion. Most commonly used precursors are acrylonitrile-butadienestyrene copolymers (ABS), polycarbonates (PC), polyethylene terephthalate glycol (PETG), water-soluble materials for support structures like polyvinyl alcohol (PVA), and polyphenylsulfone (PPSU). Surgical guides for oral implant insertion and bone-like models can be made from biocompatible filaments of polyamide-polyolefin and cellulose (PAPC). The polyetherketons like PEEK can be used with FFF printers for use in craniomaxillofacial implant manufacturing.

Simpler methods such as Inkjet Printers, Thermal inkjet printing, Inkjet-based lithography, and Aerosol Jet Printers use the deposition of droplets as AM methods. In *Inkjet Printers* technique, manufacturing is carried out by selective deposition of droplets of photopolymer or thermoplastic materials. For instance, MultiJet Printing (MJP) is an inkjet printing process that uses piezo printhead technology to deposit either photocurable plastic resin or casting wax materials, layer-by-layer with fine feature details. These high-resolution printers use meltable or dissolvable support material to simplify post-processing. This also makes support removal virtually hands-free and allows even the most delicate features and complex internal cavities to be thoroughly cleaned without damage. *Thermal inkjet printing* refers to the spraying of liquid phase materials and/or inks consisting of material dissolved or dispersed in a fixed amount of solvent material in the chamber from the nozzle in the form of

Figure 3.
A schematic view of the typical 3D-printed anterior bridge.

droplets which depend on the pressure of air bubbles that form due to the increase in temperature. The piezoelectric effect can also be used to eliminate the need for a solvent. *Inkjet-based lithography*, also known as polyjet photo-polymerization or multijet modeling, combines the advantages of lithographic methods such as high resolution and good surface quality with the advantages of inkjet methods such as high production speed and large-volume object production. In this technique, photopolymerizing resin droplets are sprayed onto a platform by hundreds of nozzles, and the layer formed is polymerized with a UV light source. *Aerosol Jet Printers* use droplets of the material with a diameter not exceeding 1–5 μm range *via* are spraying with ultrasonic energy (1.6–2.4 MHz) or pneumatic atomization. A schematic view of the typical 3D-printed anterior bridge after printing on support, after support removal, and after final polishing retouches is shown in **Figure 3**.

From the applicant's point of view, choosing the proper technology requires close evaluation of Print Speed, Reliability, Ease of Use, Software and Cloud adaptability, Material Options, Investment Cost, and Washing-Cleansing mechanisms.

3. Additive manufacturing suitable for operative dentistry

"More and more dentists are using 3D-printed dentures or 3D-printed crowns or 3D-printed fixtures that aid in dental surgery," Professor Hart (lead instructor of MIT - Additive Manufacturing for Innovative Design and Production). This statement clearly declares the state of the art and current potential of AM in dental healthcare [25]. Similarly, dental health centers commonly use slogans like "3D Crowns Printed in 10 Minutes", "Single visit dental treatment", and "One-session restoration by custom-made 3D-printing". In addition to being used in 3D printing, additive fabrication, fast prototyping, rapid manufacturing, freeform manufacturing, layered manufacturing, and solid freeform fabrication basically focus on a similar subject in additive manufacturing technology as a common practice in dentistry today [26]. The main advantages of using AM for dental restorations may include (i) Customization and personalization (cost-effective mass customization as it does not require specific molds or tools); (ii) Improved performance (complex and intricate geometries that best align with the needs of the human body); (iii) Innovative materials (strong and lightweight materials developed exclusively for AM), (iv) Cost reduction (simplifying the supply chain to reduce overall costs associated with producing end-use products) [27].

These trends and advantages show additive manufacturing is becoming an increasingly important technique for the production of dental restorations and assistive devices. Since prosthetic manufacturing in operative dentistry often involves crowns and bridges, this section will focus on additive manufacturing techniques suitable for these applications. The *build materials* and *support materials* are the main types of materials that are typically deposited in an additive dental prosthesis manufacturing process. As explained, the support material is not a component of the finished prostheses and is required to support the build material placed in voids and overhangs. The most commonly used systems for these applications are based on *vat polymerization*.

Vat Polymerization uses a vat of liquid resin photopolymer to create an object layer by layer and creates 3D objects by selectively curing and hardening liquid resin through targeted light-activated polymerization whilst a platform moves the object being made downwards/upwards after each new layer is cured [28]. As the process is liquid-based, no structural support is available for the material during the build, and support structures often need to be added. Resins are cured using a process of photopolymerization or UV light [29]. Light is directed across the surface of the resin with motor-controlled mirrors on the raster of successive layers of resin. Generally, process stages include (i) lowering the build platform from the top of the resin vat downwards by the pre-defined layer thickness; (ii) UV light curing of the resin layer by layer; (iii) continuous downwards moving of the platform and additional layers building on top of the previous; (iv) moving blade between layers to provide a smooth resin base to build on the next layer; (v) the vat draining of resin and removing 3D object. The typical layer thickness for this process is 25–500 μm. Vat polymerization additive manufacturing technologies include.

- Stereolithography (SLA)
- Digital light processing (DLP)
- Continuous liquid interface production (CLIP)
- Multiphoton polymerization (MPP)

Stereolithography (SLA) is based on the concept of photopolymerization. Photopolymerization[7] is induced by UV or visible light to induce the rapid transformation of reactive monomers, oligomers, or liquid polymers into solid substances[8]. Producing geometric cross-sections imported into the software on a light-cured resin surface by means of a laser light source controlled by mirrors requires mixtures of multifunctional monomers and oligomers (photopolymerizable monomers like acrylates or/and epoxides successively exposed to laser irradiation) in order to achieve the desired physical properties. The platform tray moves down to the layer thickness chosen and the process is repeated until parts are built, ready for washing, removal of supports, and curing of parts. Widely considered as the "it" process, SLA fabricates high-quality dental parts with high resolution and smooth surface finish.

The stereolithography of ceramic and metallic materials consists of a UV-curable metallic/ceramic suspension prepared with a pre-polymer that acts as the binder

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[7] In many cases photopolymerization and stereolithography are considered equivalent. It is considered as the original resin 3D print method.

[8] The precursor is a photopolymer; a light-activated resin is a polymer that changes its properties when exposed to light, often in the ultraviolet or visible region of the electromagnetic spectrum.

material, a photoinitiator, precursor powders, and additives. Upon polymerization, the polymer bonds the particles conferring the necessary cohesion to the obtained metallic matrix. This matrix structure is then subjected to binder removal through an appropriate thermal treatment and sintering, which ensures the final properties of the model.

Mixing photopolymer vat with metals and ceramics leads to metallic and ceramic green parts. For instance, *Lithography-based Metal Manufacturing (LMM)* is a new technique developed by Incus® which uses a curing process based on stereolithography to build green metal parts with photopolymer. As described by the supplier, "The key to LMM is its feedstock: photopolymer resin filled with metal powder. Unlike most SLA resins that are liquid during the printing process, this material remains solid but spreadable within the 20°C build chamber. "It's a consistency like butter" [30].

Dental ceramics; an important part of systems designed with the purpose of producing dental prostheses such as Crown and bridge/ Implant and abutment/Veneer/ Inlay and onlay, are dental restorations that "cap" the visible portion of a damaged or weak tooth / "Replace" missing organs/ "Treat" worn out teeth/"Repair" a damaged tooth. Ceramic dental crowns include advantages like natural appearance, nonallergic, maximum patient comfort, and biocompatibility. Ceramics-wide application inoperative and restorative dentistry has created applications such as restoration, bridge holder, implant coverage, and filling. Solid Or Monolithic Zirconia (crown, bridge, implant, and veneer), High Translucent Zirconia (ATZ: alumina toughened zirconia, nY-TZP: n mol% yttria-stabilized tetragonal zirconia polycrystal), Lithium Disilicate (crown, bridge, veneer, and inlay), Leucite Reinforced Pressable Porcelain, Alumina (crowns, bridges, implants, and abutments), Glass-ceramics (Crowns, bridges, veneers, inlays, onlays), Glass-infiltrated alumina, Fluorapatite, with additives like ceria, yttria, magnesia, and alike are the main categories of restorative dental ceramics. Due to these factors, AM production of dental ceramic restorations has gained interest, a process commonly referred to as *ceramic stereolithography (CSL)*. CSL, as a precise and high-resolution additive manufacturing (AM) technique; is developed to fabricate complex ceramic parts [31], including zirconia/alumina dental crowns and bridges, implants, core material for fixed prostheses, and even alumina-based orthodontic brackets [32].

SLA can be categorized into two subcategorizes, based on the mechanism of applying UV light to the resin layer; *projection-based stereolithography (PSL)* and *scanning-based stereolithography (SSL)*. PSL method is developed for fast and high-resolution (15–25 μm per pixel) printing of small parts (temporary crown and bridge), while SSL is suitable for printing large parts with lower resolution. The main functional difference lies in the size of patterned curing laser light. The PSL one-stage route cures the entire layer by using a light mask through which a flood lamp illuminates the resin surface at once [33]. The light mask is dynamically generated by a digital micromirror device (DMD), which produces an image of each layer with ~45 μm resolution. SSL uses a dynamic mirror system to focus and direct the laser beam over the resin surface to polymerize a set of elementary volumes known as strands. Therefore, PSL requires less printing time due to single shot printing of each layer and longer printing time is required for laser scan curing of each layer in the SSL method. The schematic irradiation process in PSL and SSL is shown in **Figure 4**.

Mask-Image-Projection-based Stereolithography (MIP-SL) processes such as *temperature-controlled mask image projection-based stereolithography (TCMIP-SL)* are introduced for manufacturing of plastic (acrylic resins) temporary restorations

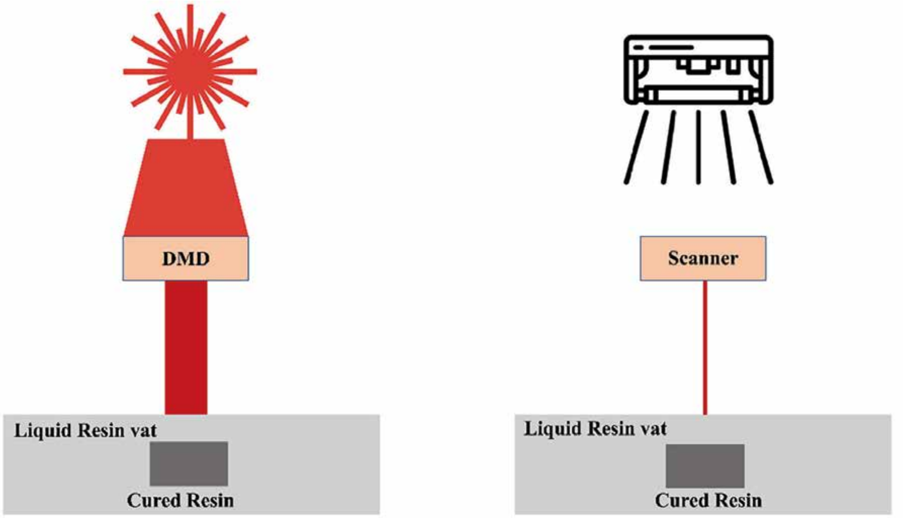

Figure 4.
The schematic irradiation process in PSL and SSL.

instead of building shells to fit patients' original teeth or fabricating the restorations directly using the molding process. While PSL is relatively fast (minutes), the precursor material (ceramic mixture polymer) refilling of a highly viscous mixture is a challenge due to the need for doctor-blading to create thin layers and direct material to the correct position. Infrared heating of the mixture (uniformly distributed) can significantly improve the rheology of the photocurable composite mixture and facilitate the MIP-SLA process fabrication of temporary crowns and bridges at higher temperatures (50–80°C). Other variations of SL like Vector Scan Stereolithography (VSSL) are carried out by selectively solidifying liquid photosensitive precursor by UV laser with resolution near 10 μm. The materials used for temporary crowns and bridges can be categorized into (i) self-cure (i.e., Poly methyl methacrylate (PMMA), Poly ethyl methacrylate (PEMA), and BIS-Acryl (divinyl methacrylate monomers)) and (ii) light-cure (REVOTEK® LC, UNIFAST™ LC acrylic resin, and Fermit ®).

Photopolymerization during SL simultaneously depends on light quantity and light quality (wavelength) with wavelength range UV (200–400 nm) and visible (400–700 nm) light. The required wavelength for photopolymerization of photomonomer is mostly in the blue region with the exception of infrared light (700–1000 nm) depending on multifunctional polymer mixture composition. Through the formation of linear chains of monomers, a cross-link can be formed between multi-linear macromolecular chains and result in a 3D network structure *via* photocrosslinking [34]. The typical mixture consists of:

- Photoinitiator (PIs)
- Oligomers
- Monomers
- Light absorber

- Wetting and dispersing agents with diluent
- Non-reactive solvent

Photoinitiators are required to generate reactive species to interact with the functional groups of monomers/oligomers. After the functional group's decomposition, the reactive double bond C=C can be formed to bond with another carbon atom and from a different monomer molecule. Through the replacement of weak van der Waals interactions between adjacent molecules with strong covalent bonds, the liquid resin transforms into a solid structure and holds ceramic powders within the bulk. After absorption of the incident UV light, free-radical PIs form free radicals (attacking double bonds of specific monomers, such as acrylates and methacrylates); while cationic PIs produce acids (reacting with vinyl ethers and epoxides and forming bonds in monomers and inducing polymerization).

Oligomers (prepolymers/macromonomers) with intermediate molecular weight and viscous liquid behavior possess a larger chain structure consisting of a few monomer units. *Monomers* in resins are used as reactive diluents, added to reduce the viscosity of oligomer and control the properties of the cured film. The free-radical reactions-based monomers (i.e., acrylates and methacrylates) require free radicals to initiate polymerization and only free-radical PIs can be used to induce the photopolymerization of this type of monomers (*via* accepting a free-radical from PIs and transferring it to another monomer to form a polymer). The cationic reactions-based monomers (i.e., epoxides, vinyl ethers, propenyl ethers, siloxanes, cyclic acetals, and furfural) polymerize under the cationic mechanism. *UV absorbers (UVAs)* also known as light stabilizing agents (i.e., benzotriazoles, benzophenones, and cyanoacrylates) enhance energy absorption from UV radiation to control possible polymer degradation. *Wetting* agents must be added as surface-active substances to improve the wetting of solid powders (See **Figure 5**). *Dispersing* agents prevent particles from flocculating by electrostatic effects, and steric effects mechanisms (i.e., hexanediol diacrylate). Most CSL slurries experience unfavorable shear-thickening behavior (viscosity increases with the rate of shear strain) [35]. Adding 1.5–2.5 wt.% dispersant changes the behavior into favorable shear-thinning [36]. A proper formulation at this stage ensures optimal ceramic powder loading in the 50–80 Vol.% range. This helps to minimize porosity, promoting high strength and fracture toughness in ceramic restorations. The

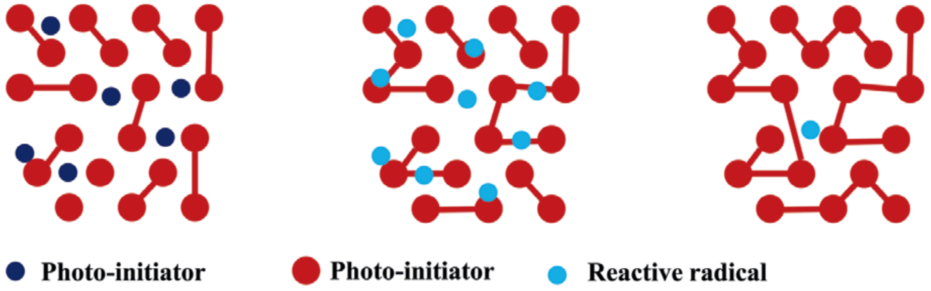

Figure 5.
Photo-polymerization of a photosensitive polymer vat: UV light irritation generates reactive radicals from photoinitiators to react with monomers and oligomers and form polymeric structure.

formulation also targets viscosity levels below 3 Pa.S, improving the spread ability of layers and homogeneity in the final restorations. Additionally, it accelerates the de-binding process, resulting in fewer flaws and higher surface finish quality. The formulation reduces the risk of part disruption, enhancing esthetics and translucency, while minimizing shrinkage, which improves marginal and internal fit. It also lowers the risk of deformation and cracking, ensuring a better contour match and reduced food impaction, producing dense and homogeneous final parts.

Overall, the CSL process includes:

- Preparing suitable photocurable ceramic suspension
- Light curing the mixture to the building of the ceramic part
- De-binding
- Sintering

During the photopolymerization of ceramic resin, monomers/oligomers act as the binding and create the matrix around the ceramic particles by bonding [37]. This matrix supplies sufficient cohesion for the fabrication of the green body; a stiff and strong composite of polymer and ceramic. The ceramic part requires two-stage thermal treatment of composite green bodies due to high organic content and weakly manufactured layer adhesion in green bodies [38]. Thermal treatments will determine the mechanical properties, transparency, and aging resistance (durability and reliability) of dental ceramics, that is, offering comparable longevity of 10 years or more in zirconia crowns.

The removal of the organic binder is conducted during the de-binding treatment at approximately 550°C. This process is time-consuming and can take anywhere from one to several days to complete the organic phase (binder) removal is carried out *via* the *de-binding* treatment step (~550°C), a time-consuming process which may require from one to several days to perform [39]. Restorative part deformation, layer delamination (layer separation), and cracks induced by pressure gradients are the results of non-proper de-binding (rapid) [40]. Following de-binding, the final thermal treatment, or sintering, is applied at much higher temperatures, ranging from 1200–1550°C. This step, which typically takes a few hours, is crucial for ensuring the durability and reliability of the parts (See **Figure 6**) [41]. Sintering or crystal densification determines residual porosity in the macrostructure and grain size in the microstructure, which in return indicates mechanical strength/fracture toughness and transparency/aging behavior, respectively. Increasing the sintering temperature rarely affects the marginal gap of typical monolithic zirconia crowns, but it could significantly improve (up to 30% with each 100°C) the compressive strength of zirconia restorations [42].

Common materials used for restorative crown AM fabrication are listed in **Table 1**. The precursor materials for operative applications are chosen based on mechano-chemical properties, aging behavior, esthetic and translucency, ease of fabrication, and comparative cost advantage. Some of the most relevant *in-vitro* (Lab) properties of restorative crown materials include:

- Work of fracture: Resistance to the propagation of damage

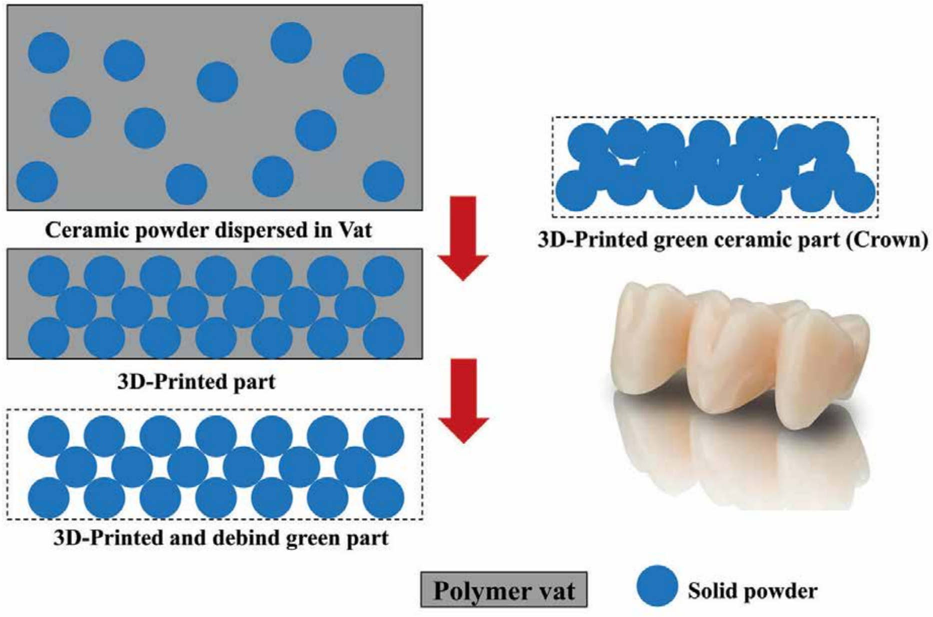

Figure 6.
The CSL process from scattered precursor polymer vat to structure-confined with polymerized mixture and de-binding (removing polymer) toward green parts.

- Fracture resistance: Maximum stress intensity before crack propagation
- Coffee staining: Change in L* A* B* colorimetric values
- Wear rate: Volume loss during 10-year wear simulation
- Durability: Aging mastication simulation in artificial saliva
- Thermal shock resistance: Thermocycle aging

Alongside developing new DLP/SLA apparatus, the hybrid composite resins have been commercialized with different sets of specifications and compatibility with different technologies (i.e., lithographic-based ceramic manufacturing (LCM)). A short summary of some of the 3D-print hybrid composite resins with main specifications is listed in **Table 2**.

Digital light processing (DLP) is also based on the principle of layer-by-layer production by the selective curing of a light-cured resin, similar to SLA. DLP is considered one of the fastest methods of 3D-printing of photopolymer. The main difference with SLA lies in the fact that the light source simultaneously polymerizes the resin in each layer of the object being produced. In addition, this technology uses a production direction opposite to SLA. The light projector must be stationed below the polymer vat so the light or energy from the projector can be transmitted through the bottom of the tray onto the resin and the layer height can be quickly and tightly controlled. Therefore, the tray in the DLP process is made with a clear or transparent bottom which permits the transmission of light from the protector to the resin. The build plate tray moves vertically in the z-axis, presses

Powder	Formula	Specification	Possible solid loading (Vol.%)	Vat mixture	Laser wavelength (λ, nm)	absorption edge (nm)	Application
Alumina	Al_2O_3	Purity >98% Size <0.5 µm	50–60	Acrylate-based monomer Polypropylene glycol Acrylamide-based monomer	300–450	~460	Crown and Bridges: Base material Crown and Bridges: Additive material
Zirconia	ZrO_2	Purity >98% Size <0.2 µm	40–50	Acryloyl morpholine Acrylate-based monomer	300–400	~245	Crown and Bridges: Base material
Silica	SiO_2	Purity >98% Size <10 µm	50–60	Acrylate-based monomer	320–350	~300	Crown and Bridges: Additive material
Titania	TiO_2	Purity >98% Size <5 µm	25–35	Acrylate-based monomer	350–400	~300	Crown and Bridges: Additive material
Ceria	CeO_2	Purity >98% Size <10 µm	10–15	Acrylate-based monomer	300–350	~380	Crown and Bridges: Additive material
Yttria	Y_2O_3	Purity >98% Size <10 µm	10–15	Acrylate-based monomer	350–400	~280	Crown and Bridges: Additive material
Hydroxyapatite	$Ca_5(PO_4)_3(OH)$	Purity >98% Size <1 µm	50–60	Acrylamide-based monomer	350–400	~200	Crown and Bridges: Reinforcement materials

Table 1.
The main ceramic materials in dental restorations used for AM fabrication.

Application	**Commercial brand**	**Shades**	**Viscosity (mPa.S)**	**Flexural strength (MPa)**	**Layer thickness**	**Wave length (nm)**
Temporary Crowns and Bridges	DENTCA Crown & Bridge	A1, A2, A3, A3.5, B1, B2, 4 BL1	U	≥ 60	U	U
Single crowns, inlays, onlays, and veneers, artificial teeth for dental prostheses	Flexcera Smile Ultra	A1, A2, A3, A3.5, B1, BL	U	U	U	U
Single crowns, inlays, onlays, and veneers	Formlabs Permanent Crown Resin	A2, A3, B1, C2	U	≥ 116	U	U
Single crowns, up to 3-unit bridges, inlays, onlays, and veneers	Irix Plus Irix Max	A1, A2, A3, A3.5, B1, N, multicolored	U	≥ 100 ≥ 80	U	U
dentures	KeyDenture Try-In	A1, B1, BL4	U	≥ 60	U	U
denture teeth	SprintRay OnX	A1, A2, A3	300–700	≥ 147	U	U
Single crowns, inlays, onlays, and veneers	SprintRay Crown	A1, A2, A3, B1, C2, D2 Bleach	300–700	≥ 150	U	U
Crowns, inlays, onlays, veneers und bridges	VarseoWax Model	A3 A2 C2	2500–6000	≥ 80	50 µm	405
Frames such as partial dentures, crowns and bridges, inlays, onlays and veneers	VarseoWax CAD/Cast	yellow	700–1500	≥ 50	50 µm	405
permanent single crowns, inlays, onlays and veneers	VarseoSmile Crown plus	A2	2500–6000	≥ 116	50 µm	405
Crowns, inlays, onlays, veneers und bridges	VarseoSmile Temp	A3 A2 C2	2500–6000	≥ 80	50 µm	405
tooth-colored ceramic-filled hybrid for permanent single crowns, inlays, onlays and veneers	VarseoSmile Crown plus BL	BL	2500–6000	≥ 116	50 µm	385

Application	Commercial brand	Shades	Viscosity (mPa.S)	Flexural strength (MPa)	Layer thickness	Wave length (nm)
bridges, single-tooth restorations, and artificial teeth	VarseoSmile TriniQ	B1	1900–6000	≥ 120	50 μm	385

U: Unspecified.

Table 2.
DLP/SLA 3D-printable hybrid composite resins for different applications with main specifications.

into the vat of resin, and creates a thin layer (25–150 μm) of resin between the build plate and the bottom of the vat.

In *Continuous liquid interface production (CLIP)*, similar principles to conventional DLP are applied with the difference of using oxygen-permeable film to inhibit polymerization on the surface close to the UV source and consequently eliminating the need for an intermediate coating step for each layer. The continuous liquid interface, also known as dead-zone facilitates an increase in manufacturing speed but also limits staircase effects in manufactured parts. CLIP is applicable for manufacturing prosthetically oriented implant placement. The dimensional accuracy of surgical guides from Keyguide® includes a layer height of 0.1 mm and a thickness basis of 1.5 mm. Horizontally manufactured surgical guides show ~0.4 RMS increased warpage, particularly in the marginal areas with up to 5 mm deviation of reference points from the original CAD file after sterilization [43]. CLIP technique is used by dental and orthodontic laboratories for the production of 3D-printed dentures with base and teeth as commercially known DENTCA® dentures [44]. Replacing oxygen flow with mobile immiscible fluorinated oil at the interface dead zone has developed the *high area rapid printing (HARP)* method which significantly reduces the adhesion between polymerized resin and the vat base.

Multiphoton polymerization (MPP) method uses "multiphoton" which refers to the simultaneous absorption of three or more photons (although with very low probability) and photopolymerization with powerful and high-tech laser sources [45]. Multiphoton absorption polymerization enables the creation of large-scale structures with feature sizes as small as 100 nm [46]. Unlike the SLA method, MPP produces the entire desired object at one stage without using the layer-on-layer technique with the potential for manufacturing extra complex structures such as mandible scaffolds and oral tissues. *Rapid Freeze Prototyping (RFP)* dental restorations using ice molds instead of traditional wax molds. This technique is a new and environmentally friendly solid-free-forming process. It can selectively deposit a water layer and then rapidly freeze it to produce a 3D ice model based on a CAD file.

"3D-printed object transforms itself into another structure" was the statement made by MIT Self-assembly Lab as a basis for a newly additively manufactured part with association to Programmable Materials.

While ceramics remain the foundation of restorative AM, the potential for dynamic, shape-shifting materials opens new avenues in prosthodontics, particularly with the development of *4D-printing*.

Incorporating the changing properties and functions dependent on external stimuli such as heat, pH, humidity, light, pressure, touch-shear, and electromagnetic radiation into 3D-printed parts has developed the 4D-Printing (4DP) concept. Unlike 3D printing of static materials with constant shape and properties throughout a lifetime, 4D-printed (4DP) are dynamic [47]. The manufacturing of these dynamic models is carried out by digital modeling designed with special software which can calculate the shape and dimensional changes which may occur and SLA photopolymerization [48]. 4D printing can be used for the production of dental restorative materials. Here are some of the design benefits of 4D-printing restorations [49]: (i) the 4D-printed restorations can transfer in certain pre-programmed directions (path of motion) and are capable of continuous self-folding adjustment. The advantages of this design include the elimination of dental adhesives (etching and bonding systems), avoiding microleakage, avoiding overhangs at the margins, and relying on mechanical means of retention rather than chemical aids. (ii) in a similar approach, 4D-printed filling restorations can be programmed to move toward the fitting surface of the cavity to ensure maximum adaptation. (iii) 4D-printed fillings are used in inaccessible areas of the oral cavity where manipulation and longevity of current restorative materials are difficult. Furthermore, 4D-printed restorations can be used in removable prosthetic dentistry with similar properties to the natural hard and soft tissues [50]. (iv) 4D-printed materials are replacements for cartilage during continuous movements compensating for articulation and occlusion. These restorative prostheses can adapt to the types and directions of forces in the oral cavity with reliable fitting and retention characteristics and optimal dynamic properties due to their self-folding nature. Similar to the natural periodontal ligaments or overlying mucosa, denture bases can be fabricated with certain structures which encompass elasticity and thermal criteria. Custom-made specifications and individual demands can also be addressed with a variety of designing options can be provided for patients. For instance, residual ridge resorption areas can be managed by installing additional materials that compensate for bone loss. The 4D-printed structures can be fused to the residual dental implants by modifying apical portion to act as a soft base under implants to avoid injury of vital structures around the implant site such as the maxillary sinus or inferior alveolar nerve. On a more sophisticated approach, stem cells can be carried on 4D-printed implants or tooth-shaped scaffolds to grow into natural teeth. The temporomandibular joint and maxillofacial can also benefit from 4D-printed materials. As a promising application for the technology, the 4D bio-printing of dental and craniofacial tissues has overcome the challenges of mimicking complex dental tissue structures with anisotropic mechanical properties and heterogeneous cell distribution.

A combination of high flexural strength, high fracture toughness, confidence intervals as high as >95%, and Weibul modulus as high as >20 guarantees high clinical reliability of dental restorations produced by AM methods [32]. **Table 3** lists ceramic crown restoration additive manufacturing systems suitable for clinical application through comparison with typical SM parts. It should be noted that the *Lower Weibull modulus* indicates greater variability and thereby less reliability in the strength due to flaws and defects and limited clinical uses.

“Add, Subtract, repeat” is a clear slogan for currently developing methods. While AM processes are introduced as versatile methods, the advantages of common subtractive manufacturing have resulted in AM-SM combinations introduced as *Hybrid Manufacturing Technologies (HM)* or additive/subtractive hybrid manufacturing (ASHM). “The best of both worlds” – subtractive and additive manufacturing technologies – hybrid manufacturing combines the subtractive and additive

Method	Resolution	Layer thickness (µm)	Material	~Trueness (µm)	Mechanical Properties	Weibull Modulus	Confidence interval (%)	Example model
BJT	20–30	20–30	3Y-TZP ATZ	External:97 Intaglio:33 Margin:23	Flexural strength: 600–750 Mpa Fracture toughness 3.9–5.2 MPa$\sqrt{m}$	5–8	90	Exone (InnoventX)
DIP-NPJ	16	10	3Y-TZP	External:42 Intaglio:23 Margin:23	Flexural strength: 700-1050 Mpa Fracture toughness 4–7.5 MPa$\sqrt{m}$	3–10	90	Xjet (Carmel 1400)
DLP	30–40	10–25	3Y-TZP ATZ	External:62 Intaglio:35 Margin:49	Flexural strength: 900–1500 Mpa Fracture toughness 5–5.5 MPa$\sqrt{m}$	8–16	95	Admaflex (Admaflex130) AON (INNI-ZIPRO) Octave Light (Octave Light R1)
LCM	23	18	3Y-TZP	External:66 Intaglio:81 Margin:86	Flexural strength: 450–800 Mpa Fracture toughness 4.5–5.5 MPa$\sqrt{m}$	5–6	90	Lithoz (CeraFab)
SLA	30–40	20–25	Alumina 3Y-TZP ATZ	External:52 Intaglio:32 Margin:26	Flexural strength: 700–1200 Mpa Fracture toughness 6–7 MPa$\sqrt{m}$	11–16	95	3DCeram (C900 Flex) Porimy (CSL100/150/200)
SM	20–25	25–35	Alumina 3Y-TZP ATZ	External:33 Intaglio:32 Margin:23	Flexural strength: 800–1250 Mpa Fracture toughness 6–6.5 MPa$\sqrt{m}$	9–11	95	* For comparison

Table 3.
Ceramic crown restoration additive manufacturing systems suitable for clinical application.

processes in a single machine. Immediate advantages in restoration manufacturing include:

- More freedom and wider path planning
- Reducing human interactions with SM methods
- Increasing part size with appropriate AM precision
- Increasing the production speed of SM
- Eliminating AM-induced defects
- Decreasing energy consumption
- Increasing productivity through decreasing waste materials

Therefore, hybrid manufacturing processes leverage the precision of subtractive manufacturing and the complexities of additive manufacturing technologies to allow a single restoration to be first additively created and then machined for a high-quality and accurate final product. Therefore, to achieve acceptable and reliable implant prosthodontic discrepancy, 3D-printing technologies and subtractive processing (electropolishing, sandblasting, or other post-processing techniques) should be combined. Compared the trueness and precision of dental frameworks manufactured through hybrid SLM/milling technique (SLM/m) and conventional milling shows similar maximum misfit of 20–35 μm in both methods with errors increasing from 8 to 16 μm in SLM/m to 9–22 μm [51]. There are a limited number of CAD/CAM systems that incorporate both additive and subtractive manufacturing approaches. Leading ASHM technology companies include 3D-Hybrid, DMG Mori, Fabrisonic, Hermle, Hybrid Manufacturing Technologies, Matsuura, Mazak, Optomec, Phillipscorp, Siemens, Sodick, and alike with commercialized systems like Procera (Nobel Bio-Care, Gothenburg, Sweden), Phlipshybris (Germany), and Wol-Ceram (Wol-Dent, Ludwigshafen, Germany).

Application of one or combinations of these methods has developed the *Indirect Temporary Dental Restorations Manufacturing methods*. In the indirect fabrication of permanent restorations with additive manufacturing technology (As shown in **Figure 7**), after scanning with an intraoral scanner; the virtual design of the restoration is preparade; the design will be reformatted to the relevant production unit in the STL layer by layer pack, the relevant restoration prostheses can be 3D-printed in accordance with the minimum thickness values; after the manufacturing (3D-printing) and post-manufacturing processes (de-binding and sintering), final preparations are carried out; and the restoration can be cemented onto the abutment tooth with the appropriate adhesive system and luting cement.

Besides direct production of AM restoration crowns, functionally graded additive manufacturing (FGAM) can be utilized to simulate the functional hierarchical structure of natural tooth enamel and dentin. The process may involve three-grade ceramic restoration crowns with an esthetic outer layer (highly translucent ceramic) covering highly mechanically stable interlayer layers (high strength ceramic) and low elastic modulus inner layers (to decrease mismatch with natural teeth and lower chance of fracture in abutment teeth and crowns).

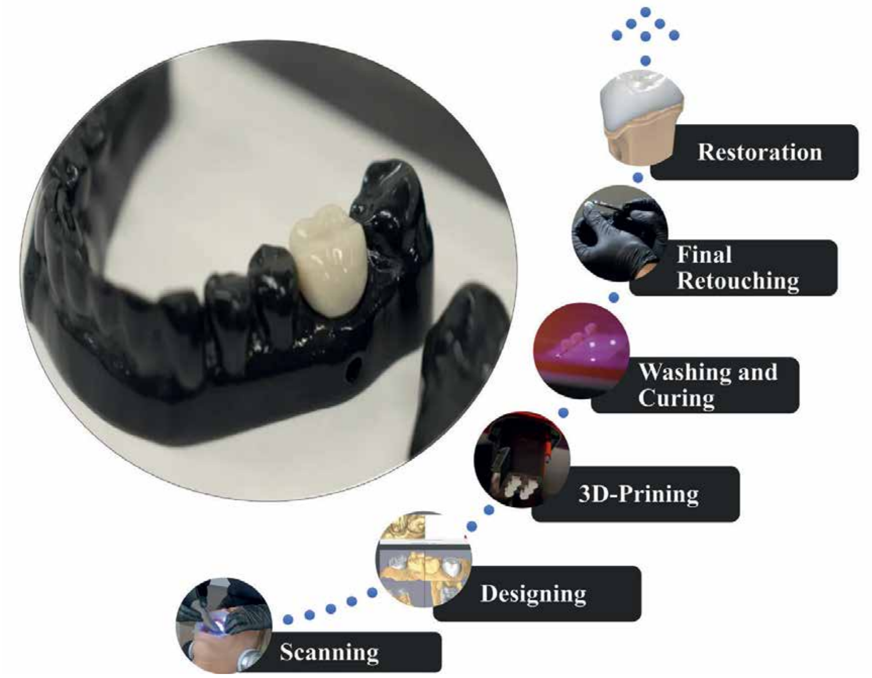

Figure 7.
The indirect fabrication of permanent restorations with additive manufacturing technology.

4. Conclusion, challenges, opportunities and future

"Soon, every specialist dentist will have one" is a statement which fairly predicts the future of AM in operative/restorative dentistry. The attractive advantages of Additive manufacturing technologies have made them an intricate and necessary aspect of the future of healthcare, especially dental parts. We have focused and streamlined this chapter on AM for operative dentistry applications in regenerative and restorative dental capacities from well-established SLA/DLP techniques to futuristic 4D-printing bioinspired parts. Primarily used in dentistry to overcome SM limitations such as high material waste and difficulties in complicated and detailed shaped parts (i.e., fine structures such as knife-edges or deep grooves/fossae), AM can be the future of Operative and Restorative Dentistry. As curved surfaces comprise most of the areas of oral restorations, surface-stepping stages in AM is the main area of limitations for operative dentistry applications. Besides increasing in manufacturing speed (from 2.5 hours to 10–15 minutes for a custom-made crown) and the compact, lightweight design of desktop apparatuses for convenient private practice use, the development in precursor materials (polymers and ceramics) and their inter-device adaptability has strongly secured the market for replacing conventional subtractive manufacturing methods with AM or hybrid ASHM methods. The current trend of improvement is focused on reducing layer thickness from the current 10 μm level to ensure higher resolutions. The current improvements in durability and reliability of AM fabricated restorations are credited to an increase in flexural strength, fracture toughness, Weibull modulus from ~10 in SM to ~15 in AM (significant improvement), and confidence interval to >95%. Intrinsic limitations in restoration materials (e.g., nY-TZP (n molar ratio -yttrium-stabilized tetragonal zirconia polycrystal) with n:3 in less translucent despite high strength, n:4 is highly translucent despite low strength, and n:5 is highly translucent with low hardness) can be resolved by AM fabrication of FGM crowns of n:5 translucent outer surface and high strength n:3 inner core. Other scientifically proven approaches such as adding additive materials (i.e., yttria and ceria) to base zirconia and alumina crown restorations have simultaneously improved translucency and mechanical properties alongside the aging behavior of AM fabricated restoration crowns. In collusion, while the significant role of additive manufacturing in dental care—particularly in operative and restorative dentistry- is well established, further collaborative efforts between academia and industry are essential to develop reliable alternatives to traditional subtractive manufacturing methods.

Abbreviations

ALM	additive layer manufacturing
AM	additive manufacturing
ASHM	additive/subtractive hybrid manufacturing
BJT	Binder Jetting
CAD	computer-aided design
CAM	computer-aided manufacturing
CLIP	continuous liquid interface production
CNC	computer numerical control
DED	directed energy deposition
DED-arc	directed energy deposition-arc
DLP	digital light processing
DMD	direct metal deposition
EBAM	electron beam additive manufacturing
FDM	fused deposition modeling
HM	hybrid manufacturing technologies
LENS	laser engineered net shaping
LSD	layer-wise slurry deposition
MEX	material extrusion
MJ	material jetting
MPP	multiphoton polymerization
NNS	near-net-shape
NPJ	nanoparticle jetting
PBF	powder bed fusion
RFP	rapid freeze prototyping
SHL	sheet lamination
SLA	stereolithography
SLS	selective laser sintering
VPP	VAT photo-polymerization

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