

IntechOpen

IntechOpen Series
Dentistry, Volume 28

Dentures

Present State-of-the-Art and
Future Perspectives

*Edited by Lavinia Cosmina Ardelean
and Laura-Cristina Rusu*



Dentures - Present State- of-the-Art and Future Perspectives

*Edited by Lavinia Cosmina Ardelean
and Laura-Cristina Rusu*

Published in London, United Kingdom

Dentures – Present State-of-the-Art and Future Perspectives

<http://dx.doi.org/10.5772/intechopen.1006766>

Edited by Lavinia Cosmina Ardelean and Laura-Cristina Rusu

Contributors

Alexandra Roxana Cristea, Anamaria Matichescu, Andrea Bors, Bejan Flavia Roxana, Codruta Victoria Tigmeanu, Dana Gabriela Budala, Dragos Ioan Virvescu, Elena Raluca Baci, Felicia Gabriela Beresescu, Flavia Roxana Bejan, Gabriela Ciavoi, Ionut Luchian, Laura-Cristina Rusu, Lavinia Cosmina Ardelean, Liliana Porojan, Monica Silvia Tatarciuc, Oana Maria Butnaru, Roxana Diana Vasiliu, Sergiu-Mihai Ciavoi, Simona Gabriela Mucenic

© The Editor(s) and the Author(s) 2025

The rights of the editor(s) and the author(s) have been asserted in accordance with the Copyright, Designs and Patents Act 1988. All rights to the book as a whole are reserved by INTECHOPEN LIMITED. The book as a whole (compilation) cannot be reproduced, distributed or used for commercial or non-commercial purposes without INTECHOPEN LIMITED's written permission. Enquiries concerning the use of the book should be directed to INTECHOPEN LIMITED rights and permissions department (permissions@intechopen.com).

Violations are liable to prosecution under the governing Copyright Law.



Individual chapters of this publication are distributed under the terms of the Creative Commons Attribution 4.0 License which permits commercial use, distribution and reproduction of the individual chapters, provided the original author(s) and source publication are appropriately acknowledged. If so indicated, certain images may not be included under the Creative Commons license. In such cases users will need to obtain permission from the license holder to reproduce the material. More details and guidelines concerning content reuse and adaptation can be found at <http://www.intechopen.com/copyright-policy.html>.

Notice

Statements and opinions expressed in the chapters are those of the individual contributors and not necessarily those of the editors or publisher. No responsibility is accepted for the accuracy of information contained in the published chapters. The publisher assumes no responsibility for any damage or injury to persons or property arising out of the use of any materials, instructions, methods or ideas contained in the book.

First published in London, United Kingdom, 2025 by IntechOpen

IntechOpen is the global imprint of INTECHOPEN LIMITED, registered in England and Wales, registration number: 11086078, 167-169 Great Portland Street, London, W1W 5PF, United Kingdom

For EU product safety concerns: IN TECH d.o.o., Prolaz Marije Krucifikse Kozulić 3, 51000 Rijeka, Croatia, info@intechopen.com or visit our website at intechopen.com.

British Library Cataloguing-in-Publication Data

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

Dentures – Present State-of-the-Art and Future Perspectives

Edited by Lavinia Cosmina Ardelean and Laura-Cristina Rusu

p. cm.

This title is part of the Dentistry Book Series, Volume 28

Topic: Prosthodontics and Implant Dentistry

Series Editor: Sergio Alexandre Gehrke

Topic Editor: Wen Lin Chai

Associate Topic Editor: Ghee Seong Lim

Print ISBN 978-1-83634-965-5

Online ISBN 978-1-83634-964-8

eBook (PDF) ISBN 978-1-83634-966-2

ISSN 2631-6218

If disposing of this product, please recycle the paper responsibly.

IntechOpen Book Series

Dentistry

Volume 28

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

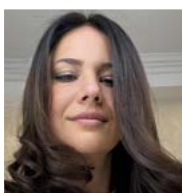


Dr. Sergio Alexandre Gehrke is a doctorate holder in two fields. The first is a Ph.D. in Cellular and Molecular Biology from the Pontificia Catholic University, Porto Alegre, Brazil, in 2010 and the other is an International Ph.D. in Bioengineering from the Universidad Miguel Hernandez, Elche/Alicante, 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



Professor Lavinia Cosmina Ardelean, DMD, Ph.D., is a Professor and Head of the Academic Department of Technology of Materials and Devices in Dental Medicine, “Victor Babes” University of Medicine and Pharmacy, Timisoara, Romania. She has authored/co-authored 20 books, 16 book chapters, and over 130 peer-reviewed papers. With a current H-index of 13, she is an editorial board member of numerous journals, including Scientific Reports, and a member of reviewer/topic boards of MDPI journals: Materials, Prosthesis, Metals, Coatings, Polymers, Dentistry, and Biomedicines. She has guest-edited 12 special issues in different journals and 10 books. As an active reviewer with more than 300 reviews to her credit, she was awarded the Top Reviewers in Cross-Field award 2019 and the Top Reviewers in Materials Science award 2019. She also received the Springer Nature Editorial Contribution Award 2025 and the Springer Nature Author Service Award 2025. She currently holds three patents. Her research interests span most areas of dentistry, with a focus on dental materials/biomaterials, dental alloys, resins, ceramics/bioceramics, CAD/CAM milling, 3D printing/bioprinting, welding, scanning, prosthodontics, and oral health care.



Professor Laura Cristina Rusu, DMD, Ph.D., is the mother of two lovely boys and a Full-Time Professor and Head of the Oral Pathology University Clinic, Faculty of Dental Medicine, “Victor Babes” University of Medicine and Pharmacy, Timisoara, Romania. Her Ph.D. thesis was centered on allergens in dental materials. In 2017, she obtained a Dr. Habil. and was confirmed as Ph.D. coordinator in the field of dental medicine. She participated in 11 research projects, including the FP7 COST Action MP 1005, and authored over 140 peer-reviewed papers. She has published 10 books and book chapters as an author and co-author. She has guest-edited 8 special issues in different journals and edited or co-edited 10 books. She currently holds four patents. With a current H-index of 18, she is a member of the editorial boards of the Journal of Science and Art and Medicine in Evolution, and a topic editor for the journal Materials. Her main scientific interests are oral pathology and oral diagnosis in dental medicine, with a focus on oral cancer.

Contents

Preface	XIII
Chapter 1 Edentulism and Systemic Disease: A Comprehensive Review of Oral-Systemic Health Interactions <i>by Felicia Gabriela Beresescu, Simona Gabriela Mucenic and Andrea Bors</i>	1
Chapter 2 Innovative Materials and Techniques for Dentures: A Contemporary Approach <i>by Dana Gabriela Budala, Ionut Luchian, Dragos Ioan Virvescu, Oana Maria Butnaru, Elena Raluca Baciuc and Monica Silvia Tatarciuc</i>	17
Chapter 3 The CAD/CAM Alternative for Processing Dental Alloys <i>by Lavinia Cosmina Ardelean, Codruta Victoria Tigmeanu and Laura-Cristina Rusu</i>	37
Chapter 4 High-Performance Polymers (HPPs) in the Field of Restorative and Prosthetic Dentistry <i>by Liliana Porojan, Flavia Roxana Bejan, Roxana Diana Vasiliu and Anamaria Matichescu</i>	51
Chapter 5 Evaluation of Mechanical and Optical Properties of Monolithic Zirconia for Restorative Dentistry <i>by Flavia Roxana Bejan, Liliana Porojan, Roxana Diana Vasiliu and Anamaria Matichescu</i>	81
Chapter 6 Assessment of the Mechanical and Optical Characteristics of Hybrid Dental Ceramics in Dental Prosthetics <i>by Roxana-Diana Vasiliu, Bejan Flavia Roxana and Liliana Porojan</i>	109
Chapter 7 Anxiety Management in Dental Prosthetics <i>by Gabriela Ciavoi, Alexandra Roxana Cristea and Sergiu-Mihai Ciavoi</i>	137

Preface

Despite considerable advances in curative and preventive dentistry, edentulism remains a global challenge. Teeth loss not only affects mastication and speech, but may also result in poor esthetics and negatively impact the individual's health status, quality of life, self-esteem, and social integration.

The treatment approach is highly dependent on the severity of tooth loss. However, with the highly effective teeth replacement solutions currently available, both function and esthetics can be completely restored. Novel material choices with improved characteristics, as well as modern manufacturing methods, underlie the selection of the most appropriate prosthetic solution to address both functional and esthetic issues.

Digital dentistry significantly speeds up treatment protocols and reduces manual work, resulting in high-quality prosthetic solutions and happy patients.

Recent developments include self-monitoring prostheses, AI-powered design platforms, and bioprinted regenerative denture bases. These advancements improve customization, durability, hygiene, and patient satisfaction. Nonetheless, challenges regarding accessibility, clinicians' and dental technicians' training, and the ethical management of digital data remain.

Practically speaking, at present, a proper prosthetic solution is available, even for the most challenging cases.

The field of denture therapy is shifting towards a new paradigm of personalized, intelligent, and sustainable prosthetics. Modern dentures have advanced way beyond the ones our grandparents used to wear.

To successfully incorporate these technologies into routine care, continuous interdisciplinary research and clinical validation are essential.

Lavinia Cosmina Ardelean

Academic Department of Technology of Materials and Devices in Dental Medicine,
“Victor Babes” University of Medicine and Pharmacy,
Timisoara, Romania

Laura-Cristina Rusu

University Clinic of Oral Pathology,
“Victor Babes” University of Medicine and Pharmacy,
Timisoara, Romania

Chapter 1

Edentulism and Systemic Disease: A Comprehensive Review of Oral-Systemic Health Interactions

*Felicia Gabriela Beresescu, Simona Gabriela Mucenic
and Andrea Bors*

Abstract

Edentulism, or complete tooth loss, is a significant public health problem with consequences that extend far beyond the oral cavity. Functionally, edentulism impairs chewing, speech, and oral proprioception, leading to progressive alveolar bone resorption and altered temporomandibular joint function. Nutritionally, edentulous individuals often adopt a softer, carbohydrate-rich diet, resulting in deficiencies of essential nutrients and contributing to systemic health deterioration. Poor mastication also stresses the gastrointestinal system, potentially leading to digestive disorders. Psychologically, toothlessness is associated with decreased self-esteem, depression, social withdrawal, and reduced quality of life. Changes in facial esthetics further exacerbate emotional distress. Systemically, edentulism is associated with increased risk of cardiovascular disease, diabetes, cognitive impairment, and mortality, likely through pathways involving chronic inflammation, malnutrition, and reduced cerebral stimulation. Effective management of edentulism requires more than prosthetic rehabilitation. While full dentures and implant-supported overdentures restore oral function, comprehensive care must also address nutrition, psychological support, and monitoring for systemic disease. With a rapidly aging global population, recognizing edentulism as a condition with broad systemic implications is critical to improving overall patient outcomes and public health strategies.

Keywords: teeth loss, edentulism, anatomic changes, physiological changes, systemic disease associated with edentulism

1. Introduction

Edentulism, or the complete loss of natural teeth, remains a major public health problem worldwide, particularly among the aging population. Despite advances in preventive dentistry, oral hygiene education and restorative technologies, edentulism continues to affect millions of people worldwide, particularly in socioeconomically disadvantaged and medically compromised groups. According to the World Health Organization, edentulism is one of the most prevalent chronic diseases with a significant impact on both oral and systemic health outcomes [1].

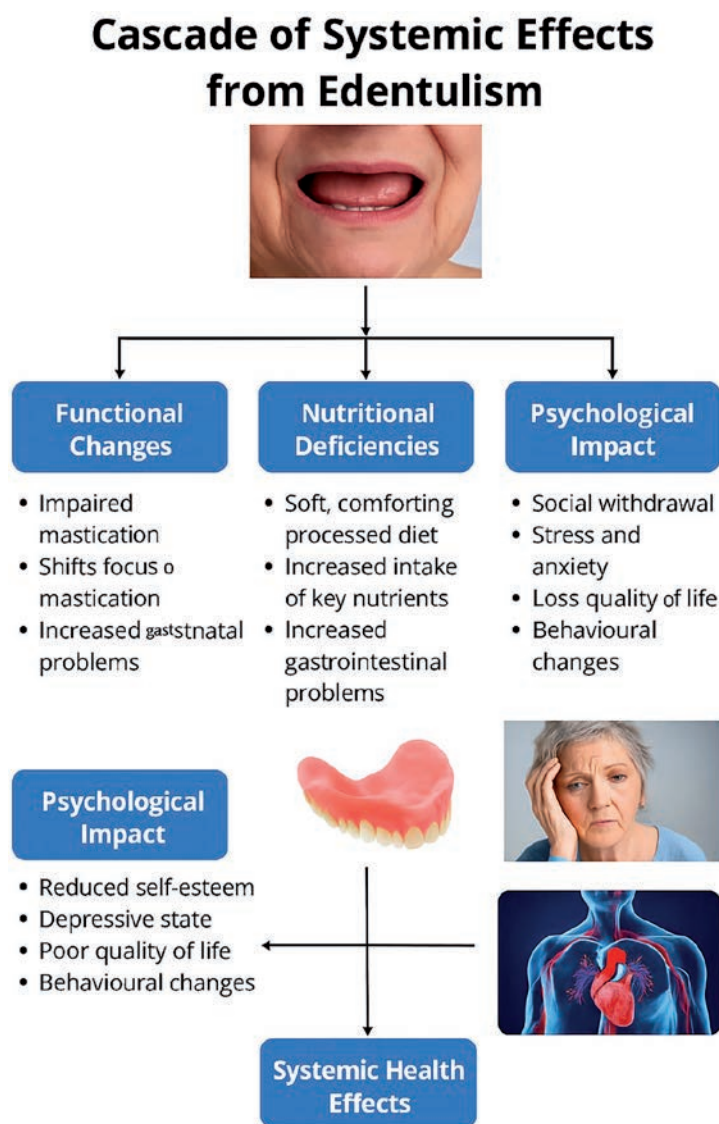


Figure 1.
Cascades of systemic effects from edentulism.

Historically viewed as an inevitable consequence of aging, the perception of edentulism has changed in recent decades. Tooth loss is now recognized as a marker of past disease burden—primarily from dental caries and periodontitis—and as an indicator of broader health inequalities [2]. Beyond its status as a clinical endpoint; however, complete tooth loss has far-reaching physiological, nutritional, psychological, and social implications for individuals. These effects extend beyond the oral cavity, affecting systemic health, general well-being, and even mortality risk [3].

This chapter reviews the multifaceted consequences of complete tooth loss on the human body, highlighting the functional, nutritional, psychological, and systemic implications and emphasizing the need for an integrated, interdisciplinary approach to management and rehabilitation (**Figure 1**).

2. Functional and structural changes

Functional and structural changes in edentulism profoundly alter the function and structure of the stomatognathic system. The absence of natural teeth results in marked changes in mastication, phonetics, proprioception, and the anatomy of the oral and maxillofacial structures. These changes not only affect daily oral activities but also initiate a cascade of degenerative changes that can have systemic implications [2].

Structurally, the absence of teeth initiates progressive alveolar bone resorption. Without the mechanical stimulation provided by the periodontal ligament, the alveolar bone undergoes continuous atrophy. Mandibular resorption typically proceeds at a faster rate than maxillary resorption, resulting in characteristic facial changes such as reduced lower facial height, deepened nasolabial folds, and a prognathic mandibular appearance. These changes not only compromise denture stability but also affect facial esthetics and psychological well-being [4, 5].

2.1 Impairment of chewing and digestive function

The immediate functional deficit of edentulism is the significant reduction in chewing efficiency. Natural teeth, supported by the periodontal ligament and alveolar bone, provide both the mechanical breakdown of food and the sensory feedback necessary for controlled, efficient mastication. With the loss of teeth, patients experience a reduction in maximum bite force of approximately 75–85% compared to dentate individuals [6]. As a result, food is often inadequately processed in the oral phase of digestion, increasing the burden on the stomach and intestines.

Inefficient chewing leads to the avoidance of hard, fibrous foods such as raw vegetables, nuts, and meat. Instead, edentulous individuals prefer softer, processed foods, contributing to an unbalanced diet, increased risk of malnutrition, and long-term systemic health consequences [7].

2.2 Alveolar bone resorption

One of the most profound structural consequences of edentulism is progressive alveolar bone resorption.

Atwood's classic studies (1971) demonstrated that residual ridge resorption follows a chronic, irreversible, and cumulative pattern. The rate of mandibular bone loss is approximately four times that of the maxilla, resulting in characteristic anatomic changes such as a narrow, knife-edge mandibular ridge and loss of vertical facial height [5].

Clinically, extensive ridge resorption complicates prosthetic rehabilitation by reducing denture stability and retention, often requiring more complex treatments such as implant-supported overdentures or extensive ridge augmentation procedures [8, 9].

2.3 Changes in facial morphology and esthetics

Edentulism has a dramatic effect on facial morphology, contributing to an aged and collapsed appearance. The loss of alveolar support results in:

- Decreased inferior facial height (vertical dimension of occlusal collapse).
- Deepening of the nasolabial folds and marionette lines.
- Thinning and drooping of the lips due to loss of lip support.

- Increased chin prominence (pseudopognathism).
- Flattened midface profile.

These esthetic changes often have a profound psychological and social impact on patients, further emphasizing the link between functional loss and emotional well-being [10].

2.4 Changes in the temporomandibular joint (TMJ)

The stomatognathic system is based on the harmonious interaction of teeth, muscles, and joints. Edentulism disturbs this balance.

The loss of occlusal support alters the mandibular posture and leads to anterior rotation of the mandible. Patients often compensate with abnormal muscle patterns, which can lead to muscle fatigue, myofascial pain, and temporomandibular disorders (TMD) [9].

In cases of severe alveolar ridge resorption and poorly fitting dentures, excessive functional loading of the condyles can further aggravate degenerative changes in the TMJ complex, leading to joint dysfunction, pain, and limitation of mandibular movement [9, 10].

2.5 Loss of proprioception and neuromuscular control

Following edentulism, the loss of periodontal proprioception leads to a reduction in oral sensory capacity. Patients have a reduced ability to modulate bite force and chewing rhythm, often resulting in inefficient and uncoordinated mastication [11].

This neuromuscular deficit is particularly challenging for elderly patients who already suffer from age-related declines in sensorimotor control, exacerbating functional deficits and difficulties in adapting to dentures.

2.6 Speech disorders

Teeth play an essential role in the articulation of certain phonetic sounds. Loss of front teeth affects the production of fricative sounds (“f,” “v,” “s,” “z”) and sibilants [12].

Edentulous patients often complain of slurred speech, whistling, or difficulty pronouncing certain words, which can contribute to social embarrassment and withdrawal. Therefore, appropriate prosthetic rehabilitation must not only restore mastication but also facilitate phonetic function through careful placement of dentures and contouring of denture bases [12].

Comprehensive rehabilitation strategies must address both the mechanical and biological aspects of edentulism to restore not only oral health but also overall quality of life.

3. Nutritional and gastrointestinal implications

The functional impairment caused by edentulism has a significant impact on dietary intake and gastrointestinal health. Tooth loss, by limiting chewing efficiency, triggers a series of dietary changes and physiological adaptations that adversely affect systemic nutrition and digestion. These effects are particularly severe in the elderly, who are already prone to malnutrition and gastrointestinal dysfunction [7].

The systemic implications are profound, with associations between nutritional deficiencies associated with edentulism and an increased risk of cardiovascular disease, diabetes mellitus, osteoporosis, and cognitive decline. Thus, the impact of edentulism on nutrition and gastrointestinal function plays a key role in the deterioration of systemic health [13].

3.1 Dietary changes and reduced nutrient intake

One of the most immediate consequences of edentulism is a change in dietary choices. Edentulous individuals consistently report avoiding foods that are difficult to chew, such as fresh fruits, raw vegetables, nuts, and meat [7]. Several large-scale epidemiologic studies, including data from the National Health and Nutrition Examination Survey (NHANES), have confirmed that edentulous individuals consume significantly fewer servings of fruits and vegetables and lower levels of fiber, calcium, vitamin C, and vitamin D than those with teeth [13, 14].

This shift away from nutrient-rich foods leads to chronic deficiencies that can compromise immune function, delay wound healing, and exacerbate the aging process [13].

3.2 Increased risk of malnutrition and sarcopenia

Malnutrition is a major public health problem among older edentulous patients. According to studies by Walls and Steele [15], edentulism is independently associated with malnutrition, even after controlling socioeconomic status and other health-related behaviors [15].

Inadequate intake of high-quality protein, essential fatty acids, and micronutrients contributes to the development of sarcopenia—the age-related loss of skeletal muscle mass and strength. Sarcopenia significantly increases the risk of falls, frailty, hospitalization, and mortality in older adults [16].

The interaction between poor oral health and systemic frailty highlights the need to consider oral rehabilitation as an integral part of geriatric care planning.

3.3 Gastrointestinal consequences of poor mastication

Mechanical breakdown of food during chewing is the first step in digestion and is essential for reducing particle size and increasing the surface area available for enzymatic action. Inadequate chewing due to tooth loss results in the ingestion of larger food particles, which has several adverse effects on gastrointestinal function [17, 18]:

- Delayed gastric emptying: larger food particles require more time to break down in the stomach, leading to prolonged gastric emptying time and symptoms of bloating and postprandial discomfort [17].
- Dyspepsia and gastroesophageal reflux: inadequately chewed food can contribute to gastroesophageal reflux disease (GERD) and dyspeptic symptoms by increasing intragastric pressure and disrupting normal digestive processes.
- Reduced nutrient bioavailability: larger food particles may not be fully digested, reducing the efficiency of absorption of essential nutrients such as iron, calcium, and protein in the small intestine [18].

These gastrointestinal disorders not only affect quality of life, but over time may contribute to systemic nutrient depletion and the development of chronic gastrointestinal diseases.

3.4 Association with systemic diseases

Nutritional deficiencies associated with edentulism have been implicated as risk factors for several systemic diseases:

- Cardiovascular disease: low intake of antioxidant-rich foods (e.g., fruits, vegetables) increases oxidative stress and inflammation, key factors in atherosclerosis [19].
- Diabetes mellitus: poor dietary control and low fiber intake may exacerbate insulin resistance.
- Osteoporosis: low calcium and vitamin D intake increases the risk of bone demineralization.
- Cognitive decline: inadequate intake of essential fatty acids, vitamins B6, B12, and folate, which are essential for brain health, may accelerate neurodegeneration [4].

Recognizing and addressing these nutritional and gastrointestinal consequences through early prosthetic rehabilitation, dietary counseling, and interdisciplinary care are essential to improving health outcomes and quality of life for edentulous patients.

4. Psychological and social impact

Tooth loss impacts not only physical function but also psychological well-being and social life. The facial changes caused by edentulism often lead to low self-esteem, embarrassment, and social withdrawal. Many patients avoid speaking or eating in public because of concerns about denture stability or speech clarity, which can contribute to depression and isolation. In addition, reduced chewing ability has been linked to cognitive decline, highlighting the broader neurological consequences of edentulism, especially in older adults [10, 12, 20].

4.1 Impact on self-esteem and body image

Teeth contribute significantly to facial esthetics, speech and expression and are an essential part of individual identity and social presence. Tooth loss often leads to significant changes in facial appearance, including sunken cheeks, thinner lips, accentuated chin prominence, and general facial collapse due to loss of vertical dimension [12].

These changes can drastically affect a person's perception of their physical appearance, leading to low self-esteem and negative body image. One study found that tooth loss is consistently associated with feelings of inferiority, embarrassment, and premature aging [10].

4.2 Development of social anxiety and isolation

Missing teeth significantly affects important social functions such as smiling, speaking, and eating in public. Many edentulous individuals feel embarrassed about their appearance or fear that their dentures will fall out during conversations or meals. As a result, they may limit their social activities, avoid eating in public, and minimize social interactions [21].

Social isolation, in turn, has well-documented associations with adverse health outcomes, including increased risk of depression, cognitive decline, and cardiovascular disease [20]. The cyclical relationship between edentulism, social withdrawal, and systemic health deterioration underscores the broad impact of tooth loss on overall well-being [20, 21].

4.3 Mental distress and depression

Several studies have found a direct relationship between edentulism and symptoms of depression. Gerritsen et al. conducted a systematic review and found that edentulous individuals reported higher levels of psychological distress than those with natural teeth [22].

In the older population, particularly those already at risk for mood disorders due to factors such as retirement, loss of a loved one, and declining health, edentulism may exacerbate mental health vulnerabilities [22].

4.4 Communication difficulties and language disorders

Speech disorders can increase social anxiety, leading to further isolation and decreased self-confidence. Particularly in professional settings where clear speech is essential, edentulous individuals may suffer significant occupational disadvantages [23].

Prosthetic rehabilitation can improve speech outcomes, but even well-fitting dentures may not fully restore natural phonetic abilities, especially in cases of severe alveolar ridge resorption or neuromuscular deficiencies [20–23].

4.5 Cognitive and psychological links

Recent research suggests a possible association between edentulism and cognitive decline. Masticatory dysfunction caused by tooth loss may lead to reduced cerebral blood flow and decreased stimulation of neural pathways associated with memory and learning [4].

Although causality has not been conclusively established, observational studies have consistently found higher rates of mild cognitive impairment and dementia in edentulous individuals compared to those who retain their natural dentition [24].

The psychological and social consequences of edentulism are profound and significantly reduce quality of life, emphasizing the need for a holistic and interdisciplinary approach to the care of edentulous patients that includes not only prosthetic rehabilitation but also psychological support, social reintegration, and mental health monitoring.

5. Impact on systemic health

The systemic health consequences of edentulism are extensive and multifactorial. Edentulism is associated with an increased risk of cardiovascular disease, in part due

to chronic systemic inflammation resulting from periodontal infections that precede tooth loss. Poor dietary quality in edentulous individuals further exacerbates oxidative stress and inflammatory processes and promotes atherogenesis [3].

Most concerning, edentulism is associated with an increased risk of all-cause mortality. The confluence of malnutrition, systemic inflammation, frailty, psychological stress, and chronic disease contributes to increased mortality in the edentulous population compared with those with natural dentition.

5.1 Edentulism and cardiovascular disease

Several epidemiologic studies have found a strong association between edentulism and increased cardiovascular morbidity and mortality. One study showed that people with fewer than 10 teeth have a significantly higher risk of fatal cardiovascular events than those with a full set of teeth [3].

Proposed mechanisms include

- **Chronic inflammation:** edentulism is often the final stage of periodontal disease, a condition characterized by chronic low-grade inflammation. Persistent systemic inflammation promotes endothelial dysfunction, atherosclerosis, and thromboembolic events [25].
- **Nutritional deficiencies:** the inadequate diet associated with edentulism reduces the intake of antioxidants, fiber, and healthy fats, thereby increasing oxidative stress and inflammation, both of which are recognized contributors to cardiovascular disease [26].

Thus, tooth loss may serve both as a marker of past inflammatory burden and as an active factor contributing to cardiovascular risk.

5.2 Edentulism and diabetes mellitus

The bidirectional relationship between periodontal disease and diabetes mellitus is well established; however, edentulism introduces additional complexities. Edentulous individuals often consume a diet high in refined carbohydrates and low in fiber, which exacerbates glycemic control problems [27, 28].

In addition, the inflammatory environment resulting from residual periodontal infection prior to tooth loss may persist systemically, potentially exacerbating insulin resistance. Therefore, edentulous patients, especially those with diabetes or at risk for diabetes, require careful metabolic monitoring and dietary counseling to mitigate these risks [27, 28].

5.3 Edentulism and respiratory diseases

The oral cavity is a natural barrier to pathogens. Edentulous individuals may experience changes in the oropharyngeal microbial flora, increasing the risk of respiratory infections such as pneumonia and chronic obstructive pulmonary disease (COPD) [27, 28].

Aspiration of pathogenic bacteria from poorly maintained dentures, particularly in elderly or debilitated patients, has been identified as a significant contributor to aspiration pneumonia—a major cause of morbidity and mortality in institutionalized elderly patients [29].

Maintaining optimal dental hygiene and ensuring regular dental check-ups can help to reduce the bacterial load and lower the risk of respiratory infections in vulnerable populations.

5.4 Edentulism and osteoporosis

Bone metabolism is a systemic process influenced by hormonal, nutritional and mechanical factors. Postmenopausal women and older adults with osteoporosis have been shown to experience accelerated and more extensive alveolar bone resorption after tooth loss [30].

Conversely, severe alveolar bone loss and edentulism may serve as early clinical indicators of underlying systemic osteoporosis. Dentists, especially prosthodontists who treat edentulous patients, are therefore in a unique position to identify individuals at risk for systemic bone disease and refer them for further medical evaluation.

5.5 Edentulism and cognitive decline

Emerging evidence suggests that edentulism is associated with an increased risk of cognitive impairment and dementia. Proposed mechanisms include

- Masticatory dysfunction: reduced mastication decreases cerebral blood flow and neural stimulation, potentially accelerating neurodegenerative processes [4].
- Nutritional effects: deficiencies in vitamins (especially B12, folate) and essential fatty acids for brain health are more common in edentulous individuals.
- Inflammatory pathways: systemic inflammation caused by chronic oral infections contributes to the development of vascular dementia and Alzheimer's disease [24].

Takeuchi et al. [24] reported that community-dwelling older adults with poor posterior occlusion had higher rates of mild cognitive impairment than those with better preserved dentition, even after adjusting for confounders [24].

These findings suggest that maintaining oral function through timely prosthetic rehabilitation may have a protective effect against cognitive decline in the elderly population.

5.6 Increased risk of all-cause mortality

Cumulative studies indicate that edentulous individuals have an increased risk of all-cause mortality compared with individuals who retain some or all their natural teeth [31]. This increased risk is multifactorial and includes nutritional compromise, systemic inflammation, higher prevalence of chronic diseases, and psychosocial factors such as depression and social isolation [31].

Thus, edentulism should be considered not only as an endpoint of dental disease, but as a critical health issue with serious systemic consequences.

6. Management and prosthetic rehabilitation

Treatment of edentulism must be holistic, addressing not only the mechanical replacement of missing teeth but also the broader functional, nutritional,

psychological, and systemic consequences. Prosthetic rehabilitation is the cornerstone of treatment. Although conventional full dentures can restore basic oral functions, they often fail to provide optimal stability and comfort, especially in the mandible [32, 33].

Long-term care is essential for successful rehabilitation. Regular dental examinations are necessary to monitor tissue health, evaluate denture function, and reinforce denture hygiene practices. Preventive maintenance reduces the risk of complications such as denture stomatitis, alveolar ridge resorption, and respiratory infections [34].

6.1 Prosthetic rehabilitation

6.1.1 Conventional full dentures

Full dentures remain the most common method of restoring edentulous arches. Properly fabricated dentures can significantly improve chewing, speech, esthetics, and self-confidence [33].

Key elements of successful denture therapy include:

- Accurate impression techniques: capture functional and anatomical details to maximize stability and retention.
- Correct vertical dimension and occlusion: restoring facial height and ensuring harmonious jaw movement.
- Phonetic and esthetic considerations: careful placement of prosthetic teeth to optimize speech and appearance [33].

However, challenges remain with conventional dentures, particularly regarding instability of mandibular dentures due to severe ridge resorption [8]. Such limitations necessitate consideration of more advanced options.

6.1.2 Implant-retained overdentures

Implant-retained overdentures have revolutionized the management of edentulism, particularly in the mandible. As established by the York Consensus Statement [35], two-implant mandibular overdentures are now considered the standard of care for edentulous patients seeking improved function [35].

Advantages include:

- Superior stability and retention: improved chewing efficiency, speech clarity and comfort.
- Alveolar bone preservation: mechanical stimulation from implants helps slow ridge resorption [34].
- Improved patient satisfaction: higher quality of life scores compared to conventional dentures [36].

Implant overdentures should be strongly considered for patients who have the anatomical, financial, and medical capacity to undergo surgery [36].

6.1.3 Fixed implant prosthodontics

For selected patients, fixed, full-arch, implant-supported prosthodontics (e.g., all-on-4, all-on-6 concepts) provide the highest level of function, esthetics and patient satisfaction. These solutions, while more expensive and surgically demanding, offer lifelike replacement of the dentition and nearly complete restoration of natural oral function [34, 36].

6.2 Nutritional counseling and intervention

Given the strong association between edentulism and nutritional compromise, dietary counseling should be an integral part of rehabilitation [7]. Collaboration with dietitians may be helpful:

- Promote a balanced, nutrient-dense diet.
- Suggest changes in food texture without compromising nutritional value.
- Prevent malnutrition, sarcopenia, and associated systemic diseases [7].

Prosthetic rehabilitation alone may not fully restore dietary diversity; therefore, active dietary management remains necessary after prosthesis provision.

6.3 Psychological support and social reintegration

The psychosocial impact of edentulism requires psychological assessment and support strategies [10]. Management approaches may include

- Pre-treatment counseling: setting realistic expectations for prosthodontic performance and adaptation periods.
- Support groups: facilitating patient participation in peer support groups to share experiences and coping strategies.
- Referral to mental health professionals: For patients with significant depression, anxiety, or social withdrawal [10].

Holistic rehabilitation must prioritize emotional recovery in addition to functional restoration.

6.4 Maintenance and long-term follow-up

Successful management of edentulism extends beyond the initial delivery of the prosthesis. Regular follow-up visits are essential to

- Evaluate tissue health and prosthesis fit.
- Relining, rebasing or remanufacturing dentures as ridge resorption progresses.
- Reinforcing denture hygiene instructions to prevent stomatitis and respiratory infections [29].
- Monitor nutritional status and systemic health markers.

Proactive maintenance schedules can prevent minor problems from escalating into major complications and ensure long-term patient satisfaction [29].

6.5 Future directions: Digital technologies and bioengineering

Digital workflows, including CAD/CAM prostheses, are improving the precision, efficiency, and personalization of prosthetic rehabilitation [33]. These technologies offer:

- Improved fit and esthetics.
- Reduced chair time and lab turnaround.
- Easy duplication of lost or damaged prostheses through digital records.

Looking further into the future, advances in tissue engineering and regenerative dentistry may eventually offer biologically integrated solutions, such as bioengineered teeth or alveolar regeneration therapies [32].

7. Conclusion

Edentulism is far more than a localized dental condition; it is a complex, multifactorial public health issue with profound implications for the overall health and quality of life of affected individuals. The psychological and social impact of toothlessness is profound, often leading to low self-esteem, depression, and social isolation. These problems, along with close associations with systemic diseases such as cardiovascular and cognitive disorders, emphasize the broad public health implications of edentulism.

Effective management of edentulism requires a multidisciplinary approach that combines prosthetic rehabilitation with nutritional counseling, psychological support, and regular follow-up. Advances in digital technologies have improved prosthetic outcomes, and future innovations in regenerative dentistry may offer biological solutions. With an aging population, it is imperative that edentulism be treated as a systemic health problem and that comprehensive care be integrated into clinical and public health strategies.

Conflict of interest

The authors declare no conflict of interest.

Author details

Felicia Gabriela Beresescu*, Simona Gabriela Mucenic and Andrea Bors
George Emil Palade University of Medicine, Pharmacy, Science,
and Technology of Targu Mures, Targu Mures, Romania

*Address all correspondence to: felicia.beresescu@umfst.to

IntechOpen

© 2025 The Author(s). Licensee IntechOpen. This chapter is distributed under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/4.0>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited. 

References

- [1] Escobar GAA, Cartagena FJR, de González WYE, de Rodríguez KAA, Bravo M, Mesa F, et al. Edentulism and quality of life in the Salvadoran population: A cross-sectional study. *BMC Oral Health*. 2024;**24**(1):928
- [2] Kassebaum NJ, Bernabé E, Dahiya M, Bhandari B, Murray CJ, Marcenes W. Global burden of severe tooth loss: A systematic review and meta-analysis. *Journal of Dental Research*. 2014;**93**(suppl. 7):20S-28S
- [3] Ishikawa S, Konta T, Susa S, Ishizawa K, Togashi H, Ueno Y, et al. Association between presence of 20 or more natural teeth and all-cause, cancer-related, and cardiovascular disease-related mortality: Yamagata (Takahata) prospective observational study. *BMC Oral Health*. 2020;**20**(1):353
- [4] Jang JH, Kim JL, Kim JH. Association between denture use, chewing ability, and all-cause mortality in middle-aged and older adults who exercised regularly in Korea. *Scientific Reports*. 2021;**11**(1):6061
- [5] Atwood DA. Reduction of residual ridges: A major oral disease entity. *The Journal of Prosthetic Dentistry*. 1971;**26**(3):266-279
- [6] Kihara M, Ogino Y, Matsushita Y, Morita T, Sawae Y, Ayukawa Y, et al. In vitro assessment of the effect of implant position on biomechanical behaviors of implant-supported removable partial dentures in Kennedy Class II condition. *Materials (Basel)*. 2021;**14**(9):2145
- [7] Su JN, Pan YH, Dorj O, Lin JC, Salamanca E, Chen IW, et al. Association between oral health status and occlusal bite force in young adults. *Journal of Dental Sciences*. 2024;**19**(2):1182-1189
- [8] Carlsson GE. Clinical morbidity and sequelae of treatment with complete dentures. *The Journal of Prosthetic Dentistry*. 2018;**119**(5):541-546
- [9] Carlsson GE, Magnusson T. Management of Temporomandibular Disorders in the General Dental Practice. Quintessence Publishing; 1999. Available from: <https://books.google.co.uk/books?id=3AhqAAAAMAAJ>
- [10] Alalawi H, Alhumaily H. Professional assessment compared to patients' attitudes toward tooth replacement: A cross-sectional study. *BMC Oral Health*. 2023;**23**(1):634
- [11] Srinivasan M, Cantor R, Papaspyridakos P, Weber HP. Edentulism, implant rehabilitation, and oral and general health: A review. *Journal of Clinical Medicine*. 2020;**9**(8):2434
- [12] Zarb GA, Bolender CL, Eckert SE. Prosthodontic Treatment for Edentulous Patients. 13th ed. Elsevier; 2013. Available from: <https://www.us.elsevierhealth.com/prosthodontic-treatment-for-edentulous-patients-9780323078443.html>
- [13] Nowjack-Raymer RE, Sheiham A. Association of edentulism and diet and nutrition in US adults. *Journal of Dental Research*. 2003;**82**(2):123-126
- [14] Hung HC, Willett W, Ascherio A, Rosner BA, Colditz G, Joshupura KJ. Tooth loss and dietary intake. *Journal of the American Dental Association (1939)*. 2003;**134**(9):1185-1192
- [15] Walls AWG, Steele JG. The relationship between oral health and nutrition in older people. *Mechanisms of Ageing and Development*. 2004;**125**(12):853-857

- [16] O'Connor D, Molloy AM, Laird E, Kenny RA, O'Halloran AM. Sustaining an ageing population: The role of micronutrients in frailty and cognitive impairment. *The Proceedings of the Nutrition Society*. 2023;**82**(3):315-328
- [17] Lee DJ, Saponaro PC. Management of edentulous patients. *Dental Clinics of North America*. 2019;**63**(2):249-261
- [18] Bousiou A, Konstantopoulou K, Polychronopoulou A, Halazonetis DJ, Schimmel M, Kossioni AE. Sociomedical and oral factors affecting masticatory performance in an older population. *Clinical Oral Investigations*. 2022;**26**(4):3477-3486
- [19] Chopra A, Jayasinghe TN, Eberhard J. Are inflamed periodontal tissues endogenous source of advanced glycation end-products (AGEs) in individuals with and without diabetes mellitus? A systematic review. *Biomolecules*. 2022;**12**(5):642
- [20] Cacioppo JT, Cacioppo S. Social relationships and health: The toxic effects of perceived social isolation. *Social and Personality Psychology Compass*. 2014;**8**(2):58-72
- [21] Al-Rafee MA. The epidemiology of edentulism and the associated factors: A literature review. *Journal of Family Medicine and Primary Care*. 2020;**9**(4):1841-1843
- [22] Mira R, Newton JT, Sabbah W. The longitudinal relationship between edentulism and the progress of multimorbidity. *Nutrients*. 11 Jul 2024;**16**(14):2234
- [23] Rubenstein JE, Powers JM, Kiat-Amnuay S. Speech intelligibility in patients with conventional complete dentures versus implant-retained overdentures: A systematic review. *The Journal of Prosthetic Dentistry*. 2016;**116**(2):190-195
- [24] Takeuchi K, Izumi M, Furuta M, et al. Posterior teeth occlusion and cognitive decline in community-dwelling older people: The Hisayama study. *The Journals of Gerontology. Series A, Biological Sciences and Medical Sciences*. 2019;**74**(10):1596-1602
- [25] Tonetti MS, Van Dyke TE. Periodontitis and atherosclerotic cardiovascular disease: Consensus report of the joint EFP/AAP workshop. *Journal of Periodontology*. 2013;**84**(4-s):S24-S29
- [26] Jung YS, Park T, Kim EK, Jeong SH, Lee YE, Cho MJ, et al. Influence of chewing ability on elderly adults' cognitive functioning: The mediating effects of the ability to perform daily life activities and nutritional status. *International Journal of Environmental Research and Public Health*. 2022;**19**(3):1236
- [27] Tung HJ, Ford R. Incident edentulism and number of comorbidities among middle-aged and older Americans. *Gerodontology*. Dec 2023;**40**(4):484-490
- [28] Chapple IL, Genco R. Diabetes and periodontal diseases: Consensus report of the Joint EFP/AAP Workshop on Periodontitis and Systemic Diseases. *Journal of Clinical Periodontology*. 2013;**40**(Suppl. 14):S106-S112
- [29] Terpenning MS. Geriatric oral health and pneumonia risk. *Clinical Infectious Diseases*. 2005;**40**(12):1807-1810
- [30] Dervis E. Oral implications of osteoporosis. *Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology, and Endodontics*. 2005;**100**(3):349-356
- [31] Tsakos G, Watt RG, Rouxel PL, de Oliveira C, Demakakos P. Tooth loss

associated with physical and cognitive decline in older adults. *Journal of the American Geriatrics Society*. 2010;**58**(2):220-225

[32] Duailibi MT, Duailibi SE, Young CS, Bartlett JD, Vacanti JP, Yelick PC. Bioengineered teeth from cultured rat tooth bud cells. *Journal of Dental Research*. 2004;**83**(7):523-528

[33] Goodacre BJ, Goodacre CJ. Digital prosthodontics: History, trends, and opportunities. *Journal of Prosthodontic Research*. 2018;**62**(2):131-139

[34] Misch CE. *Contemporary Implant Dentistry* [Electronic Resource]. 3rd ed. Mosby Elsevier; 2008

[35] AlHelal AA, Alzaid AA, Almujeel SH, Alsaloum M, Alanazi KK, Althubaitiy RO, et al. Clinical peri-implant parameters and marginal bone loss for early mandibular implant overdentures: A follow-up of 60 months. *Medicina (Kaunas, Lithuania)*. 2024;**60**(4):588

[36] Nejatidanesh F, Savabi O, Savabi G, Razavi M. How the initial retentive force of implant-supported overdentures can be affected with splinted and unsplinted attachments systems. *Dental Research Journal (Isfahan)*. 2021;**18**:101

Chapter 2

Innovative Materials and Techniques for Dentures: A Contemporary Approach

*Dana Gabriela Budala, Ionut Luchian,
Dragos Ioan Virvescu, Oana Maria Butnaru,
Elena Raluca Baciuc and Monica Silvia Tatarciuc*

Abstract

This chapter delves into modern advancements in denture fabrication, emphasizing the use of innovative materials and state-of-the-art techniques. Topics include the integration of biocompatible nanomaterials, advanced ceramics, and next-generation polymers that enhance durability, esthetics, and functionality. Cutting-edge technologies like 3D printing and CAD/CAM systems enable precise customization and rapid prototyping, ensuring superior patient comfort and tailored solutions. The chapter also highlights minimally invasive approaches and their role in oral rehabilitation, addressing the growing demand for effective, esthetic, and long-lasting dental solutions. These innovations not only improve patient satisfaction but also enhance the efficiency of clinical workflows. The synergy between advanced materials and technology paves the way for a new era in prosthodontics.

Keywords: dentures, CAD-CAM systems, polymers, 3D printing, nanoparticles

1. Introduction

Advancements in denture manufacturing have become a cornerstone in modern dentistry, addressing the ever-changing needs and expectations of patients and professionals alike. While traditional fabrication methods have laid the groundwork for prosthetic dentistry, their limitations often fall short of the precision, comfort, and durability demanded by contemporary standards [1].

These traditional techniques, though historically effective, frequently require time-consuming adjustments and replacements, reflecting the need for innovation in materials and methodologies. In recent years, the introduction of advanced materials such as biocompatible polymers, high-impact acrylics, and nanotechnology-infused resins has revolutionized the field.

These innovations not only enhance the strength and longevity of dentures but also improve their esthetic appeal, aligning closely with the preferences of today's patients. By addressing issues such as microbial adhesion and wear resistance, these materials provide solutions that significantly reduce the need for frequent repairs and replacements, thus elevating the overall patient experience [2]. At the same time, technological breakthroughs like CAD/CAM systems and 3D printing have ushered in a new era of precision and personalization in denture fabrication. These technologies enable dental professionals to create prosthetics tailored to the unique anatomy of each patient, offering superior fit and functionality [1, 2]. Digital scanning techniques eliminate the discomfort associated with traditional impressions, streamlining the process and minimizing errors. Such advancements not only reduce chair time for patients but also enhance the efficiency of dental practices, making high-quality prosthetics accessible to a broader population.

These innovations in denture manufacturing also align with the growing emphasis on minimally invasive procedures. By reducing the reliance on traditional methods that often involve discomfort and extended recovery times, advanced techniques ensure a smoother and more patient-friendly experience [2, 3]. Moreover, the integration of emerging trends such as regenerative materials and smart technologies points to a future where dentures not only restore oral functionality but also contribute to proactive health monitoring.

This forward-thinking approach to denture fabrication signifies a paradigm shift, blending science and technology to meet the complex needs of modern dentistry. The progress achieved thus far underscores the importance of continuing research and development in this domain, ensuring that patients benefit from solutions that not only enhance their oral health but also improve their overall quality of life.

2. History of dentures

The development and manufacture of dentures has progressed over many centuries, reflecting the never-ending human desire to remedy tooth loss and regain the use of oral functionality. Denture fabrication has come a long way from its humble origins using natural materials to provide state-of-the-art prosthetic solutions. This incredible journey is a testament to the amazing advances achieved in dentistry, material science, and technology.

2.1 The beginnings of dentures

Dentures have been around since ancient times, when people started using what they could find in nature to fill up gaps resulting from missing teeth. Some of the earliest denture designs that have been documented date back to ancient Etruscan in Italy, who lived approximately 700 BC [4]. These early prosthetic devices, made from a combination of animal and human teeth set on gold rings, served their purpose well. In the same manner, ancient Egyptian artisans used gold wires to fix false teeth in partial dentures. Due to the high cost of the materials and the need for experienced artisans, dentures were mostly created for the aristocracy and the privileged class of that time. Oftentimes, these early designs were more for esthetic effect than utility, and they were not very durable or functional [4].

2.2 Medieval and renaissance period

Due to the stagnation of scientific and medical knowledge throughout the Middle Ages, denture production witnessed little advancement. Nonetheless, dental technology advanced throughout the Renaissance.

Dentists started experimenting using elephant or hippopotamus ivory for denture bases in the sixteenth century. The natural teeth that remained were typically held in place by these handmade dentures, which were attached with silk threads or metal springs [5].

2.3 The eighteenth and nineteenth centuries: The age of innovation

The introduction of porcelain as a dental material in the eighteenth century was a turning point in the history of denture production. French dentist Nicolas Dubois de Chémant revolutionized the dental profession in 1774 when he debuted porcelain dentures. Compared to earlier materials, porcelain was more esthetically pleasing and long-lasting, and it looked more like real teeth. The lack of durability and resilience of these dentures made them impractical [6].

Dentures were mass-produced in the nineteenth century, thanks to industrialization, which led to additional improvements. Denture bases made of vulcanized rubber, which Charles Goodyear developed in 1839, were popular because of the material's low cost, malleability, and simplicity of molding. Using vulcanite dentures in conjunction with porcelain teeth made a more affordable option available to a broader population [4, 7]. "Waterloo teeth," dentures fabricated from the jawbones or cadavers of fallen soldiers, also appeared at this time and were mounted on various bases [7].

2.4 The twentieth century: A paradigm shift in denture fabrication

Thanks to developments in materials science and technology, a new age of invention began in the twentieth century. The 1930s saw the rise of acrylic resin over vulcanized rubber as the material of choice for denture bases. Denture manufacturing has traditionally relied on acrylic due to its high processing ease, biocompatibility, and excellent esthetics.

To overcome porcelain's shortcomings, synthetic polymers were used to make denture teeth more durable and resistant to wear. Improved shade and morphological customization were other benefits of these materials that contributed to dentures a more realistic appearance [5].

The development of impression materials and techniques, among other technological advancements, completely transformed the process of making dentures. More precise impressions were made possible by elastomeric and alginate impression materials, which improved the fit and performance of dentures. The production process was further simplified with the creation of dental laboratories that have state-of-the-art instruments [6].

Midway through the twentieth century, individualized partial dentures, overdentures, and full dentures were developed with an emphasis on patient comfort and usefulness. Furthermore, dental education progressed, with an increased focus on prosthodontics as a subspecialty of general dentistry.

2.5 The twenty-first century and beyond

The use of digital technology and new materials has caused an enormous shift in denture production in the twenty-first century. The efficiency and accuracy of denture manufacture has been greatly enhanced by computer-aided design and manufacturing (CAD/CAM) technologies. With the advent of digital workflows like intraoral scanning and 3D printing, many one manual processes have been automated, leading to better fit and comfort with less manufacturing time and fewer mistakes [8].

Biocompatible polymers, nanocomposites, and improved ceramics are only a few examples of the remarkable developments in materials science. These alternatives to conventional acrylic and porcelain overcome the drawbacks of the former with their enhanced strength, longevity, and esthetic appeal.

In line with eco-friendly policies, additive manufacturing processes (such as 3D printing) reduce material waste. Furthermore, these technologies are improving denture manufacture because of their price and accessibility, allowing a greater population to have access to high-quality dentures [9].

With the combination of AI, robots, and biomimetic materials, denture manufacture will be rethought, opening the door to a new age of customized, efficient, and environmentally friendly solutions in dentistry.

3. Evolution of polymers in denture fabrication

In the history of prosthodontics, polymers have been instrumental in revolutionizing denture production, which in turn has improved patient care. Decades of innovation, research, and adaptation have marked the journey of polymer science in dentistry, from its humble beginnings as a basic material to the creation of complex blends designed to address particular clinical needs. This evolution has been driven by the rising demands for long-term durability, esthetics, functionality, and patient comfort (**Figure 1**).

Unlike more conventional dental materials like ivory, porcelain, and vulcanized rubber, polymers have their roots in the early twentieth century [4, 5, 9]. Despite its popularity, vulcanite—the first material for denture bases—had several drawbacks. Its emergence in the middle of the nineteenth century provided a practical and inexpensive substitute for more costly materials; nonetheless, it was far from perfect due to its lack of esthetic value and flexibility. The introduction of polymethyl methacrylate (PMMA), more often known as acrylic resin, in the 1930s marked a turning point. Lightweight, long-lasting, and esthetically beautiful, PMMA swiftly became the material of choice for denture bases, causing a revolution in denture manufacture [4, 9, 10].

PMMA overcame a lot of the problems that were present with older materials. Patients were able to enjoy a more realistic dentures because of its translucency, which mirrored the look of real oral tissues. Furthermore, dental specialists were able to produce perfect fits with PMMA during manufacturing, which improved the usefulness and comfort of dentures [4]. The benefits of PMMA were not without their downsides, though. Researchers began to investigate methods to enhance its mechanical characteristics in response to its weakness in resistance to wear and its ease of fracture under extreme stress, sparking a new era of innovation in the field of polymer science.

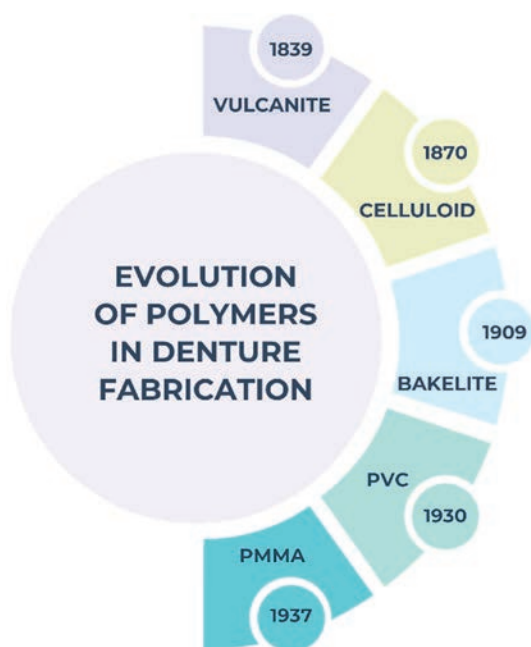


Figure 1.
Evolution of polymers in denture fabrication.

Efforts to improve PMMA included adding cross-linking agents to make it more structurally strong throughout the middle of the twentieth century. The lifespan of dentures was increased because to the increased resistance to cracking and deformation displayed by cross-linked PMMA. Moreover, developments in curing processes, such heat- and pressure-curing procedures, increased PMMA's density and homogeneity, decreased its porosity, and enhanced its overall performance [8, 11].

A major step forward in the development of dental polymers was the introduction of high-impact acrylics in the latter part of the twentieth century. In order to make a material that could endure higher impact pressures without breaking, these modified acrylics mixed rubber-like particles—like butadiene-styrene copolymers—with the PMMA matrix [9]. Patients who have a tendency to misplace their dentures or who need prosthesis in situations with high levels of stress may find this innovation very helpful. A huge improvement over conventional PMMA, high-impact acrylics overcome the material's mechanical shortcomings without sacrificing its good looks or ease of handling [10].

At the same time, a new class of polymeric materials called soft liners was introduced to the profession with the express purpose of making patients more comfortable. Patients with delicate oral tissues or complicated anatomical characteristics frequently experienced irritation or pain due to traditional denture bases. Cushioning pressures during chewing are absorbed by soft liners, which are usually constructed of silicone or plasticized acrylics, lowering the likelihood of discomfort. Patients suffering from xerostomia or resorbed ridges benefited greatly from these products. Nevertheless, there has been continuous study to enhance their biocompatibility and endurance due to concerns such material deterioration and microbial colonization [11, 12].

The development of polymers for dentures entered a new revolutionary phase with the advent of flexible denture materials. Thermoplastic resins, which include nylon-based polymers, are perfect for creating clasps and partial dentures because of their extreme pliability and durability. Lightweight, discrete, and pleasant alternatives were provided to patients using flexible polymers that conformed to the shape of the oral cavity instead of using metal frameworks. Because of their transparent appearance, these materials were able to mix in with natural tissues, which addressed esthetic problems as well. Further improvements in material compositions were necessitated due to the processing needs and poorer dimensional stability of flexible polymers, which, although advantageous, presented obstacles [13].

As concerns about patient safety and environmental sustainability grew, biocompatibility became an important factor in dental polymer research. The development of hypoallergenic and non-toxic materials was facilitated by developments in polymer chemistry, which in turn improved patient outcomes by decreasing the likelihood of adverse responses [14]. Another long-standing problem with denture surfaces becoming colonized by microbes was solved by new antibacterial polymers. To combat diseases like denture stomatitis, these materials included antimicrobial chemicals or coatings that actively prevented the growth of fungal organisms and bacteria.

The use of polymers in denture production has been greatly expedited by the rise of digital dentistry. With the use of CAD/CAM technology, polymer-based dentures were able to be precisely manufactured with minimum opportunity for human mistake. Denture manufacture has also been revolutionized by the advent of 3D printing technology, which enables the quick creation of prototypes and individualization of prostheses made of polymers. By streamlining production and reducing material waste, additive manufacturing processes are in line with ecologically friendly practices [15].

The future of denture production is bright, thanks to studies of smart polymers. Because of their adaptable characteristics, such as shape memory and self-healing capabilities, these materials can instantly adjust to new conditions in the oral cavity. There is great promise in smart polymers as a means to improve the performance and durability of dentures, providing patients with solutions that may change with their changing demands [16]. For example, dentures made of shape-memory polymers might be designed to fit tightly even when the oral cavity undergoes natural changes like resorption or aging.

Future denture manufacture possibilities may be reimagined by combining regenerative medicine with polymer technology. The creation of dentures that assist the regeneration of oral tissues might be made possible by advances in tissue engineering and bioresorbable polymers. These advancements show potential in providing patients with really restorative remedies to the problems caused by severe alveolar resorption or complicated anatomical anomalies [7].

More and more, research is pushing the boundaries of polymer technology, which bodes well for the future of denture manufacture. The prosthesis that patients get will not only fulfill their needs but also exceed them. Synergy between material innovation and digital technology will shape the next chapter of dental polymers' evolution, further solidifying their place as vital components of modern dentistry.

4. Emerging trends in denture fabrication

Denture manufacturing is one area where artificial intelligence (AI) has had a profound impact on the dentistry business, thanks to the improvements in accuracy, efficiency, and patient outcomes it has brought about. Traditionally, creating dentures

requires multiple patients visits, meticulous manual work and significant time investment. AI-driven systems are transforming this process by integrating advanced technologies such as machine learning, computer-aided design (CAD), and computer-aided manufacturing (CAM), leading to improved accuracy and reduced production times [17].

Denture fabrication in particular has been impacted by the technological revolution in computer-aided design and computer-aided manufacturing (CAD/CAM). These technologies allow dental professionals to create highly accurate 3D models of patients' oral structures, ensuring a more precise fit and reduced adjustment time.

By combining digital processes, this revolutionary technology overcomes many of the drawbacks of conventional denture-making techniques while simultaneously producing prosthetic solutions that are precise, efficient, and uniquely suited to each patient. Dental practices that have embraced CAD/CAM have seen an increase in accuracy standards, a decrease in production mistakes, a marked improvement in patient comfort, and a simplification of clinical operations [18].

As the need for faster and more accurate prosthetic fabrication grew, computer-aided design and manufacturing (CAD/CAM) technology made its way into the dentistry industry [19]. The quality, uniformity, and accuracy of denture manufacture were frequently compromised by traditional methods, which were mostly dependent on hand craftsmanship and labor-intensive processes. Dentists and technicians had to deal with a number of intricate processes that were susceptible to human mistake, such as acquiring impressions, casting models, and manufacturing dentures. In response to these difficulties, computer-aided design and manufacturing (CAD/CAM) technologies introduced digital workflows that automate and improve several steps in the denture production process [20].

4.1 The digital workflow in denture fabrication

Initial steps in the computer-aided design and manufacturing process start with data gathering, usually in the form of digital impressions captured using intraoral scanners. Instead of using typical impression materials, these devices may record three-dimensional reconstructions of the patient's oral anatomy, which are very detailed. Not only can digital impressions increase precision but they also improve the patient experience by decreasing pain and chairside time [21].

It is with computer-aided design (CAD) software that the prosthesis is created once digital impressions have been taken. Dentists and technicians may use the software's exact customization capabilities to customize the denture's size, form, occlusion, and esthetics to suit each patient's specific needs. Before these ideas are sent to the manufacturing stage, they are examined and improved in real time to make sure they fit and work well [19–21].

After the final design is uploaded to a computer numerically controlled (CAM) system, the denture is made using milling or 3D printing, two examples of sophisticated manufacturing processes. These mechanized procedures ensure precision and uniformity that would be challenging to do by hand. Thanks to the accuracy of the computerized workflow, the finished dentures are polished and fitted to the patient with few adjustments needed (**Figure 2**).

4.2 Benefits of CAD/CAM Technology

Denture manufacture becomes much more precise with the use of CAD/CAM technology, which is a major benefit. With digital impressions, every detail of the

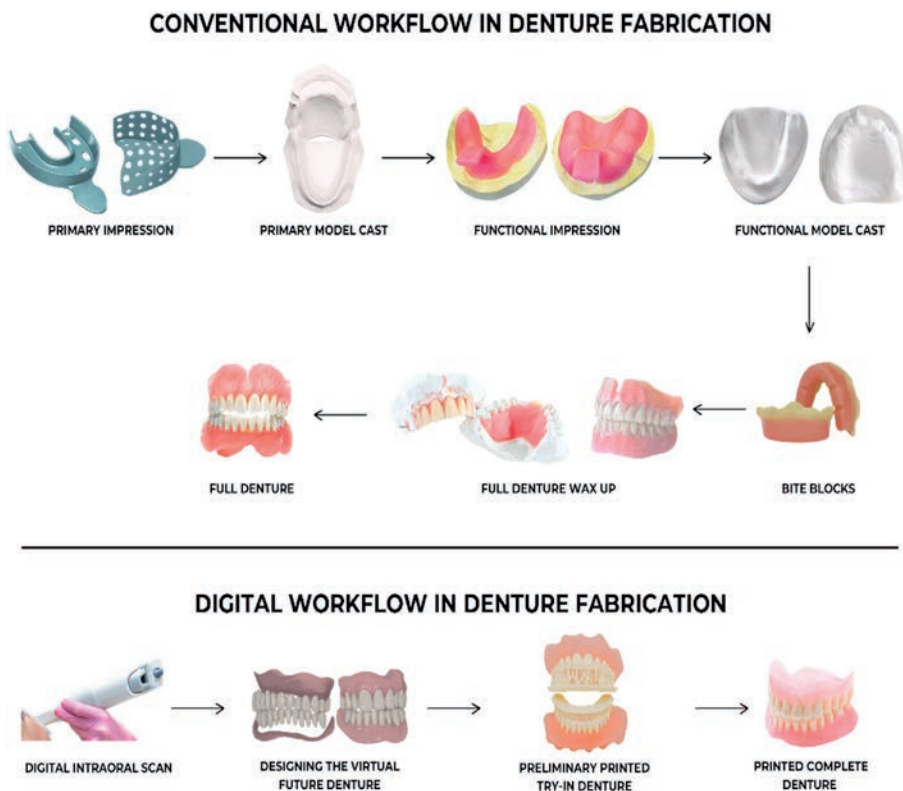


Figure 2.
Conventional and digital workflow in denture fabrication.

oral cavity may be precisely reproduced, guaranteeing a tight, comfortable fit for the prosthesis. Clinicians and patients alike will appreciate the time savings that result from this degree of accuracy, since it minimizes the need for manual modifications during fitting sessions. As a result of the dentures' increased stability and usefulness thanks to a better fit, the patient's self-confidence in chewing, speaking, and smiling is improved [22].

Errors can occur at several phases of the traditional denture-making process, including acquiring impressions, casting models, and manufacturing. Improperly fitted dentures, caused by these mistakes, may necessitate costly repairs or replacements. Automating critical processes and making use of very precise digital tools, CAD/CAM technology reduces the probability of such mistakes. Consistent outcomes across several instances are guaranteed by the computerized workflow, which eradicates variability caused by human factors [20, 23].

Completely individualized dentures that fit the patient's mouth and look perfect are now possible because of computer-aided design and manufacturing (CAD/CAM) technology. The program enables the user to customize the dentures' form, shade, and occlusal surface to match the patient's esthetic and functional requirements. Because of this personalization, patients are more satisfied overall, and they report feeling more comfortable and enjoying a more natural look [24]. The fabrication of dentures is now faster thanks to digital processes than it was in the past. Manufacturing, design, and scanning all work together to cut out the intermediary steps, which speeds up the production process.

In spite of the high cost at entry point, CAD/CAM technology pays for itself in the long run because of its precision and efficiency. Dental offices and their patients can save money in the long run because of less material waste, fewer remakes, and less time spent. Dental labs that handle a large number of cases benefit greatly from CAD/CAM systems because of their capacity for expansion [25].

Cutting down on material waste during fabrication is one way that CAD/CAM technology fits nicely with today's environmental aims. The use of extra material during casting and the need for hand corrections are two aspects of traditional denture-making processes that add to the environmental effect. In conjunction with additive manufacturing processes, such as 3D printing, digital workflows maximize material use [26].

Although there are many advantages to CAD/CAM technology, there are also several obstacles to its widespread use. Smaller dental offices and labs may not be able to afford the high upfront costs of software and equipment. It may be necessary to invest time and resources in specialized training for physicians and technicians in order for them to use CAD/CAM systems efficiently.

The degree to which CAD/CAM systems are compatible with preexisting workflows is an additional factor to think about [27]. Changes may be necessary for integration with conventional processes and materials, especially for practices making the switch from analogue to digital workflows. Another important issue is making sure all the CAD/CAM systems are reliable and consistent [28].

Emerging technology, improved materials, and new processes are going to revolutionize denture manufacture in the future. New opportunities in patient care are being opened up by these innovations, which attempt to solve long-standing problems in prosthodontics include increasing fit, function, durability, and esthetics [29]. A giant step forward in oral rehabilitation has been achieved with the integration of AI, robotic dentistry, regenerative materials, and smart denture systems.

4.3 Artificial intelligence (AI) in denture fabrication

Artificial intelligence (AI) has the ability to revolutionize denture design and manufacture, and it is quickly becoming an essential component of contemporary dentistry. In order to provide effective and efficient treatment regimens, AI-powered algorithms can sift through mountains of data found in patient records, digital impressions, and imaging systems [30, 31]. Denture fabrication workflows are about to undergo a revolutionary change with the inclusion of AI. This technology will automate complicated operations and drastically reduce the risk of human mistakes.

When it comes to making dentures, predictive modeling is where artificial intelligence shows the most promise [32]. Artificial intelligence algorithms may analyze a person's chewing dynamics, esthetic preferences, and oral anatomy to create customized designs that look great and fit tightly [33–35]. Additionally, these algorithms have the ability to accurately predict how the oral cavity will change over time, which paves the way for the development of adaptable dentures that can adapt to the changing anatomy of the patient without compromising their functioning [36, 37].

Additionally, patient education and communication are also impacted by the incorporation of AI. With the use of AI-driven virtual simulations, patients may get a better feel for the treatment process and establish reasonable expectations by seeing how their dentures will seem and work before the procedure even begins. Clinicians may also use these tools to provide individualized suggestions, which improves treatment for patients [38].

4.4 Dentures as drug delivery systems: A revolutionary road in prosthodontics

The possibility for smart dentures to function as medication delivery devices is another fascinating use application. Denture that includes micro-reservoirs built into the base allow for the direct administration of drugs into the oral cavity. Patients who need medicines that may be applied locally, including antifungal drugs for denture stomatitis or analgesics for post-operative discomfort, would benefit greatly from this [39].

The idea of using dentures as drug delivery systems leverages their constant presence in the oral cavity. Unlike traditional drug delivery methods, such as oral tablets or topical ointments, smart dentures allow for direct and localized application of medication. This ensures that therapeutic agents are delivered precisely where they are needed, minimizing systemic absorption and potential side effects.

Using micro-reservoirs or cross-linked polymers in the denture structures is where this technology really shines [40]. Medications including antifungal agents, antibiotics, analgesics, and anti-inflammatory medicines can be stored in these reservoirs and released gradually. A regulated and focused therapeutic response is made possible by the release being triggered by certain stimuli, such as changes in temperature, pH, or enzyme activity.

Fungal infections, such as *Candida albicans*, can lead to denture stomatitis, an inflammatory illness that many people with dentures deal with. Creams and pills intended to eradicate fungus are the mainstays of traditional therapy, but they may be unpleasant for patients to apply and can have systemic adverse effects if not taken properly. A better option is to use smart dentures, which gradually release antifungal drugs into the suffering tissues [41–43].

An example of a smart denture that can offer ongoing therapeutic activity without the need for repeated manual applications is one that is integrated with a slow-releasing antifungal drug. This denture can reduce fungus burden and promote healing. Not only does this make therapy more effective, but it also makes patients more compliant and makes their daily tasks easier.

By directing the medicine to the precise location where it will have the greatest impact, localized drug delivery increases the treatment's effectiveness while decreasing its systemic adverse effects. In cases of inflammation or infections, when exact administration greatly improves therapeutic results, this focused method is ideal.

The danger of systemic absorption and associated negative effects is much diminished because the medicine is contained within the mouth. Patients with preexisting conditions or who are very young may be more prone to serious side effects from medications; therefore, this is of crucial significance for them [44]. Several obstacles must be overcome before drug-delivering smart dentures may achieve popular use, notwithstanding their potential:

The dentures' structural integrity, fit, or esthetics must not be compromised when medication reservoirs and release mechanisms are integrated. Scientists need to find ways to make prostheses that are both durable and comfortable while also incorporating therapeutic functions into biocompatible materials. It is important that medications kept in dentures be able to withstand changes in temperature, saliva, and oral bacteria for long periods of time [39, 40]. A significant problem for producers is guaranteeing the efficacy and stability of these medications.

Highly developed engineering and material science skills are required for the design of accurate and dependable release mechanisms that react to certain triggers, such as pH or enzyme activity. Over- or under-dosing on medicine distribution might occur if these systems fail.

Compared to traditional prostheses, the cost of smart dentures that can dispense drugs is expected to be higher. Affordable production and delivery methods are essential for making these advancements available to all patients, especially those from underprivileged communities. Dentures that distribute drugs must be approved after extensive testing to guarantee their safety and effectiveness as medical devices. It may take a lot of time and energy to meet regulatory criteria.

The advent of drug-delivering smart dentures has revolutionized the field of prosthodontics by providing a more practical, streamlined, and personalized method of dental hygiene treatment. Improved patient outcomes and quality of life may be possible with the help of these sophisticated prostheses by alleviating pain, controlling chronic illnesses, and avoiding infections through the regulated and localized release of medicine [45, 46]. Despite the obstacles, these devices are set to become standard equipment in modern dentistry thanks to continuing research and technical developments, which will revolutionize the management and treatment of oral health.

5. Contemporary techniques in dentures fabrication

The emergence of 3D printing has transformed the process for manufacturing dentures. Several 3D printing technologies (**Figure 3**), including Stereolithography (SLA), Selective Laser Sintering (SLS), and Fused Deposition Modeling (FDM), play pivotal roles in the production of complete dentures. Each of these technologies brings unique advantages and capabilities to the field, enabling dental professionals to address diverse patients' needs [47]. This thorough examination investigates the details of SLA, SLS, FDM, and various other 3D printing technologies relevant to denture production, emphasizing their processes, materials, and roles in contemporary dentistry.

5.1 Stereolithography (SLA)

Stereolithography (SLA) is one of the earliest and most widely used 3D printing technologies in dentistry. It operates on the principle of photopolymerization, where a liquid resin is solidified layer by layer using a laser beam. SLA is particularly valued for its ability to produce highly detailed and smooth dental components, making it ideal for fabricating complete dentures [48].

The SLA process starts with a reservoir filled with liquid resin. A UV laser precisely cures the resin according to a digital 3D model, solidifying exact cross-sectional layers of the design. The build platform gradually descends as each layer is added, continuing until the final structure is achieved. After printing, the denture needs to

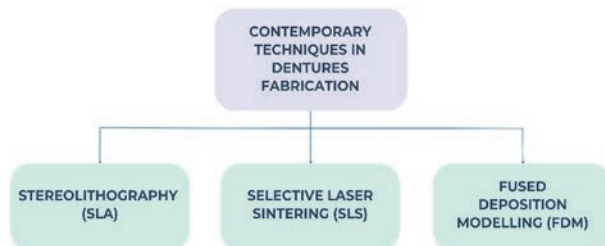


Figure 3.
Contemporary techniques in denture fabrication.

be cleaned to eliminate any uncured resin and may also be subjected to further curing to improve its mechanical properties (**Figure 4**).

- Advantages
 - Precision
 - Customization
 - Complex geometry
- Limitations
 - Can be relatively slow compared to other methods due to layer-by-layer curing process
 - The need for post-processing including washing and curing can add to production time and complexity

5.2 Selective laser sintering (SLS)

Selective Laser Sintering (SLS) is another prominent 3D printing technology used in denture fabrication. Unlike SLA, which uses liquid resin, SLS employs powdered materials that are fused together using a high-powered laser. This technology is known for its robustness and ability to produce durable dental components.

In SLS, a layer of powder material is spread evenly across a build platform. A laser selectively fuses the powder particles based on the 3D design. After each layer is completed, a new layer of powder is applied, and the process is repeated until the entire denture is built. The unfused powder acts as a support structure during printing and is later removed (**Figure 5**) [49, 50].

- Advantages
 - Durability
 - Support-free design
 - Speed
- Limitations
 - Tends to produce a rougher surface finish, requiring post-processing for esthetic purposes
 - The equipment and materials are often more expensive compared to SLA



Figure 4.
Advantages of SLA.



Figure 5.
Advantages of SLS.

5.3 Fused deposition Modeling (FDM)

Fused Deposition Modeling is a widely accessible and cost-effective 3D printing technology. It involves the extrusion of thermoplastic materials through a heated nozzle, which deposits the material layer by layer to build a denture. FDM begins with a spool of thermoplastic filament. The material is heated and extruded through a nozzle onto the build platform, following the digital design. Each layer fuses to the previous one as the material cools and solidifies. Supports may be added during the process to stabilize complex geometries, which are later removed (**Figure 6** and **Table 1**) [50, 51].

- Advantages
 - Affordability
 - Accessibility
 - Customization
- Limitations
 - The surface finish of FDM-printed dentures is typically rougher compared to SLS or SLA, requiring additional polishing
 - Limited material options and lower resolution may impact the esthetic and functional quality of the final product

The incorporation of 3D printing technologies in denture fabrication has transformed contemporary dentistry. SLA, SLS, and FDM each present distinct benefits and



Figure 6.
Advantages of SLA.

Technology	Precision	Material	Speed	Surface finish	Cost
SLA	High	Medium	Moderate	Smooth	Moderate
SLS	Moderate	High	Fast	Rough	High
FDM	Low	Medium	Moderate	Rough	Low

Table 1.
Comparative Analysis of 3D Printing Technologies.

drawbacks, enabling dental professionals to choose the most suitable technique according to clinical requirements [52, 53]. SLA stands out for its precision and esthetic appeal, SLS is known for its durability and scalability, while FDM is recognized for its cost-effective customization. With ongoing advancements, 3D printing is set to become a pivotal element in providing high-quality, patient-specific dental prosthetics [54].

6. Conclusions

In conclusion, the convergence of advanced materials and state-of-art techniques has fundamentally transformed the landscape of denture fabrication. These innovations have elevated the standards of care in restorative dentistry, addressing both functional and esthetic needs of patients with unprecedented precision and reliability.

The integration of cutting-edge digital workflow and high-performance materials ensures that dentures not only improve oral functionality but also restore confidence and quality of life for patients. Furthermore, as technology continues to evolve. The potential for future breakthroughs in comfort, efficiency, and accessibility is boundless.

These advancements underscore the dynamic and patient-focused nature of contemporary denture fabrication, promising even greater strides in years to come. By embracing these innovations, the dental field reaffirms its commitment to excellence and continuous improvement ensuring that denture fabrication will remain at the forefront of restorative solutions in modern healthcare.

Acknowledgments

The authors acknowledge the use of QuillBot for language polishing of the manuscript.

Conflict of interest

The authors declare no conflict of interest.

Author details

Dana Gabriela Budala, Ionut Luchian*, Dragos Ioan Virvescu, Oana Maria Butnaru, Elena Raluca Baciuc and Monica Silvia Tatarciuc
Faculty of Dentistry, University of Medicine and Pharmacy “Grigore T. Popa”, Iasi, Romania

*Address all correspondence to: ionut.luchian@umfiasi.ro

IntechOpen

© 2025 The Author(s). Licensee IntechOpen. This chapter is distributed under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/4.0>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited. 

References

- [1] Lefrançois E, Delanoue V, Morice S, Ravalec X, Desclos-Theveniau M. A digital approach for a complete rehabilitation with fixed and removable prostheses: A technical procedure. *Dental Journal*. 2025;**13**:7. DOI: 10.3390/dj13010007
- [2] Deeban Y. Effectiveness of CAD-CAM milled versus DMLS titanium frameworks for hybrid denture prosthesis: A narrative review. *Journal of Functional Biomaterials*. 2024;**15**:376. DOI: 10.3390/jfb15120376
- [3] Sajjad A. Computer-assisted design/ computer-assisted manufacturing systems: A revolution in restorative dentistry. *The Journal of Indian Prosthodontic Society*. 2016;**16**:96-99. DOI: 10.4103/0972-4052.164905
- [4] Stephens C. A brief history of the development and use of vulcanised rubber in dentistry. *British Dental Journal*. 2023;**234**(8):607-610
- [5] Cheramie TJ, Strother EA. The dentist's armamentarium: A collection of 19th century instruments in the Louisiana State University School of dentistry library. *Journal of the History of Dentistry*. 2008;**56**(3):107-118
- [6] Ring ME. New York dentistry a century and a quarter ago. Selections from an upstate dentist's diary. *The New York State Dental Journal*. 1997;**63**(10):27-34
- [7] Osborne J. Clinical survey of acrylic resin dentures. *British Dental Journal*. 1945;**78**:324-329
- [8] Papadiochou S, Pissiotis AL. Marginal adaptation and CAD-CAM technology: A systematic review of restorative material and fabrication techniques. *The Journal of Prosthetic Dentistry*. 2018;**119**:545-551. DOI: 10.1016/j.prosdent.2017.07.001
- [9] Srinivasan M, Kamnoedboon P, McKenna G, Angst L, Schimmel M, Özcan M, et al. CAD-CAM removable complete dentures: A systematic review and meta-analysis of trueness of fit, biocompatibility, mechanical properties, surface characteristics, color stability, time-cost analysis, clinical and patient-reported outcomes. *Journal of Dentistry*. 2021;**113**:103777. DOI: 10.1016/j.jdent.2021.103777
- [10] Mallineni SK, Nuvvula S, Matinlinna JP, Yiu CK, King NM. Biocompatibility of various dental materials in contemporary dentistry: A narrative insight. *Journal of Investigative and Clinical Dentistry*. 2013;**4**(1):9-19. DOI: 10.1111/j.2041-1626.2012.00140.x
- [11] Alhallak K, Hagi-Pavli E, Nankali A. A review on clinical use of CAD/CAM and 3D printed dentures. *British Dental Journal*. 9 Jan 2023. DOI: 10.1038/s41415-022-5401-5
- [12] Goodacre CJ, Garbacea A, Naylor WP, Daher T, Marchack CB, Lowry J. CAD/CAM fabricated complete dentures: Concepts and clinical methods of obtaining required morphological data. *The Journal of Prosthetic Dentistry*. 2012;**107**(1):34-46. DOI: 10.1016/S0022-3913(12)60015-8
- [13] Infante L, Yilmaz B, McGlumphy E, Finger I. Fabricating complete dentures with CAD/CAM technology. *The Journal of Prosthetic Dentistry*. 2014;**111**(5):351-355. DOI: 10.1016/j.prosdent.2013.10.014
- [14] Sun YC, Sun R, Deng KH, Wang Y, Zhou YS. Research and development of

- digital design and fabrication of complete denture. *Zhonghua Kou Qiang Yi Xue Za Zhi*. 2018;**53**(1):60-65. DOI: 10.3760/cma.j.issn.1002-0098.2018.01.013
- [15] Ribeiro AKC, de Freitas RFCP, Costa RTF, de Moraes SLD, Srinivasan M, Carreiro ADFP. Maxillomandibular relationship record methods for computer-engineered complete dentures: A scoping review. *Clinical Oral Investigations*. 2024;**28**(6):320. DOI: 10.1007/s00784-024-05706-2
- [16] Manoharan PS, Wase PR, Sivakumar S. Challenges and solutions in clinical workflow for the rehabilitation of completely edentulous patients through CAD/CAM dentures: A case study. *Cureus*. 2024;**16**(3):e55394. DOI: 10.7759/cureus.55394
- [17] Arora O, Ahmed N, Siurkel Y, Ronsivalle V, Cicciù M, Minervini G. A comparative evaluation of physical properties of CAD/CAM complete denture resins- an in vitro study. *BMC Oral Health*. 2024;**24**(1):65. DOI: 10.1186/s12903-023-03708-2
- [18] Ciocca L, Maltauro M, Cimini V, Breschi L, Montanari A, Anderlucci L, et al. Analysis of the trueness and precision of complete denture bases manufactured using digital and analog technologies. *Journal of Advanced Prosthodontics*. 2023;**15**(1):22-32. DOI: 10.4047/jap.2023.15.1.22
- [19] Miyazaki T, Hotta Y, Kunii J, Kuriyama S, Tamaki Y. A review of dental CAD/CAM: Current status and future perspectives from 20 years of experience. *Dental Materials Journal*. 2009;**28**(1):44-56. DOI: 10.4012/dmj.28.44
- [20] Janeva NM, Kovacevska G, Elencevski S, Panchevska S, Mijoska A, Lazarevska B. Advantages of CAD/CAM versus conventional complete dentures - a review. *Open Access Macedonian Journal of Medical Sciences*. 2018;**6**(8):1498-1502. DOI: 10.3889/oamjms.2018.308
- [21] Perea-Lowery L, Minja IK, Lassila L, Ramakrishnaiah R, Vallittu PK. Assessment of CAD-CAM polymers for digitally fabricated complete dentures. *The Journal of Prosthetic Dentistry*. 2021;**125**(1):175-181. DOI: 10.1016/j.prosdent.2019.12.008
- [22] Anadioti E, Musharbash L, Blatz MB, Papavasiliou G, Kamposiora P. 3D printed complete removable dental prostheses: A narrative review. *BMC Oral Health*. 2020;**20**(1):343. DOI: 10.1186/s12903-020-01328-8
- [23] Alhallak KR, Nankali A. 3D printing Technologies for Removable Dentures Manufacturing: A review of potentials and challenges. *The European Journal of Prosthodontics and Restorative Dentistry*. 2022;**30**(1):14-19. DOI: 10.1922/EJPRD_2208Alhallak06
- [24] Herpel C, Tasaka A, Higuchi S, Finke D, Kühle R, Odaka K, et al. Accuracy of 3D printing compared with milling - a multi-center analysis of try-in dentures. *Journal of Dentistry*. 2021;**110**:103681. DOI: 10.1016/j.jdent.2021.103681
- [25] Lo Russo L, Zhurakivska K, Guida L, Chochlidakis K, Troiano G, Ercoli C. Comparative cost-analysis for removable complete dentures fabricated with conventional, partial, and complete digital workflows. *The Journal of Prosthetic Dentistry*. 2024;**131**(4):689-696. DOI: 10.1016/j.prosdent.2022.03.023
- [26] Bencharit S, Hunsaker CA, Brenes CB. In vitro analysis of bonding and Wear properties of 3D printed denture tooth materials. *Cureus*.

2024;**16**(7):e65388. DOI: 10.7759/cureus.65388

[27] Alshali S, Basunbul G, Basunbul A, Giordano IR. Comparison of the flexural strength of printed and milled denture base materials. *BMC Oral Health*. 2024;**24**(1):929. DOI: 10.1186/s12903-024-04695-8

[28] Choi JJE, Uy CE, Plaksina P, Ramani RS, Ganjigatti R, Waddell JN. Bond strength of denture teeth to heat-cured, CAD/CAM and 3D printed denture acrylics. *Journal of Prosthodontics*. 2019;**4**:5. DOI: 10.1111/jopr.13125

[29] Schwindling FS, Stober T. A comparison of two digital techniques for the fabrication of complete removable dental prostheses: A pilot clinical study. *The Journal of Prosthetic Dentistry*. 2016;**116**(5):756-763. DOI: 10.1016/j.prosdent.2016.03.022

[30] Saponaro PC, Yilmaz B, Heshmati RH, McGlumphy EA. Clinical performance of CAD-CAM-fabricated complete dentures: A cross-sectional study. *The Journal of Prosthetic Dentistry*. 2016;**116**(3):431-435. DOI: 10.1016/j.prosdent.2016.03.017

[31] Bidra AS, Farrell K, Burnham D, Dhingra A, Taylor TD, Kuo CL. Prospective cohort pilot study of 2-visit CAD/CAM monolithic complete dentures and implant-retained overdentures: Clinical and patient-centered outcomes. *The Journal of Prosthetic Dentistry*. 2016;**115**(5):578-586.e1. DOI: 10.1016/j.prosdent.2015.10.023

[32] Wang C, Shi YF, Xie PJ, Wu JH. Accuracy of digital complete dentures: A systematic review of in vitro studies. *The Journal of Prosthetic Dentistry*. 2021;**125**(2):249-256. DOI: 10.1016/j.prosdent.2020.01.004

[33] Jafarpour D, Haricharan PB, de Souza RF. CAD/CAM versus traditional complete dentures: A systematic review and meta-analysis of patient- and clinician-reported outcomes and costs. *Journal of Oral Rehabilitation*. 2024;**51**(9):1911-1924. DOI: 10.1111/joor.13738

[34] Rexhepi I, Santilli M, D'Addazio G, Tafuri G, Manciocchi E, Caputi S, et al. Clinical applications and mechanical properties of CAD-CAM materials in restorative and prosthetic dentistry: A systematic review. *Journal of Functional Biomaterials*. 2023;**14**(8):431. DOI: 10.3390/jfb14080431

[35] Tasaka A, Okano H, Shimizu T, Kato Y, Higuchi S, Yamashita S. Influence of reinforcement bar on accuracy of removable partial denture framework fabricated by casting with a 3D-printed pattern and selective laser sintering. *Journal of Prosthodontic Research*. 2021;**65**(2):213-218. DOI: 10.2186/jpr.JPOR_2020_10

[36] Graf T, Schweiger J, Goob J, Stimmelmayer M, Lente I, Schubert O. Dimensional reliability in CAD/CAM production of complete denture bases: A comparative study of milling and various 3D printing technologies. *Dental Materials Journal*. 2024;**43**(5):629-636. DOI: 10.4012/dmj.2023-215

[37] Simeon P, Unkovskiy A, Saadat Sarmadi B, Nicic R, Koch PJ, Beuer F, et al. Wear resistance and flexural properties of low force SLA- and DLP-printed splint materials in different printing orientations: An in vitro study. *Journal of the Mechanical Behavior of Biomedical Materials*. 2024;**152**:106458. DOI: 10.1016/j.jmbbm.2024.106458

[38] Lee HE, Alauddin MS, Mohd Ghazali MI, Said Z, Mohamad ZS. Effect of different vat polymerization

- techniques on mechanical and biological properties of 3D-printed Denture Base. *Polymers (Basel)*. 2023;**15**(6):1463. DOI: 10.3390/polym15061463
- [39] Bettencourt AF, Costa J, Ribeiro IAC, Gonçalves L, Arias-Moliz MT, Dias JR, et al. Development of a chlorhexidine delivery system based on dental relined acrylic resins. *International Journal of Pharmaceutics*. 2023;**631**:122470. DOI: 10.1016/j.ijpharm.2022.122470
- [40] Wen J, Jiang F, Yeh CK, Sun Y. Controlling fungal biofilms with functional drug delivery denture biomaterials. *Colloids and Surfaces. B, Biointerfaces*. 2016;**140**:19-27. DOI: 10.1016/j.colsurfb.2015.12.028
- [41] Imazato S, Kitagawa H, Tsuboi R, Kitagawa R, Thongthai P, Sasaki JI. Non-biodegradable polymer particles for drug delivery: A new technology for "bio-active" restorative materials. *Dental Materials Journal*. 2017;**36**(5):524-532. DOI: 10.4012/dmj.2017-156
- [42] Paradowska-Stolarz A, Wieckiewicz M, Owczarek A, Wezgowiec J. Natural polymers for the maintenance of Oral health: Review of recent advances and perspectives. *International Journal of Molecular Sciences*. 2021;**22**(19):10337. DOI: 10.3390/ijms221910337
- [43] Venante HS, Chappuis-Chocano AP, Marcillo-Toala OO, da Silva RA, da Costa RMB, Pordeus MD, et al. Fibrin biopolymer incorporated with antimicrobial agents: A proposal for coating denture bases. *Materials (Basel)*. 2021;**14**(7):1618. DOI: 10.3390/ma14071618
- [44] Malakhov A, Wen J, Zhang BX, Wang H, Geng H, Chen XD, et al. Rechargeable anticandidal denture material with sustained release in saliva. *Oral Diseases*. 2016;**22**(5):391-398. DOI: 10.1111/odi.12456
- [45] Rathi S, Reche A, Dhamdhare N, Bolenwar A. Perspectives on the application of nanomaterials in medical and dental practices. *Cureus*. 2023;**15**(8):e43565. DOI: 10.7759/cureus.43565
- [46] Abdelnabi MH, Swelem AA. 3D-printed complete dentures: A review of clinical and patient-based outcomes. *Cureus*. 2024;**16**(9):e69698. DOI: 10.7759/cureus.69698
- [47] Díez-Pascual AM. PMMA-based nanocomposites for odontology applications: A state-of-the-art. *International Journal of Molecular Sciences*. 2022;**23**(18):10288. DOI: 10.3390/ijms231810288
- [48] Dimitrova M, Vlahova A, Hristov I, Kazakova R. Bonding efficiency between artificial teeth and Denture Base in CAD/CAM and Conventional complete removable dentures. *Materials (Basel)*. 2024;**17**(13):3138. DOI: 10.3390/ma17133138
- [49] Kane B, Shah KC. In vitro analysis of shear stress: CAD milled vs printed Denture Base resins with bonded denture tooth. *Journal of Prosthodontics*. 2023;**32**(S1):29-37. DOI: 10.1111/jopr.13552
- [50] Neena AF, Abd-Ellah ME. Trueness of artificial teeth for CAD-CAM complete dentures fabricated with additive manufacturing implementing different denture base-tooth offset values: An in vitro study. *The Journal of Prosthetic Dentistry*. 2024;**131**(4):705.e1-705.e7. DOI: 10.1016/j.prosdent.2024.01.001
- [51] Soeda Y, Kanazawa M, Hada T, Arakida T, Iwaki M, Minakuchi S.

Trueness and precision of artificial teeth in CAD-CAM milled complete dentures with custom disks. *The Journal of Prosthetic Dentistry*. 2022;**128**(4):695-701. DOI: 10.1016/j.prosdent.2020.12.049

[52] Ahmed N, Abbasi MS, Haider S, Ahmed N, Habib SR, Altamash S, et al. Fit accuracy of removable partial denture frameworks fabricated with CAD/CAM, rapid prototyping, and conventional techniques: A systematic review. *BioMed Research International*. 2021;**6**(2021):3194433. DOI: 10.1155/2021/3194433

[53] Lo Russo L, Guida L, Zhurakivska K, Troiano G, Chochlidakis K, Ercoli C. Intaglio surface trueness of milled and 3D-printed digital maxillary and mandibular dentures: A clinical study. *The Journal of Prosthetic Dentistry*. 2023;**129**(1):131-139. DOI: 10.1016/j.prosdent.2021.05.003

[54] Thu KM, Molinero-Mourelle P, Yeung AWK, Abou-Ayash S, Lam WYH. Which clinical and laboratory procedures should be used to fabricate digital complete dentures? A systematic review. *The Journal of Prosthetic Dentistry*. 2024;**132**(5):922-938. DOI: 10.1016/j.prosdent.2023.07.027

Chapter 3

The CAD/CAM Alternative for Processing Dental Alloys

*Lavinia Cosmina Ardelean, Codruta Victoria Tigmeanu
and Laura-Cristina Rusu*

Abstract

CAD/CAM technologies, both subtractive and additive, have been used for dental purposes since 1980–1990, with growing success. While initially used for manufacturing a limited range of dental appliances, CAD/CAM technologies enable the fabrication of various types of complex dental constructs, including 3D-printed tissues. Among the wide choice of materials used for manufacturing CAD/CAM prosthodontics, alloys play a certain role, being firstly used for the fabrication of fixed and removable dentures infrastructures, as well as for implant production. Due to their characteristics, the currently most used dental alloys for CAD/CAM applications in dentistry are Co-Cr and Ti alloys. Depending on the CAD/CAM technology, dental alloys are being manufactured by milling (alloy blocks) or 3D printing powder bed fusion (alloy powder). CAD/CAM manufacturing in dentistry enables not only high-speed fabrication but also the achievement of high-quality dental constructs.

Keywords: dental alloys, CAD/CAM, additive manufacturing, powder bed fusion, SLS, SLM

1. Introduction

Base metal alloys have been used in dentistry since the 1930s, mainly for fixed or removable partial dentures infrastructures, traditionally processed by casting, and dental implants. Characterized by strength, durability and corrosion resistance, Co-Cr and Ti alloys are the current most frequently choices in prosthodontics, as precious alloys are too expensive and Ni-based alloys proved to be highly allergenic [1].

While Co-Cr is mainly used for manufacturing removable partial dentures frameworks and metal-ceramic/metal-polymeric fixed dentures infrastructures, Ti alloys are primarily indicated for dental implants, due to their osseointegration capacity, exceptional biocompatibility and corrosion resistance. However, Ti alloys are used for manufacturing dentures infrastructures as well [2, 3].

Characterized by high hardness, traditionally casted Co-Cr alloys are often difficult to process. In order to overcome this shortcoming, substitutes, such as Co-Cr alloys enriched with precious metals were attempted. As they proved to be a disappointment, the focus was ultimately put on new manufacturing alternatives [4].

The most frequently used Ti alloy for prosthodontics is Ti-6Al-4V. Ti alloys are characterized by a high melting point and ease of oxidizing at high temperatures; thus, special casting machines are needed. Ti casting machines require arc-melting pressure casting (vacuum or centrifugation) in a protected gas (argon) environment [2].

Due to the manufacturing and processing difficulties of both Co-Cr and Ti dental alloys, alternative methods to traditional casting were considered. CAD/CAM technologies, often regarded as the next industrial revolution, enable not only high-speed manufacturing but also the achievement of high-quality various dental constructs [5].

2. CAD/CAM systems-brief description

CAD/CAM systems, either subtractive or additive, became available for dental application in the late 1980s-early 1990s. At first used for manufacturing fixed partial dentures, later on, due to further development, their range of use widened, enabling the fabrication of removable partial or total dentures, as well as a broad range of dental appliances. Additive CAD/CAM technology has a future promising outcome for dental application in tissue engineering and regenerative medicine as well [6].

CAD/CAM systems are made up of three major components: the data acquisition unit, the software, and the manufacturing device. The data acquisition is achieved by intraoral or extraoral scanning. Intraoral scanning acquires data directly from the area of the preparation, adjacent, and opposing structures, while extraoral scanning uses a conventional impression and model for data acquisition. Either way, the collected data are converted into virtual models. The software is involved in virtually designing the future denture or dental appliance, and establishing the manufacturing parameters. The third component is the one that makes the difference between the subtractive and additive CAD/CAM systems. Subtractive technology uses a milling machine to process a block-shaped material. The additive technology uses a 3D printer, the material, in liquid, slurry, powder or thermoplastic filament form, being dependent on the 3D printing technology used (Figure 1) [7, 8].

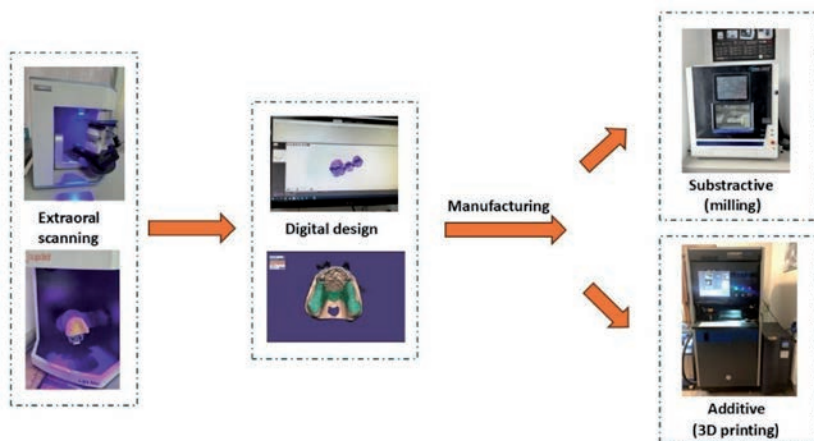


Figure 1.
CAD/CAM workflow in the dental laboratory.



Figure 2.
Components of a laboratory CAD/CAM system.

Some of the main advantages of CAD/CAM systems are short manufacturing time, low cross-contamination hazard, and automated fabrication with minimal inaccuracies. The previously saved digital data may be easily accessed if further needed [9].

The subtractive method has the advantage of using homogenous materials, however, its major drawback is the material loss, which means higher costs. The additive method addresses this drawback by using different material layering technologies [10].

Probably, the main disadvantage of both chairside and laboratory CAD/CAM systems (**Figure 2**) is the high initial cost. To address this issue, centralized production centers emerged, which take over the CAM step. The data acquired by intraoral or extraoral scanning, along with the desired design, are digitally transferred to the production center, which takes care of the fabrication step. In case aesthetic layering of an infrastructure is needed, it is subsequently accomplished in the laboratory, as usual [9, 11].

3. CAD/CAM manufacturing—Evolution

The French inventor Francois Duret is considered the godfather of digital dentistry, as, in the 1970s, he developed the first CAD/CAM system suitable for manufacturing single-tooth restorations. The Duret system was patented and marketed as the Sopha Bioconcept System. However, because of its high cost and complexity, it did not last long on the dental market [12].

In 1987, Werner Mormann and Marco Brandestini developed Cerec (Sirona, Bensheim, Germany), the first viable dental CAD/CAM subtractive system. Initially, Cerec was designed to be a chairside system used to fabricate feldspathic ceramic inlays using Vita Mark I blocks (Vita Zahnfabrik, Bad Sackingen, Germany). The Cerec 1 milling machine, which used a grinding wheel, was later replaced by Cerec 2, which was equipped with an additional cylinder diamond, thus enabling the manufacture of partial and full crowns. Cerec 3, released in 2006, had a two-bur system. Later on, aiming to gain higher precision, the “step bur” was introduced. InLab, the dental laboratory version, was released in 2006 [13–15].

The current available subtractive CAD/CAM systems enable the manufacture of a wide range of prosthetic restorations, including inlays, onlays, veneers, anterior and



Figure 3.
Five-axis milling.

posterior crowns and bridges, copings, provisionals, bridge frameworks, telescope crowns, bars, attachments, denture bases, as well as implant mesostructured and surgical guides [16].

Chuck Hull is considered to be the inventor of additive manufacturing, as he patented the “stereolithography” technology in 1986, describing it as a method to build solid objects by “printing” successive thin layers of a UV-curable liquid photopolymer [17]. The computer-controlled UV light beam draws each layer of the designed object, thus transforming the liquid into solid. Shortly after, Hull realized that the principle is suitable for “any material capable of solidification” or “material capable of altering its physical state” and filed for a broadened patent [18].

First used for dental purposes in the 1990s, 3D printing technologies were mainly used for processing resin-based materials and alloys, but, more recently, 3D printers for ceramic materials became available. Unlike the subtractive methods, 3D printing allows not only the fabrication of various prosthetics but tissue constructs as well [19].

In their 30-year history, CAD/CAM systems have undergone substantial changes. The optical cameras primarily used for data acquisition evolved to contact digitization and laser scanning. Sophisticated designing software choices are currently available. The 5-axis modern milling machines (**Figure 3**), the choice of dry or wet milling, and novel 3D printing technologies, including multi-material ones, enable the fabrication of complex fixed and removable dentures, as well as various other dental appliances.

The wide range of materials suitable for CAD/CAM processing include various types of ceramics and resins, high-performance polymers, composite materials and dental alloys [5, 6].

4. Current manufacturing technologies for dental alloys

Manufacturing technologies currently available for dental alloys are:

4.1 Traditional casting

Traditional casting (the lost-wax technique) it is not only laborious and time-consuming, as it implies multiple laboratory stages but also requires high technical precision. Porosity, distortion, and defective margin formation may appear more often than expected [20].

4.2 The CAD/CAM subtractive method

The CAD/CAM subtractive method is carried out by milling prefabricated solid Co-Cr or Ti alloy blocks. The advantage is fast production with minimum structural defects. One disadvantage is the result of milling the dental restoration from a material block, which leads to a lot of material waste. When milling dental alloys, the life of the burs is limited, their continuous renewal adding additional costs. Milling dental alloy blocks is also difficult because their hardness places high demands on the manufacturing device. In the case of newer generations of four or five axis machines, the kinematics has been optimized due to the larger angulations and the possibility of wet milling [20].

A new milling system was developed by Amann Girrbaach in cooperation with the Fraunhofer Institute Dresden. Using wax-like texture Co-Cr blocks, it enables effortless dry milling. The milling is done in the green body state (unsintered metal powder held together by a binder), with minimal bur wear. Afterwards, the prosthetic construct is debinded and densely sintered in a special furnace, under inert gas atmosphere. The result is a homogeneous, distortion-free structure, free from contraction cavities [21, 22].

However, the ability to produce complex milled shapes is limited compared to additive manufacturing.

4.3 Spark erosion

Spark erosion or electrical discharge machining is a precision procedure, introduced in dentistry in 1982 by Gunter Rubeling, to manufacture precision attachments. It is mainly used to achieve a passive fit of implant-retained structures and fixed partial dentures and is highly efficient to process hard base alloys (Co-Cr and Ti alloys). The method uses an accurately controlled electric discharge through conductive objects immersed in a liquid medium. The technique is rapid, efficient, and accurate, but the need for highly trained personnel and the cost of the machine resulted in its limited usage [23, 24].

4.4 The CAD/CAM additive methods

The CAD/CAM additive technologies used for dental alloys are powder bed fusion (PBF) ones. Dental alloys were first processed by additive manufacturing in 2002. 3D printing of non-precious alloys was considered to be revolutionary at the time and was recognized to have an enormous potential [25, 26].

PBF technologies include selective laser sintering (SLS), selective laser melting (SLM), and electron beam melting (EBM) and use heat to fuse materials in powder form (**Figure 4**). While SLS is used for printing not only alloys but also polymeric, composite, and ceramic-based materials, SLM and EBM are specifically used for metals [27].

In principle, these technologies are very much alike, the differences are due to the process itself (operational parameters such as melting temperature, layer thickness, build orientation), the energy source (its type and power), and the grain size of the powder material used. In SLS and SLM, a laser beam, operated under an inert atmosphere, is used to fuse powder particles, whereas EBM uses an electron beam in a vacuum environment as the energy source. In SLM and EBM, the fully melted powders are well fused and create denser parts with enhanced mechanical properties, compared to SLS. Despite other types of additive manufacturing technologies,



Figure 4.
Dental alloy in powder form (3D printing).

which need additional support for the building process, in PBF ones, the powder bed that surrounds the construct takes over this task, resulting in cost reduction, due to material saving (the remaining powder can be reused), and avoiding the support structures removal part. The fact that no support structure is needed also results in complex and flexible geometric design and faster production time [28, 29].

4.4.1 Selective laser sintering

Selective laser sintering (SLS) was developed by Carl Deckard in Austin, USA. He licensed the technology and founded Desk Top Corp (DTM) in 1987. DTM was acquired by 3D Systems (Rock Hill, SC, USA) in 2001 [30].

In SLS, a high-power moving laser beam is used to selectively fuse partially melted powder form materials into a final solid mass, representing the previously designed 3D object. Different alloys, polymers, and certain ceramics may be processed by SLS. Firstly, a thin layer of powder is evenly spread on the build platform. The first layer of the construct is fabricated by means of laser scanning and selective sintering of the powder based on the CAD data. As the laser beam meets the surface, due to the heat, which is generated, the powder particles are partially melted and fused together. The build platform is then lowered by one layer thickness. Additional powder is added and the layer-by-layer deposition is repeated until the desired construct is finished. In the end, the free powder used as support is removed. The fabrication chamber is maintained at an elevated temperature, just below the melting point of the powder, so that it fuses faster and with less energy upon laser exposure. Moisture, as a result of the laser beam hitting the surface, may cause oxidation when sintering metals. To prevent oxidation, the sintering process takes place in a protected environment (nitrogen or argon inert gas) [31].

As SLS involves locally, partial melting, not throughout the particles, the constructs are often characterized by high internal porosity and rough surface. Post-processing by thermal annealing improves structural stability and mechanical properties [32, 33].

4.4.2 Selective laser melting

Selective laser melting (SLM) started in 1995 at the Fraunhofer Institute ILT in Aachen, Germany. The technology uses powerful high-quality lasers, which

completely melt the metallic powder, resulting in high-density metallic constructs (**Figure 5**). The main differences to SLS are the power of the laser beam and the way the particles are fused together. The heat generated in the area where the laser beam hits is higher than in SLS, being directly proportional to the laser power. The process takes place in a tightly controlled inert atmosphere (argon or nitrogen) to prevent oxidation [34].

The first commercial system, EOSINT M 250, was launched in 1995 by Electro Optical Systems (EOS, Krailling, Germany), one of the world leaders in providing 3D printing solutions, making the transition of additive manufacturing from plastics to metals. The technology was marketed by EOS under the name DMLS and is quite often wrongly categorized as SLS based. In fact, DMLS is the acronym for “Direkt Metall Laser Schmelzen,” which translates into English as Direct Metal Laser Melting. It involves complete melting during production, resulting in dense constructs with high resolution due to thin deposition layers and fine powder [35].

SLM is currently accepted as the best additive method for manufacturing metallic structures in dentistry, including copings, bridges infrastructure, or removable partial dentures frameworks (**Figure 6**), as well as customized implants and abutments [36].

Although the superficial finish of SLM constructs is considered of higher quality, the possibility of developing internal stresses caused by thermal contraction might still be an issue, and therefore, post-processing by additional heat treatment is required [32, 37].

4.4.3 Electron beam melting

Electron beam melting (EBM) was developed by ARCAM AB (Molnlycke, Sweden) in 2002, and it is still the only company that produces this type of equipment. In EBM, an electron beam under vacuum, in an inert environment, is used to selectively melt and solidify the metal powder, in a layer-by-layer form, until completion of the final object. Initially, due to the heating of a tungsten filament, a cloud of electrons is emitted. Subsequently, the electrons are accelerated and focused in a beam-form, then directed toward the powder bed to melt the metal powder. Due to the rapid scan speed, coupled with a high penetration depth of the electron beam, fast

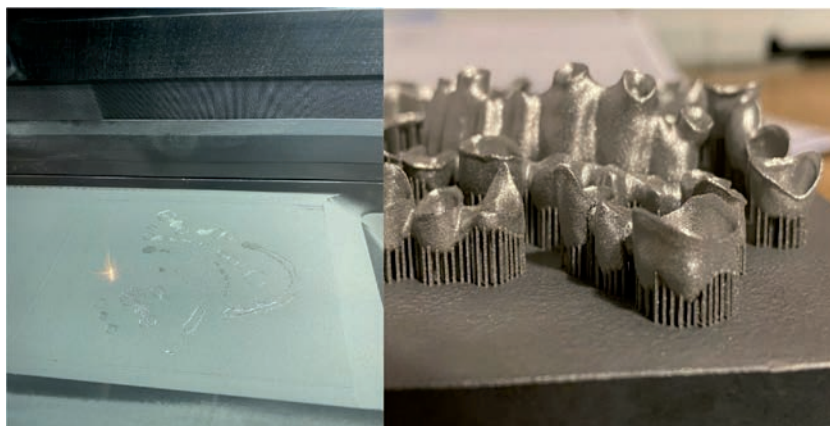


Figure 5.
The SLM process and SLM metallic infrastructures.



Figure 6.
SLM metallic infrastructures, before and after finishing.

build rates can be achieved. At the end of the building process, the part remains inside the chamber to cool down. Working under vacuum is advantageous, the process of being highly energy efficient. EBM is about 10 times more energy efficient than SLM. The vacuum atmosphere also enables handling reactive metal powders, including Ti and its alloys, which are difficult to process by means of conventional techniques because they oxidize easily. Although the vacuum systems in the EBM process are more expensive, they show lower residual stress than laser-based systems. However, EBM facilities are relatively expensive, and their availability is still limited [38–40].

4.5 Hybrid manufacturing

Hybrid manufacturing in dentistry consists of a combination of additive and subtractive stages. It combines the efficiency of additive manufacturing with the precision of milling. Datron AG (Mühlthal, Germany) started developing this technology in 2015. In collaboration with Follow Me Technology Group (Munich, Germany), they used smart networking to implement the hybrid workflow to milling machines, resulting in a 30–50% decrease in manufacturing costs. Briefly, measuring pins are added to the additive building platform. The pins are detected by the milling unit by means of an infrared touch probe, thus enabling the exact position detection of the 3D printed constructs, which are further processed by milling [18, 41, 42].

4.6 Future perspectives

One of the greatest challenges in additive manufacturing is the need for support structures during printing, which are absolutely necessary to prevent deformations during metal layering. The need for support structures leads to material waste and increased energy consumption. The researchers and manufacturers have constantly tried to develop more efficient support structures. Advancements in limiting the support structures have been made by adjusting the laser power. Smart fusion,

developed by EOS (Krailling, Germany) is an “intelligent thermal management method, tailored to allow printing of components with minimal support,” providing “a closed loop feedback control solution by real-time monitoring and adaptive process adjustments” [43].

5. Conclusion

Duret’s prediction regarding CAD/CAM, made in 1991: “The systems will continue to improve in versatility, accuracy, and cost-effectiveness, and will be a part of routine dental practice by the beginning of the twenty-first century,” proved to be accurate [44].

The evolution of CAD/CAM systems currently provides increasing user-friendliness, improved quality and complexity, a wide range of applications, and extended capabilities.

Conflict of interest

The authors declare no conflict of interest.

Author details

Lavinia Cosmina Ardelean^{1*}, Codruta Victoria Tigmeanu¹ and Laura-Cristina Rusu²

1 Academic Department of Technology of Materials and Devices in Dental Medicine, Multidisciplinary Center for Research, Evaluation, Diagnosis and Therapies in Oral Medicine, “Victor Babeș” University of Medicine and Pharmacy, Timisoara, Romania

2 University Clinic of Oral Pathology, Multidisciplinary Center for Research, Evaluation, Diagnosis and Therapies in Oral Medicine, “Victor Babeș” University of Medicine and Pharmacy, Timisoara, Romania

*Address all correspondence to: lavinia_ardelean@umft.ro

IntechOpen

© 2025 The Author(s). Licensee IntechOpen. This chapter is distributed under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/4.0>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited. 

References

- [1] Bechir F, Bataga SM, Ungureanu E, Vranceanu DM, Pacurar M, Bechir ES, et al. Experimental study regarding the behavior at different pH of two types of Co-Cr alloys used for prosthetic restorations. *Materials (Basel)*. 2021;**14**:4635. DOI: 10.3390/ma14164635
- [2] Nicholson JW. Titanium alloys for dental implants: A review. *Prosthesis*. 2020;**2**:100-116. DOI: 10.3390/prosthesis2020011
- [3] Rexhepi I, Santilli M, D'Addazio G, Tafuri G, Manciocchi E, Caputi S, et al. Clinical applications and mechanical properties of CAD-CAM materials in restorative and prosthetic dentistry: A systematic review. *Journal of Functional Biomaterials*. 2023;**14**:431. DOI: 10.3390/jfb14080431
- [4] Reclaru L, Ardelean LC. Alternative processing techniques for CoCr dental alloys. In: Narayan R, editor. *Encyclopedia of Biomedical Engineering (Biomaterials: Science and Engineering)*. 1st ed. Amsterdam: Elsevier; 2019. pp. 1-15
- [5] Suganna M, Kausher H, Tarek Ahmed S, Sultan Alharbi H, Faraj Alsubaie B, Ds A, et al. Contemporary evidence of CAD-CAM in dentistry: A systematic review. *Cureus*. 2022;**14**:e31687. DOI: 10.7759/cureus.31687
- [6] Maiti N, Mahapatra N, Patel D, Chanchad J, Saurabhbbhai Shah A, Mahboob Rahaman SK, et al. Application of CAD-CAM in dentistry. *Bioinformation*. 2024;**20**:547-550. DOI: 10.6026/973206300200547
- [7] Padrós R, Giner L, Herrero-Climent M, Falcao-Costa C, Ríos-Santos JV, Gil FJ. Influence of the CAD-CAM systems on the marginal accuracy and mechanical properties of dental restorations. *International Journal of Environmental Research and Public Health*. 2020;**17**:4276. DOI: 10.3390/ijerph17124276
- [8] Jokusch J, Özcan M. Additive manufacturing of dental polymers: An overview on processes, materials and applications. *Dental Materials Journal*. 2020;**39**:345-354. DOI: 10.4012/dmj.2019-123
- [9] Tigmeanu CV, Ardelean LC, Rusu LC, Negrutiu ML. Additive manufactured polymers in dentistry, current state-of-the-art and future perspectives—A review. *Polymers*. 2022;**14**:3658. DOI: 10.3390/polym14173658
- [10] Alanazi KK, Alzaid AA, Elkaffas AA, Bukhari SA, Althubaitiy RO, Alfaifi KA, et al. Mechanical assessment of CAD/CAM fabricated hybrid ceramics: An in vitro study. *Applied Sciences*. 2024;**14**:7939. DOI: 10.3390/app14177939
- [11] Krastev T, Payer M, Krastev Z, Pena Cardelles JF, Vegh A, Banyai D, et al. The utilisation of CAD/CAM technology amongst Austrian dentists: A pilot study. *International Dental Journal*. 2023;**73**:430-434. DOI: 10.1016/j.identj.2022.09.004
- [12] Duret F, Blouin JL, Duret B. CAD-CAM in dentistry. *Journal of the American Dental Association (1939)*. 1988;**117**:715-720. DOI: 10.14219/jada.archive.1988.0096
- [13] Mormann WH, Brandestini M. Cerec-system: Computerized inlays, onlays and shell veneers. *Zahnärztliche Mitteilungen*. 1987;**77**:2400-2405

- [14] Mormann WH, Brandestini M, Lutz F. The cerec-system: Computer assisted preparation of direct ceramic inlays in 1 setting. *Die Quintessenz*. 1987;**38**:457-470
- [15] Mormann WH. The evolution of the cerec system. *The Journal of the American Dental Association* (Chicago, IL). 2006;**137**:7S-13S. DOI: 10.14219/jada.archive.2006.0398
- [16] Moraru E, Dontu GO, Apostolescu TC, Cartal LA, Gramescu B, Dawod N. Aspects regarding subtractive and additive CAD-CAM processes applied in prosthetic dentistry. In: Machado J, Soares F, et al., editors. *Innovations in Mechanical Engineering II, Lecture Notes in Mechanical Engineering*. Cham: Springer; 2023. pp. 91-102. DOI: 10.1007/978-3-031-09382-1_9
- [17] Wikipedia. Chuck Hull. Available from: https://en.wikipedia.org/wiki/Chuck_Hull [Accessed: January 8, 2025]
- [18] Schweiger J, Edelhoff D, Güth JF. 3D printing in digital prosthetic dentistry: An overview of recent developments in additive manufacturing. *Journal of Clinical Medicine*. 2021;**10**:2010. DOI: 10.3390/jcm10092010
- [19] Compendiumlive.com. 2020. Available from: <https://www.aegisdentalnetwork.com/cced/2020/11/the-invention-of-3d-printing-and-its-impact-on-dentistry-an-interview-with-chuck-hull> [Accessed: January 8, 2025]
- [20] Stoian C, Ardelean LC, Negruțiu ML, Miclău M, Casut C, Sinescu C, et al. Crystalline structure assessment of ceramic veneered Co-Cr-W dental alloy substructures obtained by selective laser melting—A pilot study. *Applied Sciences*. 2023;**13**:8052. DOI: 10.3390/app13148052
- [21] Hong MH, Lee DH, Hanawa T, Kwon TY. Comparison of microstructures and mechanical properties of 3 cobalt-chromium alloys fabricated with soft metal milling technology. *The Journal of Prosthetic Dentistry*. 2022;**127**:489-496. DOI: 10.1016/j.prosdent.2020.07.037
- [22] Barazanchi A, Li KC, Al-Amleh B, Lyons K, Waddell JN. Adhesion of porcelain to three-dimensionally printed and soft milled cobalt chromium. *Journal of Prosthodontic Research*. 2020;**64**:120-127. DOI: 10.1016/j.jjpor.2019.05.007
- [23] Jo LJ. Spark erosion process: An overview. *Journal of Dental Implants*. 2011;**1**:2-6. DOI: 10.4103/0974-6781.76424
- [24] Guident [Internet]. Available from: <https://www.guident.net/articles/prosthodontics/SPARK-EROSION-PROCESS:-A-NEW-SPARK-IN-DENTISTRY...html> [Accessed: January 8, 2025]
- [25] Alwan EH, Sabiha MK. Methods of additive manufacturing for dental Co-Cr alloys: Systematic review. *Journal of Technology*. 2022;**2022**(4):80-85. DOI: 10.51173/jt.v4i33.641
- [26] Kessler A, Hickel R, Reymus M. 3D printing in dentistry—State of the art. *Operative Dentistry*. 2020;**45**:30-40. DOI: 10.2341/18-229-L
- [27] Esgünoglu Çelik G, Balkaya MC. Metal manufacturing techniques used in prosthetic dentistry. *Essentials of Dentistry*. 2023;**2**:135-140. DOI: 10.5152/EssentDent.2023.23019
- [28] Revilla-León M, Meyer MJ, Özcan M. Metal additive manufacturing technologies. *International Journal of Computerized Dentistry*. 2019;**22**:55-67

- [29] Nouri A, Rohani Shirvan A, Li Y, Wen C. Additive manufacturing of metallic and polymeric load-bearing biomaterials using laser powder bed fusion: A review. *Journal of Materials Science and Technology*. 2021;**94**:196-215. DOI: 10.1016/j.jmst.2021.03.058
- [30] Peed E, Lee N. 3D printing, history of. In: Lee N, editor. *Encyclopedia of Computer Graphics and Games*. Cham: Springer; 2024. pp. 26-33. DOI: 10.1007/978-3-031-23161-2_279
- [31] EOS [Internet]. Available from: <https://www.eos.info/about-us/what-we-do/sls> [Accessed: January 8, 2025]
- [32] Sola A, Nouri A. Microstructural porosity in additive manufacturing: The formation and detection of pores in metal parts fabricated by powder bed fusion. *Journal of Advanced Manufacturing and Processing*. 2019;**1**:e10021. DOI: 10.1002/amp.2.10021
- [33] Schweiger J, Güth JF, Erdelt KJ, Edelhoff D, Schubert O. Internal porosities, retentive force, and survival of cobalt-chromium alloy clasps fabricated by selective laser sintering. *Journal of Prosthodontic Research*. 2019;**64**:210-216. DOI: 10.1016/j.jpor.2019.07.006
- [34] Camacho Presotto AG, Cordeiro JM, Camacho Presotto JG, Cipriano Rangel E, Cristino da Cruz N, Landers R, et al. Feasibility of 3D printed Co–Cr alloy for dental prostheses applications. *Journal of Alloys and Compounds*. 2021;**862**:158171. DOI: 10.1016/j.jallcom.2020.158171
- [35] EOS [Internet]. Available from: <https://www.eos.info/about-us/what-we-do/dmls> [Accessed: January 8, 2025]
- [36] Tregermann I, Renne W, Kelly A, Wilson D. Evaluation of removable partial denture frameworks fabricated using 3 different techniques. *The Journal of Prosthetic Dentistry*. 2019;**122**:390-395. DOI: 10.1016/j.prosdent.2018.10.013
- [37] Element [Internet]. Available from: <https://www.element.com/nucleus/2016/dmls-vs-slm-3d-printing-for-metal-manufacturing> [Accessed: January 8, 2025]
- [38] Internet Archive [Internet]. Available from: <https://web.archive.org/web/20200205205135/http://www.arcam.com/technology/electron-beam-melting> [Accessed: January 8, 2025]
- [39] Pirozzi C, Franchitti S, Borrelli R, Diodati G, Vattasso G. Experimental study on the porosity of electron beam melting-manufactured Ti6Al4V. *Journal of Materials Engineering and Performance*. 2019;**28**:2649-2660. DOI: 10.1007/s11665-019-04038-7
- [40] Nouri A, Sola A. Electron beam melting in biomedical manufacturing. In: Wen C, editor. *Metallic Biomaterials Processing and Medical Device Manufacturing*. Cambridge: Woodhead Publishing; 2020. pp. 271-314. DOI: 10.1016/B978-0-08-102965-7.00008-4
- [41] Torii M, Nakata T, Takahashi K, Kawamura N, Shimpo H, Ohkubo C. Fitness and retentive force of cobalt-chromium alloy clasps fabricates with repeated laser sintering and milling. *Journal of Prosthodontic Research*. 2018;**62**:342-346. DOI: 10.1016/j.jpor.2018.01.001
- [42] Nakata T, Shimpo H, Okhubo C. Clasp fabrication using one-process molding by repeated laser sintering and high-speed milling. *Journal of Prosthodontic Research*. 2017;**61**:276-282. DOI: 10.1016/j.jpor.2016.10.002

[43] EOS [Internet]. Available from:
[https://www.eos.info/content/blog/
support-free-smart-fusion](https://www.eos.info/content/blog/support-free-smart-fusion) [Accessed:
January 8, 2025]

[44] Duret F, Preston J. CAD/CAM
imaging in dentistry. *Current Opinion in
Dentistry*. 1991;**1**:150-154

High-Performance Polymers (HPPs) in the Field of Restorative and Prosthetic Dentistry

*Liliana Porojan, Flavia Roxana Bejan,
Roxana Diana Vasiliu and Anamaria Matichescu*

Abstract

Because of their unique qualities, thermoplastic high-performance polymers (HPPs) have sparked a growing interest in restorative and prosthetic dentistry. The most popular of them is polyetheretherketone (PEEK), which has excellent mechanical qualities, high temperature resistance, chemical stability, great polishing potential, low specific weight, little wear resistance, and high biocompatibility. The modulus of elasticity of PEEK is low, similar to those of bone, and is therefore advantageous from a biomechanical point of view. To improve their mechanical properties, ceramic-reinforced PEEK has been developed. Polyetherketoneketone (PEKK) shows better mechanical properties in terms of flexure, tensile, and compressive strength. Due to the favorable biomechanical properties, white color and low specific weight, HPPs allow achieving lighter metal-free removable partial dentures (RPDs), eliminating the esthetically unacceptable display of metal components. Even if HPP materials are developed as esthetic alternatives, fixed restorations have to be veneered in esthetic areas because of their opaque color. In vitro studies were developed in order to investigate the long-term effects of a simulated oral environment, like the combined actions of aging, water saturation and immersing solutions on the optical properties, color stability, surface characteristics, microhardness, wear resistance, and adaptability related to different HPP materials. The investigations highlighted the indications and limitations of these materials placed on the top of the polymer pyramid. Promising results are developed for HPP materials with regard to their potential use in the field of restorative and prosthetic dentistry. Different applications and specific designs have to be further assessed and taken into consideration.

Keywords: high-performance polymers, dentistry, in vitro behavior, optical properties, surface characteristics

1. Introduction

The introduction of high-performance polymers (HPPs) in dentistry as metal-free alternative materials offers a new perspective for restorative and prosthetic applications. The polymer pyramid places HPPs in the highest class of plastics because they

are more challenging to make, are made of complex monomers, have good mechanical qualities, are highly stable at high temperatures and chemicals, and are typically rather costly.

Polyaryletherketone (PAEK) is a crystalline polymer formed by linking phenylene rings through oxygen bridges and carbonyl groups (ketones). Additionally, HPPs are composed of repeating macromolecule units that result in three-dimensional long polymeric chain architectures (**Figure 1**) [1].

The PAEK family shows ultra-high mechanical performances and chemical resistance among all the thermoplastic polymers. They are naturally radiolucent. A variety of closely related high-performance thermoplastics, such as aryl ketone polymer (AKP), polyetheretherketone (PEEK), and polyetherketoneketone (PEKK), are referred to as PAEK. The relative amount of ketone and ether groups affects their mechanical characteristics (E-modulus of 3.5–5.1 GPa) [2–4].

PEEK is a linear, aromatic, semi-crystalline thermoplastic that was created by nucleophilically substituting aromatic dihalides and bisphenol salts. Aromatic rings are present in both PEEK and PEKK architectures, although the proportion of ether to the keto group varies [5, 6].

Among all these materials, PEEK is the most used in practice. It was first used in 1990 for biomedical applications. It is a homopolymer having a single monomer [1]. PEEK is well-known for its excellent mechanical qualities, low specific weight, low plaque affinity, low temperature resistance, chemical stability, high polishing potential, low specific weight, low wear resistance, and good bond strength with luting cements and veneering composites. From a biomechanical perspective, PEEK is superior to other dental materials like zirconia, glass ceramics, and metal alloys because it has a low modulus of elasticity that is comparable to that of bone. It lessens the forces applied to the abutment teeth by absorbing functional stresses.

To absorb and transmit occlusal stresses from the polymeric matrix to the more robust fillers, reinforcing elements may be employed [7–9]. PEEK composites reinforced with carbon fibers (CFR-PEEK) have a higher elastic modulus (18 GPa) [1, 3, 10–13]. PEEK is an exceptionally strong polymer that has a balanced composition of ether groups that give its structure flexibility and ketone groups that provide it stiffness [14].

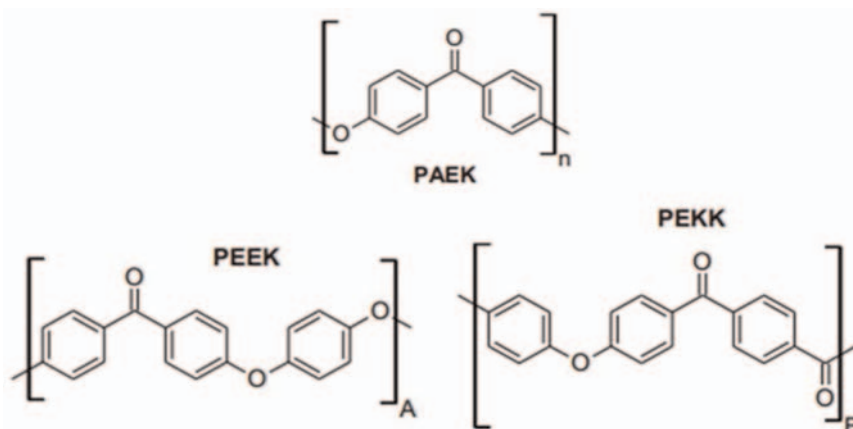


Figure 1. Construction of (A) polyetheretherketone (PEEK) and (B) polyetherketoneketone (PEKK), from (n) polyaryletherketone (PAEK) [1].

PEEK is a stiff, white, radiolucent material that has excellent thermal stability up to 335.8°C. It has a modest affinity for plaque and is not allergenic. PEEK has a tensile strength of 100.69 MPa, a compressive strength of 118–169 MPa, a flexural modulus of 140–170 MPa, a reduced density of 1.32 g/cm³, and a thermal conductivity of 0.29 W/mK. PEEK has a reasonably high Young's modulus (3–4 GPa), comparable to that of human bone, enamel, and dentin. When compared to other materials, PEEK has one of the best biocompatibilities, is non-toxic, and is resistant to hydrolysis. PEEK's unique chemical structure demonstrates stable physical and chemical characteristics [3]. Compared to PMMA and composites, PEEK has the lowest solubility and water sorption values. It also has excellent tribological qualities, superior chemical resistance against nearly all solvents, and nearly zero water uptakes [15–21].

Because PEKK offers desirable and promising biomechanical qualities like compressive (246 MPa), tensile (115 MPa), and flexure strength (200 MPa), its use in the medical and dentistry fields has expanded recently. PEKK has a comparatively greater Young's modulus, at roughly 5.1 GPa. Aside from that, the material is more adaptable in surface changes, bonding, and better melting temperature than PEEK due to the addition of ketone groups within its molecular structure [22]. PEKK exhibits shock-absorbing qualities in a simulated intraoral environment and an elastic modulus that is remarkably similar to bone (**Table 1**).

The crystallinity of PEEK is higher than the crystal structure of PEKK because it contains less ketone. PAEK polymers tend to crystallize as a consequence of chain packing induced by the ether and ketone linkages. Compared to the ether linkages, the ketone linkages are less flexible and slow the packing of chains. PEKK possesses both amorphous and crystalline behavior [1, 21].

2. Processing technologies in the field of restorative and prosthetic dentistry

PAEKs may be processed with different manufacturing techniques, including milling, vacuum pressing from pellets or granules, and additive manufacturing [2, 14].

Selective laser sintering (SLS) and fused deposition modeling (FDM) or fused filament fabrication (FFF) are the two 3D printing methods that can be used to produce PEEK. SLS is a method that creates a solid structure by selectively fusing areas of a powder bed together layer by layer using thermal energy from an electron beam or laser. A feeder motor is usually used to load the filament into the printing machine in FDM printing technology. The entire thing is then created by heating it to a semi-liquid condition, extruding it via a nozzle, and printing it layer by layer on a bed. SLS printers have a resolution of 50–100 µm; however, they cost a lot more than

Mechanical property	PEEK	PEKK
Compressive strength (MPa)	118–169	246
Tensile strength (MPa)	100.69	115
Flexure strength (MPa)	140–170	200
Young's modulus (GPa)	3–4	5.1

Table 1.
Mechanical properties of PEEK vs. PEKK [3, 22].

FDM printers. Therefore, although operating at a resolution of 100–150 μm , FDM printers are commonly used. The majority of applications, nevertheless, are still in the research stage. PEEK will be presented for use in dentistry based on the advancement of research on the material in relation to additive manufacturing processes [14, 23].

Nowadays in dental technology, HPP can be processed by pressing the extruded material with a special vacuum-pressing device. The materials are supplied in granular or pellet form. By milling HPP restorations from prepressed blanks, computer-aided design (CAD) and computer-aided manufacturing (CAM) technology allow for an alternate manufacturing procedure [5] (**Figure 2**).

Related to the processing technology, studies proved that fixed and removable prostheses showed appropriate mechanical properties [22]. The mechanical results of inlays and onlays made of HPP were encouraging, but in order to be practical in vivo and serve as a substitute dental material, advancements in accuracy and esthetics will be necessary [24].

Removable partial dentures (RPDs) may be produced in the CAD/CAM workflow (**Figure 3**) and also using vacuum-pressing technology.

For fixed restorations, as well, both technologies are indicated. These can be processed by milling from prepressed blanks (**Figure 4**) or pressed in molds using specific devices, like for 2 press 2 (Bredent, Senden, Germany) (**Figure 5**).

Given the stringent requirements for fit, corrosion resistance, and wear resistance, PEEK seems to be a viable substitute metal-free material for telescopic crown production [25]. All primary and secondary crowns may be achieved by PEEK, by different processing technologies, and examples are presented below.

For the primary crowns, a CAD design was achieved, and copings were milled from Cercon base cast blanks (Dentsply Sirona, Hanau, Germany). The copings were embedded, and the restorations were obtained by hot vacuum-pressing (**Figure 6**).

For the secondary crowns, wax patterns were achieved, and restorations were obtained also by hot vacuum-pressing (**Figure 7**).

Overdenture was completed (**Figure 8**).

3. Optical properties

Because of their opaque grayish-brown or pearl-white appearance, PEEK materials must be veneered with composite resin in esthetic regions, even though they were created as an attractive substitute for metallic frameworks. A portion of the framework is still visible in the oral cavity if the veneer is only partially applied.



Figure 2.
Presentation of HPP materials: (a) PEEK blank and (b) reinforced PEEK pellets.

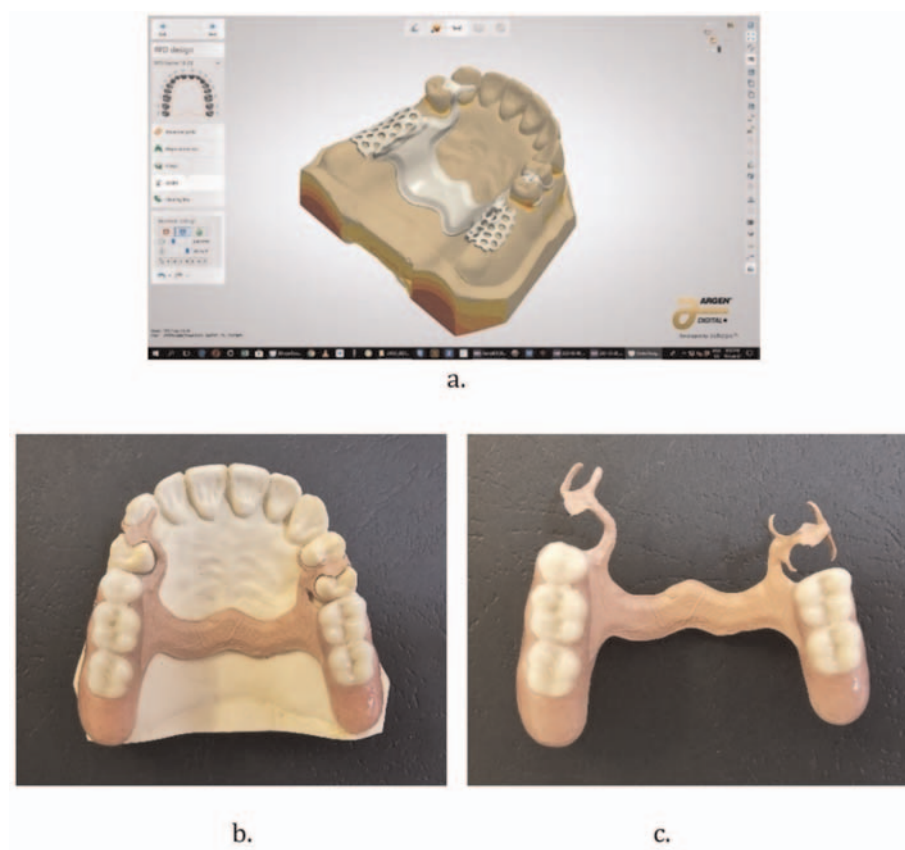


Figure 3. Removable partial dentures with PEEK framework; (a) design of a removable partial denture framework, (b) removable partial denture on the cast, and (c) removable partial denture with PEEK framework.

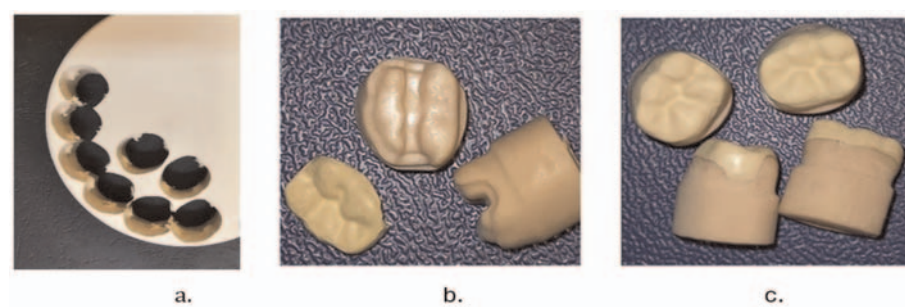


Figure 4. PEEK onlays achieved by CAD/CAM technology: a. PEEK blank after milling the onlays, b. milled onlay and abutment, c. onlays cemented on resin abutments.

Furthermore, their compounds—whether connectors, direct retainers, clasps, attachments, or double crowns—will be seen in the oral cavity when the material is used for the frameworks of removable partial dentures. As a result, finishing and surface processing ought to be difficult.

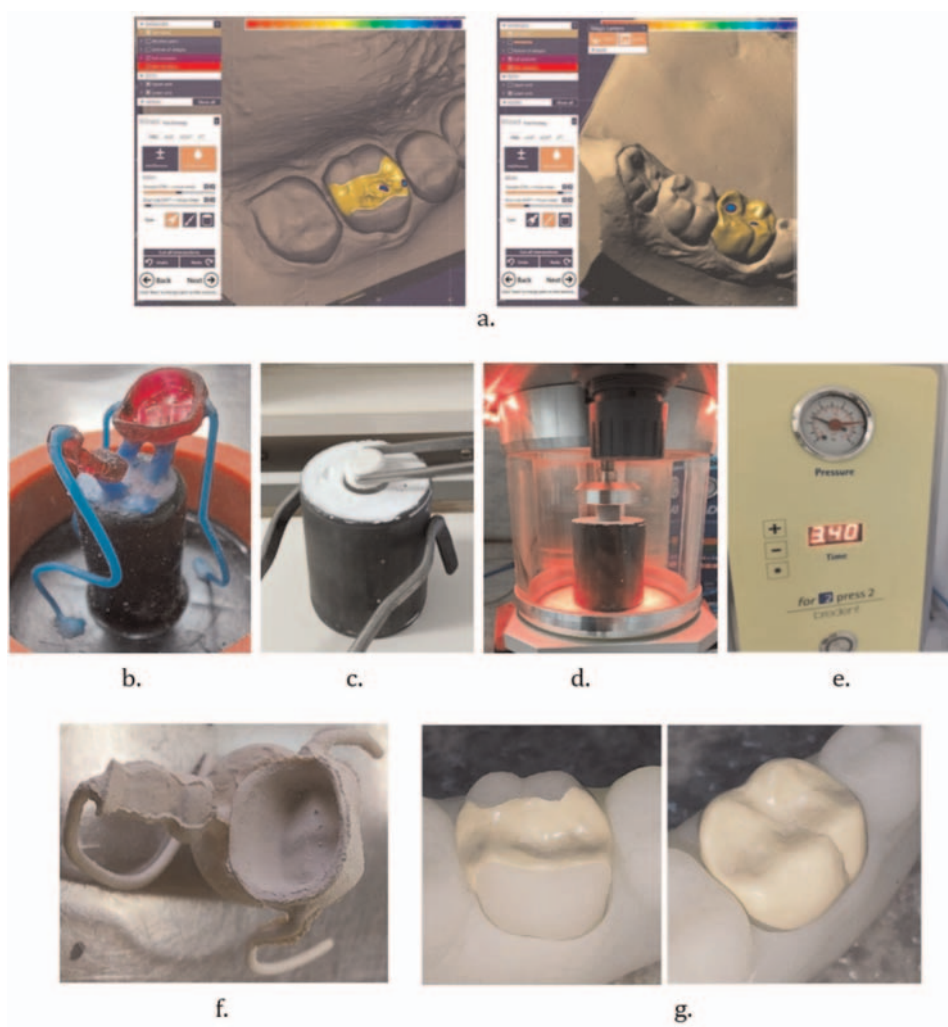


Figure 5.

PEEK restorations achieved by vacuum-pressing technology: (a) design of the restoration, (b) coping prepared for embedding, (c) mold with the pellet, (d) pressing step, (e) pressing device, (f) restoration after pressing, and (g) finished single tooth restorations on the cast.

Extrinsic factors, like staining from food and beverage colorants, mouth rinses, and smoking, or intrinsic factors, like the type of resin matrix, percentage and filler size, age, and processing technology, can cause dental composite resin materials to become discolored in the oral cavity.

Surface roughness and surface-free energy during surface processing have a major impact on color stability. According to multiple research, a high surface roughness is positively correlated with dental resin yellowing, which can be explained by the increased contact area [6, 11].

In vitro investigations were used to examine the long-term impacts of the combined activities of aging and immersing solutions on the optical characteristics and color stability of PEEK materials connected to surface treatments (polishing or glazing) [6]. The goal of the study was to determine how various staining and aging techniques affected the surface roughness, color changes, and optical characteristics

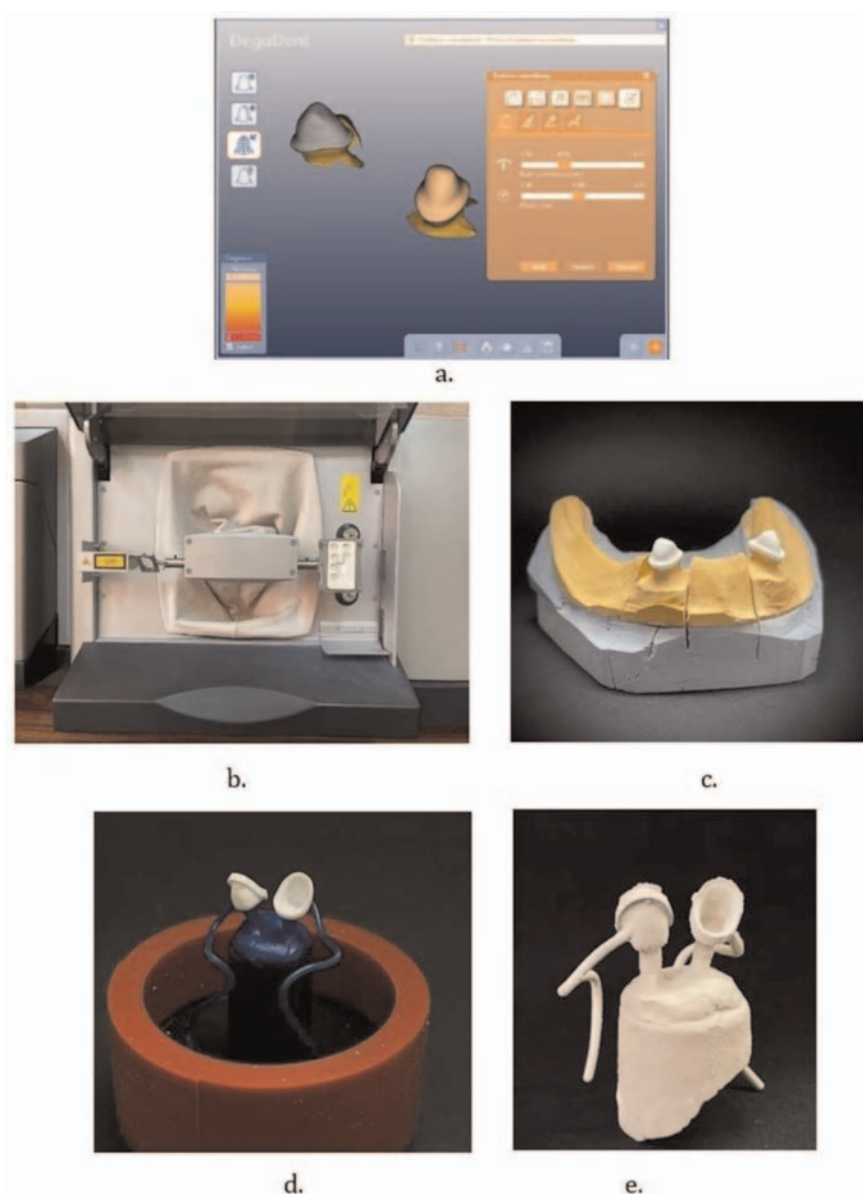


Figure 6.
 Achieving of the primary crowns: (a) CAD of the primary crowns, (b) milling of the base cast blank, (c) milled copings on the cast, (d) copings prepared for embedding, and (e) pressed primary crowns.

of an HPP material with 20% ceramic fillers that was between 0.3 and 0.5 microns in size and reinforced PEEK material (BioHPP, Bredent, Senden, Germany).

To obtain dependable restorations, the behavior of the materials during clinical usage is crucial, and depending on the kind of material and processing method, in vitro research may mimic the oral environment. In order to estimate the clinical stability over the long period, studies conducting thermal cycling tests to simulate oral environmental variables are the most used [6]. Thermal cycling is a useful method to accelerate the artificial aging of the samples, by prolonged deterioration. Using baths

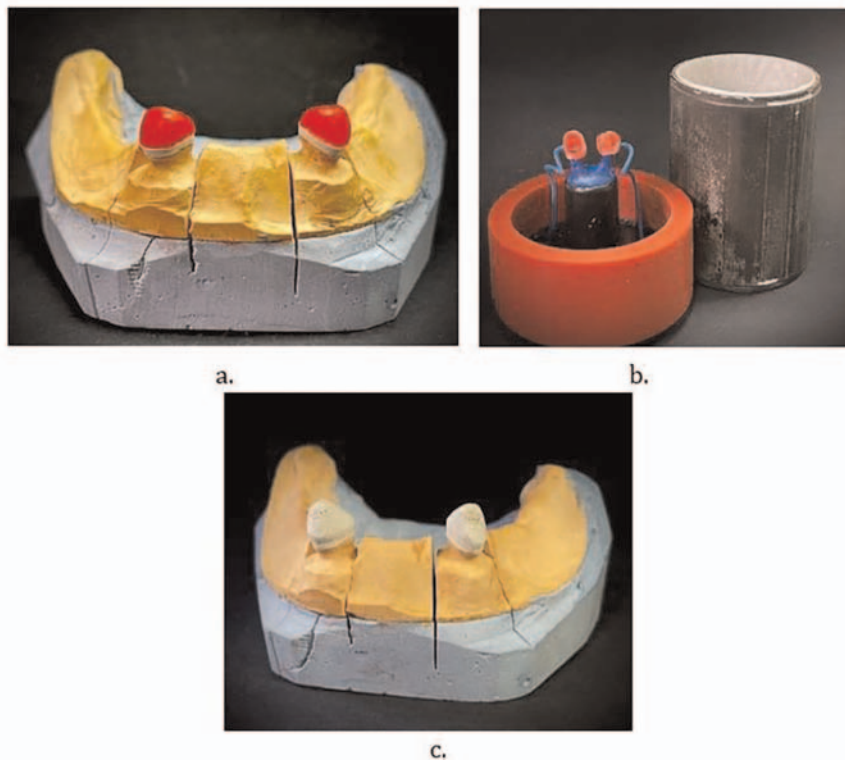


Figure 7.
Achieving of the secondary crowns: (a) wax pattern on the cast, (b) wax pattern prepared for embedding, (c) pressed secondary crowns on the cast.



Figure 8.
Overdenture on PEEK telescopic crowns: (a) primary telescopic crowns on the cast and (b) overdenture with the secondary telescopic crowns.

that range in temperature from 5 to 55°C for multiple cycles, the water aging process incorporates standardized thermal changes. In order to simulate a clinical period of 6 months, 5000 cycles of the thermal aging protocol were used in the artificial aging simulation [6, 26]. However, the staining cycling period has been compared to an immersion of 2 minutes per day, which equates to 360 minutes over 6 months, or 720 cycles for each sample and beverage. In order to stain, thermal cycling was carried

out in two different baths: one with distilled water (37°C) and a hot coffee bath (55°C) and another with cold juice (5°C) and distilled water (37°C) [6].

Translucency and opalescence, two optical characteristics of dental materials, are essential for esthetics and for simulating the restorations' natural look. A spectrophotometer gadget measuring the color difference at uniform thickness between black and white backings is called translucency. The translucency parameter (TP) value is zero if the substance is totally opaque. The material's translucency rises in tandem with the TP value. An item appears bluish and orange/brown in the reflected and transmitted color due to opalescence, which is defined as a scattering of visible light wavelengths [27, 28]. It is possible to compute opalescence parameters (OP).

TP and OP are significant optical parameters that were determined using Vita Easyshade IV (Vita Zahnfabrick, Bad Säckingen, Germany) following spectrophotometric observations. The measures were evaluated using a gray card, WhiBal G7 (White Balance Pocket Card), with black (b) and white (w) backgrounds. A material's lightness-darkness is measured by its L^* value; perfect black has a L^* of 0, and perfect white has a L^* of 100. Redness (positive value) or greenness (negative value) are represented by the a^* coordinate, and yellowness (positive value) or blueness (negative value) are measured by the b^* coordinate [6] (**Figure 9**).

The following equation was used to calculate the TP values (1):

$$TP = [(L_b - L_w)^2 + (a_b - a_w)^2 + (b_b - b_w)^2]^{1/2} \quad (1)$$

OP values were calculated using Eq. (2).

$$OP = [(a_b - a_w)^2 + (b_b - b_w)^2]^{1/2} \quad (2)$$

where w and b are color coordinates of the specimens on the white and black backgrounds.

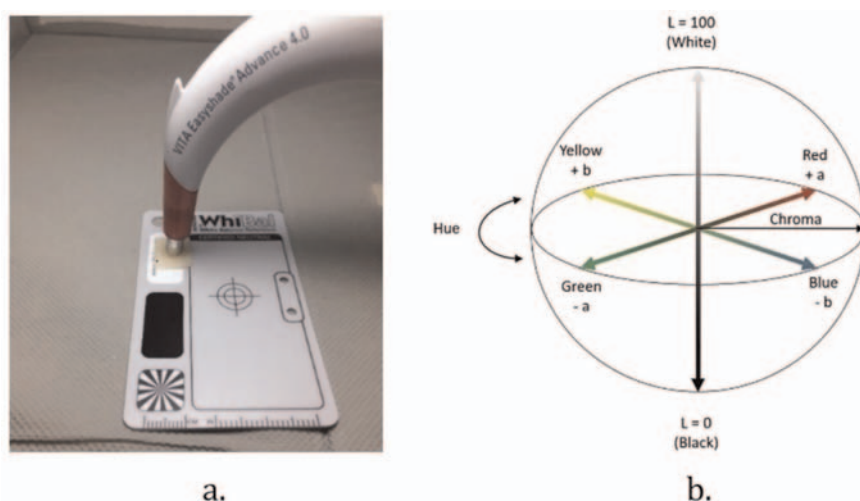


Figure 9. Optical properties determinations using: (a) a spectrophotometer, a specific card, based on (b) CIELAB color space.

The color change values (ΔE^*) were calculated based on the CIE $L^*a^*b^*$ color system.

The total ΔE^* was calculated according to Eq. (3), which represents the color difference before and after immersion:

$$\Delta E^* = \left[(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2 \right]^{1/2} \quad (3)$$

The degrees of color shift were measured using the National Bureau of Standards (NBS) approach (**Table 2**). The ΔE^* data were transformed into NBS units in order to correlate the color shift with a clinical standard: $NBS = \Delta E^* \times 0.92$ [6].

The proportional quantity of light that passes through a substance per unit thickness is known as its translucency. Surface conditions, water content, and illumination were described in relation to the factors that affect translucency. Surface topography and subsequent light scattering may be altered by surface finishing techniques. Translucency is so greatly impacted by surface polishing. TP values were discovered to be influenced by the impacts of staining and heat cycling in addition to the filler's effect on dental composite materials [28].

PEEK materials offer an attractive substitute for metallic frameworks, notwithstanding their infrequent application in monolithic restorations. As a result, their optical characteristics are crucial and must be connected to the teeth's optical characteristics. Compared to natural teeth or alternative attractive restoration materials, the mean TP values of the examined samples fell between 1.25 and 3.60.

The OP values of PEEK were registered to be in the range of 0.27–0.75, which are also lower than those of natural teeth or other esthetic restorative materials (**Figure 10**).

NBS units	Color changes
0.0–0.5	Extremely small change
0.5–1.5	Modest change
1.5–3.0	Perceptible
3.0–6.0	Significantly change
6.0–12.0	Significantly noticeable change
12.0 or more	Shift in color

Table 2.
Color alteration levels as reported by NBS [6].

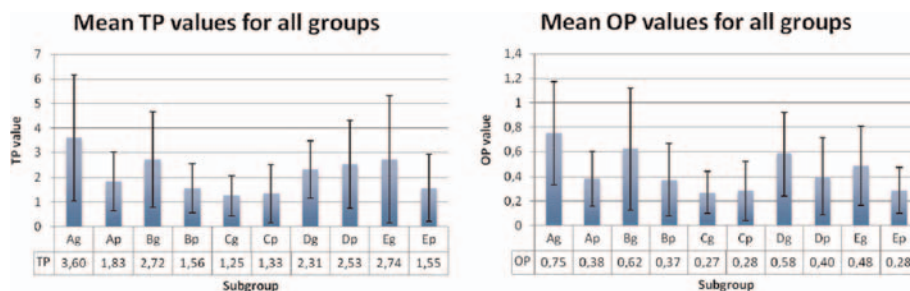


Figure 10.
TP and OP values (mean ± SD) for all tested groups [6].

The processing protocol for the subgroups included in the study is as follows [6]:

Ag, Ap: control

Bp, Bg: 7 days of distilled water storage

Cp, Cg: 7 days of distilled water storage plus thermal cycling

Dp, Dg: staining with hot coffee, thermal cycling, and distilled water storage

Ep, Eg: for instance, coloring cold fruit-flavored carbonated soft drinks with distilled water and thermal cycling

p: polished samples.

g: glazed samples.

TP and OP have a very significant positive correlation. In comparison to the polished samples, the glazed samples showed greater opalescence. The glaze layers may be the cause of this, as they intensify the samples' yellowness [29].

The roughness parameters were also taken into account because surface roughness significantly affects the restoration's color. The optical characteristics are changed by a rough surface reflecting less light than a smooth surface. For every subgroup, the average registered Ra levels were less than 0.13 μm . In hot coffee, thermal cycling and artificial aging have been shown to raise roughness values and produce noticeable discolorations. The solubility of the colorants and water absorption may be the cause of the enhanced surface roughness during a hot coffee soaking. Surface roughness (Ra) and color stability (ΔE) have a very strong positive connection ($R = 0.976$) for glazed samples and a strong positive correlation ($R = 0.634$) for polished samples [6].

PEEK glazing has a positive impact on opalescence and surface roughness. Regardless of surface treatments, artificial aging reduces the translucency and opalescence of glazed surfaces and deteriorates the color stability and roughness of PEEK [6].

It can be explained that artificial aging by thermal cycling leads to microcracks, which increase the surface roughness and enhance water uptake and dissolution. Water molecules preferentially diffuse along the interface. The difference in the coefficient of thermal expansion between PEEK and ceramic fillers means that temperature changes create significant micro-stresses at the interface. This drastically reduces flexural strength, fracture toughness, and fatigue resistance. Debonded filler particles can be plucked out from the surface, becoming third-body abrasives that accelerate the wear of both the PEEK and opposing natural teeth. The voids left by lost filler particles create micro-pores, drastically increasing the surface area and pathways for fluid ingress and stain absorption. The color changes during clinical use may be caused by stain accumulation, dissolution of material ingredients, water sorption, pigment degradation, and surface roughness [15].

According to a different study, staining beverages and cleaning techniques have an impact on the color changes and surface roughness changes of various dental PEEK materials [30]. BioHPP, a 20% ceramic reinforced PEEK (BioHPP, Bredent, Senden, Germany), Finoframe PEEK (Fino GmbH, Bad Bocklet, Germany) and Juvora medical PEEK (Juvora Ltd. Global Technology Center, Lancashire, UK), and 100% PEEK

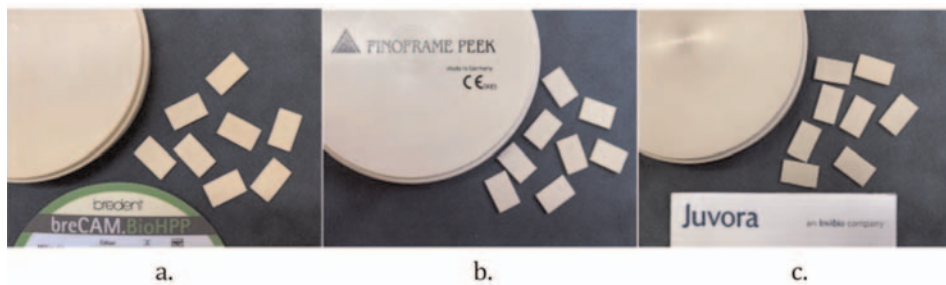


Figure 11.
Discs of PEEK materials: (a) BioHPP, (b) Finoframe, and (c) Juvora [30].

materials were taken into the study. Samples were sectioned from prepressed blanks (Figure 11).

Hot coffee, hot black tea, cold juice, and distilled water as a control were the four staining media used. A hot coffee/tea bath (55°C) and a bath filled with distilled water (37°C) were used for the staining thermal cycling, and a cold juice bath (5°C) and a bath filled with distilled water (37°C) were used for the same purpose. Mechanical brushing and chemical treatments were chosen for cleaning.

Juice and tea are examples of staining liquids that can significantly reduce the surface roughness of PEEK materials. It has been determined that discernible color changes are specific to tea (BioHPP) and coffee (Juvora). PEEK's surface and color properties may be enhanced by chemical cleaning and mechanical brushing. Regarding cleaning, only juice-immersed Juvora that has been chemically treated have shown noticeable color changes [30].

4. Water solubility

The ability of dental polymers, such as HPP, to absorb water is a key feature. Water diffuses through the resin matrix and, in the case of composites, most likely through the filler/matrix interfaces. The polymer undergoes a plasticization process that degrades the material's surface qualities and, in turn, its optical qualities.

According to studies, the majority of resin materials began to absorb water and reach saturation after 7 days of immersion. Once saturation is reached, the polymer chain separates and the hardness decreases. The amount of water sorption and the decrease in hardness do not appear to be directly correlated [15, 31]. PEEK and PEKK have water sorption rates of 0.1–0.5 and 8.7 mg/mm³, respectively [21].

Custom specimens of unmodified and modified PEEK CAD/CAM materials were investigated: BioHPP, a 20% ceramic reinforced PEEK (BioHPP, Bredent, Senden, Germany) (B), Finoframe PEEK (Fino GmbH, Bad Bocklet, Germany) (F) and Juvora medical PEEK (Juvora Ltd. Global Technology Center, Lancashire, UK) (J), 100% PEEK materials. A contact profilometer was used to assess surface roughness. Atomic Force Microscopy was used to characterize the nanosurface topography, a micro-hardness tester was used to quantify Vickers hardness, and color changes were computed.

Investigations revealed that PEEK materials reached saturation after the first week of immersion, and during in vitro aging, they lose weight. After the first week of immersion in distilled water at 37°C, the weight of all specimens increased by

0.21–0.27%, for all materials. Otherwise, the weight changes in subsequent weeks were lower than 0.05% (**Figure 12**).

Microroughness values increased significantly after the first week of water immersion, and decreased significantly after the following second week. Starting with the third week, the roughness variations become insignificant. A SurfTest SJ-201 (Mitutoyo, Kawasaki, Japan) contact 2 μm stylus profilometer was used to measure surface roughness (**Figure 13**). Maximum absolute vertical roughness (Rz) and arithmetic average roughness (Ra) measurements were made in five distinct directions, and all data were documented. For every surface, the average of the five measurements was determined. A force of 0.7 mN was applied, and the sampling length was 0.3 mm.

In addition to providing high resolution nanoscale images for the morphology, surface texture, particle size, and roughness, AFM characterization provides both qualitative and quantitative data.

A Nanosurf Easy Scan 2 Advanced Research (NanosurfAG, Liestal, Switzerland) atomic force microscope was used to evaluate samples from each group in non-contact mode. Values for the maximum amplitude of heights (Sy) and average nanoroughness (Sa) were recorded. For the sample surfaces, AFM produced matching three-dimensional profiles ($1.12 \mu\text{m} \times 1.12 \mu\text{m}$) (**Figure 14**).

Prior to being submerged in water, the samples' 3D pictures display asymmetrical surfaces with rounded edges and varying-sized depressions. B > F > J is the order in which the depressions' depth declines. B's extremely small grain size may result in consistent homogeneity. The look of the 3D surfaces changes very little during water

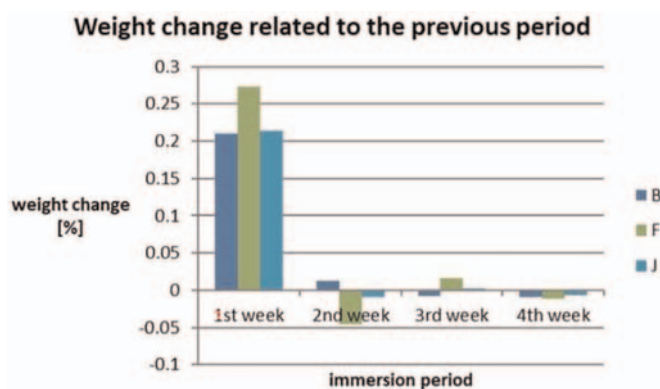


Figure 12.
Weight changes of PEEK materials during water immersion.



Figure 13.
Profilometer used for microroughness measurements.



Figure 14.
Atomic force microscope.

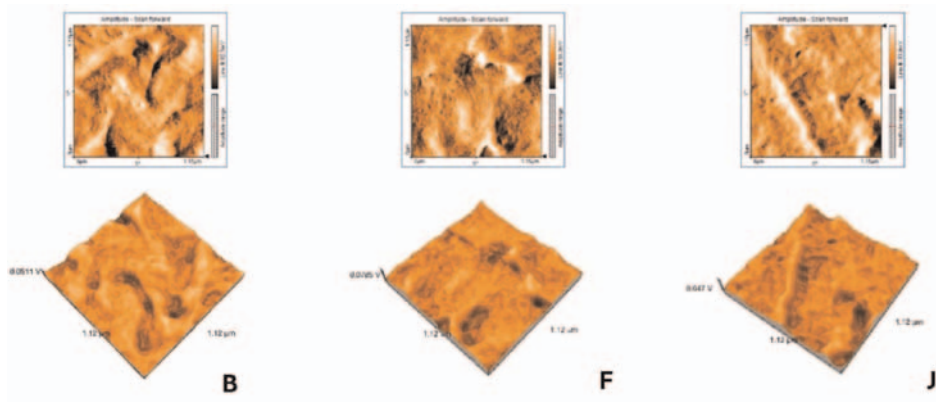


Figure 15.
Topographic images of PEEK blank samples.

immersion; therefore, the ratio of materials changes as follows during the final week of immersion: $F > J > B$. The initial report is returned after heat cycling, but the depressions are less pronounced (**Figures 15–17**).

The 3D images correlate with the average particle size (**Figures 18 and 19**).

A micro-hardness tester DM8/DM2 (Yang Yi Technology Co., Lt, Tainan City 70,960, Taiwan, China) was used to evaluate Vickers hardness (**Figure 20**). A diamond pyramidal indenter was used to apply a 300 g force for 10 seconds. The indentation dimensions were measured under a 40x microscope after the indenter was removed. Five indentations on each specimen were chosen for hardness measurements. Dry specimens, specimens submerged in water, and specimens thermocycling were all used for measurements. The following formula was used to compute the hardness values (4):

$$HV = 1.8544 F/d^2 \quad (4)$$

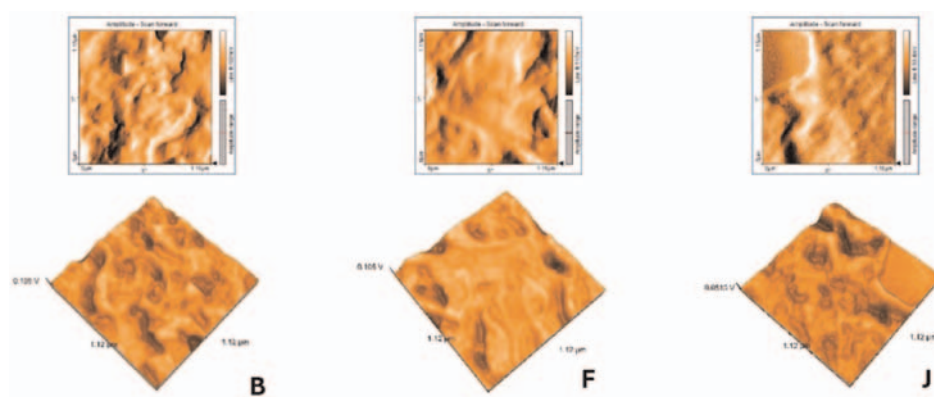


Figure 16.
 Topographic images of PEEK blank samples after water immersion.

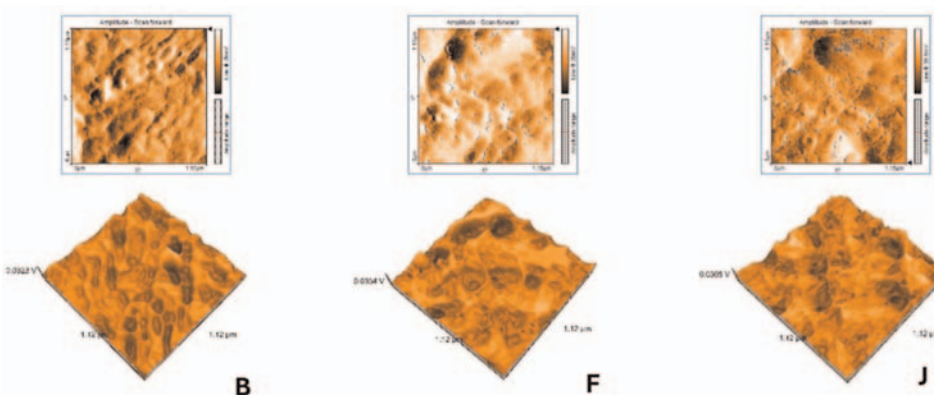


Figure 17.
 Topographic images of PEEK blank samples after thermal cycling.

where d is the diagonal length of the indentation, F is the load, and HV is the Vickers hardness number.

Water sorption was associated with a decrease in microhardness (**Figure 21**). This fact supports a moderate negative direct correlation ($R = -0.44$) between water sorption and microhardness. In relation to microhardness, the material most affected by water immersion and thermocycling is the reinforced PEEK [15]. After immersion, the PEEK with 20% ceramic filler showed the greatest hardness drop; this could be because of the filler-matrix interaction.

Studies show that, by increasing more than 20% by weight the number of nanofillers, a decline in the mechanical properties was registered, possible due to the higher amounts of nanofillers, which could restrict the mobility of the polymer chains, decreasing the degree of crystallinity [32].

Although there appears to be no direct relationship between the amount of water sorption and the reduction in hardness, water plasticization can be enhanced after saturation, leading to polymer chain separation and hardness reduction [15].

The ether (C-O-C) and ketone (C=O) groups in PEEK susceptible to slow hydrolysis. In the mouth, long-term exposure to water (saliva, beverages), changes in pH (acidic foods, bacterial plaque acids), and temperature cycling (hot/cold drinks)

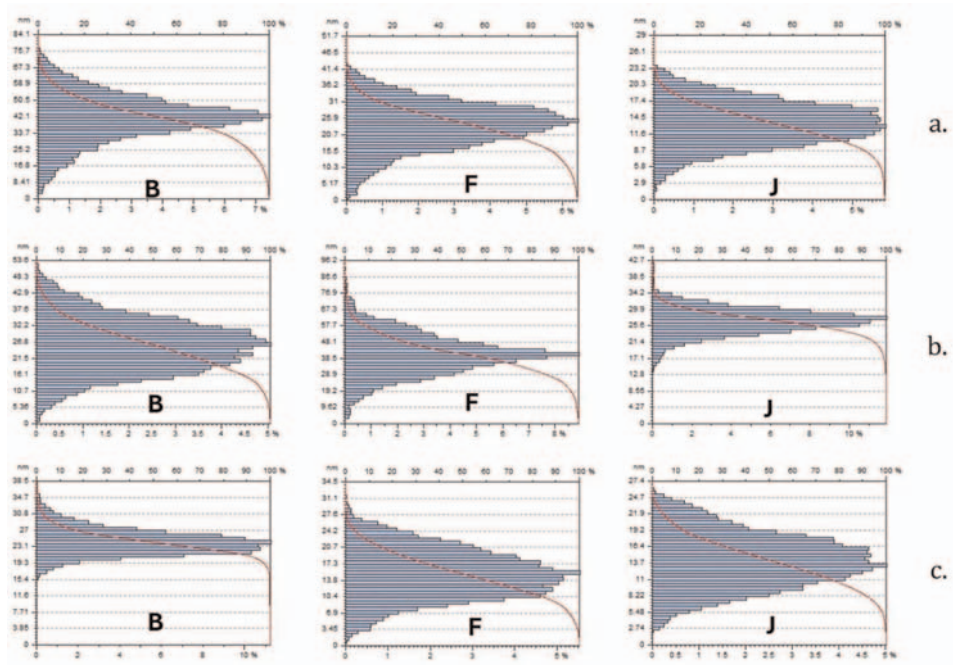


Figure 18.

Particle size distribution: (a) before immersion, (b) after water sorption and (c) after thermal cycling.

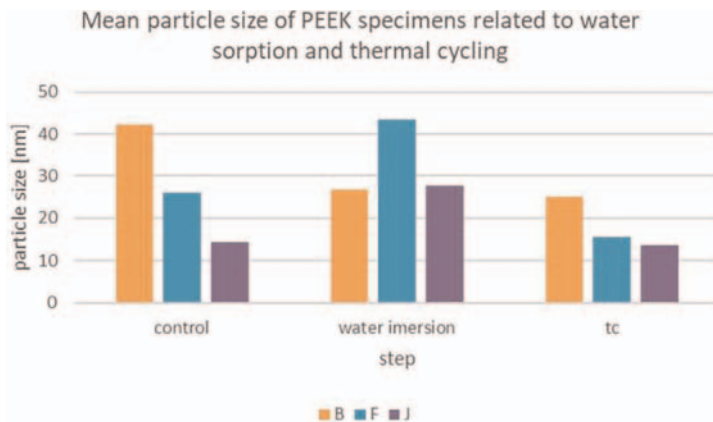


Figure 19.

Mean particle size distribution.

can facilitate this process. The hydrophilic characteristics of these monomers, and polymer network configurations are also important factors that determine composite performance. PEEK's aryl ring, which contains ketone and other compounds, gives it extremely stable chemical and physical characteristics. In contrast to other polymer-based CAD/CAM materials, it exhibits low solubility and water sorption and is stable at high temperatures [18, 19].

The hardness decrease was significant during the whole period of immersion (7.23–10.94%) and during thermocycling (0.12–2.31%). There were significant

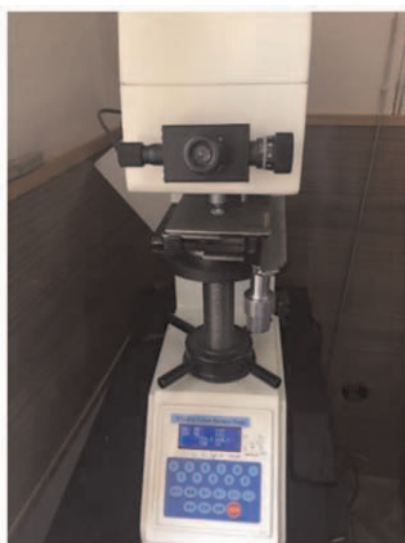


Figure 20.
 Microhardness tester.

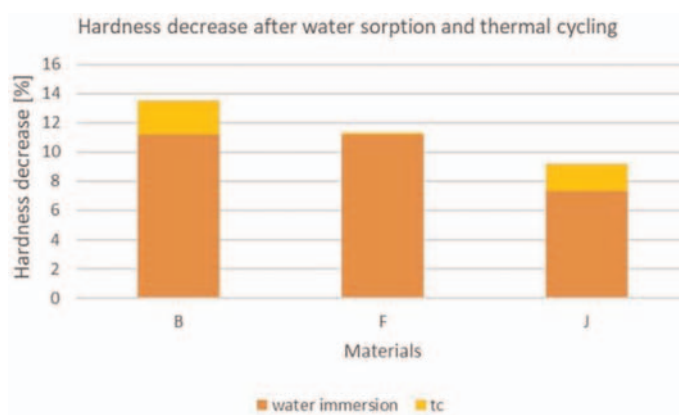


Figure 21.
 Hardness decrease after water immersion and thermal cycling.

differences between all materials. In relation to microhardness, the most affected by water immersion and thermocycling was the reinforced PEEK.

Thermal cycling, which primarily involves temperature changes and water immersion in controlled laboratory settings, can be used as an artificial aging technique. Microcracks, which raise surface roughness and improve water absorption and dissolution, are likely the result of thermal cycling [33, 34]. The present analysis showed that, while there were no appreciable variations between the materials, microroughness increased significantly with water immersion and thermocycling. The roughness is maintained within clinically recognized bounds, though. R_a and S_a were shown to have a moderate connection ($R = 0.49$), which is associated with thermal cycling. In terms of nanosurface topography and nanoroughness, the reinforced PEEK material has undergone the most aging modification. Thermal cycling and water immersion have an impact on the materials' surface properties.

Microroughness increased significantly as a result of thermal cycling, although there were no appreciable variations among the materials under study. The reinforced PEEK material underwent the greatest aging modification in relation to the nanosurface topography and roughness. For all materials, the color changes following a year of simulated in vitro aging and 4 weeks of water immersion ranged from very modest to slight.

5. HPP for removable partial dentures

The drawbacks of metallic RPD frameworks, particularly direct retainers, include their unattractiveness and the potential for allergic responses and oral galvanism in certain patients. These issues have been resolved by thermoplastic materials [2, 5].

HPP may be used for RPDs as dental clasps and frameworks. Clasps can be used to provide retention for a long time, but the design have to be customized. HPP can also be used as attachments [3].

The production of lighter metal-free RPDs is made possible by PEEK's advantageous qualities, which include excellent biocompatibility, good mechanical qualities, good thermal and chemical resistance, white color, and low specific weight. These qualities also eliminate the unsightly display of metal clasps and the possibility of metallic taste and allergies associated with traditional RDP metal frameworks [12].

Regarding PEEK materials' potential application as RDP clasps and their strong resistance to artificial aging in saliva, a prior study found encouraging results [5]. To allow the adoption of PEEK as a clasp material to a wider extent, it is important to undertake further investigations, including a variety of clasp shapes and geometries [5]. PEEK materials provide excellent esthetic results and good material homogeneity. Furthermore, PEEK materials may have a favorable outcome for patients who are prone to allergies because of their high surface resistance, minimal reactivity, and extremely inert behavior in the oral cavity [20].

After being stored in water and artificially aged using thermal cycling, clasps manufactured of various PEEK materials were compared to a Co-Cr-Mo control group to determine their retention force. In order to guarantee enough retention force, flexible PEEK may need a deeper undercut, and retention force initially decreased. PEEK clasps could be made thicker and more undercut to give enough retentive force to compensate this shortcoming. Regarding the results of the current study, it is important to highlight PEEK's encouraging performance when the clasps are repeatedly inserted and removed as well as its generally high retention force, even after artificial aging [5, 10, 35, 36].

Specific clasp designs should be designed in order to evaluate the retention force and mechanical behavior. Due to the PEEK's low elastic modulus compared to CoCrMo alloys, clasps may not withstand during a repetitive insertion and removal. The parameters of the thickness should be increased, and a greater undercut is provided for an adequate retentive force. Studies in the field of attachments should be extended. Conducting in vitro studies of each component of the RPD frameworks, the results should be provided for further in vivo studies.

Due to its high elasticity, PEEK could reduce stresses and distal torque on the abutment teeth during function [12, 37].

6. Marginal and internal fit HPP restorations

One important element that may affect how long prosthetic restorations last is adaptability. It depends on the frequency and size of gaps determined by

morphological disproportion between the restoration and the dental hard tissues. The difference between the restoration's edge and the preparation line is known as the marginal gap (MG), while the difference between the restoration's interior and the dental structure is known as the internal gap (IG) [38–41].

The excellent properties of thermoplastic HPP offer new perspectives for restorative applications. These materials are strong, stiff, free of pores and free monomers, resistant to hydrolysis at different temperatures, and able to bear heavy loads.

Internal and marginal gaps are often evaluated using two non-invasive techniques: micro-computed tomography (micro-CT) and the replica technique. The replica method is acknowledged as a simple, dependable, and less costly approach. However, numerous drawbacks have been noted, including the difficulty of identifying the margins, the potential for errors due to cutting the silicone, the restricted number of locations that can be measured, and the fact that the accuracy varies depending on the measurement method and kind of impression material. Cementing the specimens without cutting them allows Micro-CT, a 3D imaging technology, to do the study. By rotating and seeing the samples as virtual slices, any parameter can be measured and compared at various stages of the experiment [39].

Three distinct HPP were used to create the MOD onlays: 20% ceramic reinforced PEEK-BioHPP (Bredent group GmbH & Co.KG, Senden, Germany); PEEK-Juvora Natural Dental (Juvora Ltd. Global Technology Center, Lancashire, UK); and PEKK-Pekkton ivory (Cendrez + Metaux, Biel/Bienne, Switzerland).

By measuring the cement layer's thickness at various internal and marginal points and statistically analyzing the mean values found in the two sagittal and coronal sections for the polymer and among the materials, the adaptability was evaluated (**Figure 22**) [39].

The accuracy was affected by the type of polymer (composition, mechanical characteristics, and machinability). The ceramic-reinforced PEEK material has the best

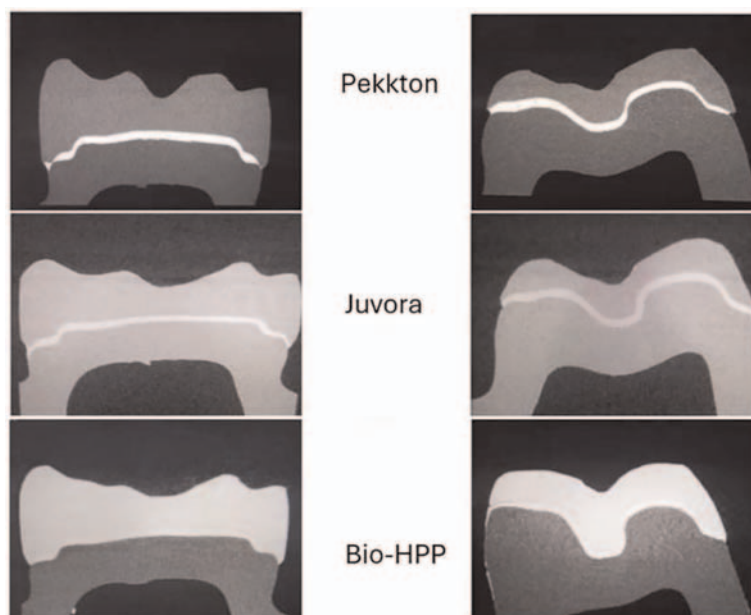


Figure 22.
CT images with sagittal and coronal sections [39].

behavior, followed by PEKK and untreated PEKK. In terms of adaptability, all of the polymers are clinically acceptable. For all three materials, the internal gap values were substantially higher than the marginal gap values.

There is no standard threshold for clinically acceptable marginal precision, but it has been stated that the greatest marginal gap is 120 microns. Research indicates that compared to PEEK pressed copings, the marginal precision of PEEK CAD-CAM produced copings exhibited noticeably reduced mean marginal gap values. The marginal gap mean values reported were all within a clinically acceptable range [42–44].

7. Wear behavior of HPP restorations

The wear resistance of dental restorative materials is an important factor for clinical decisions and the success in maintaining the vertical dimension. Little information is available for the long-term wear behavior of HPP restorations. In vitro studies are facile and faster options for the evaluation of the wear behavior of these materials.

Wear is described as a continuous and gradual loss of surface material, resulting from mechanical interaction between two surfaces which exhibit motion. This bio-mechanical phenomenon may be simulated with focus on attrition, through two-body wear interactions. The selection of clinical relevant wear parameters that can be applied for in vitro studies is important. For quantifications, usually the area of the wear region and volumetric loss is used [45].

Pressed and milled BioHPP, 20% ceramic reinforced PEEK materials (Bredent, Senden, Germany), Finoframe PEEK (Fino GmbH, Bad Bocklet, Germany) and Pekkton (Cendrez + Metaux, Biel/Bienne, Switzerland) were taken into the study, due to their indication areas in prosthodontics.

Flat specimens were worn against spherical antagonist, using a rotating ball-on-flat customized tribometer testing machine [46]. Metallic balls with a radius of 6.35 mm were used as antagonists. The hardness of the metallic balls was measured (mean Vickers hardness: 902.8 GPa).

In relation to dental materials, this configuration offers an advantage over other simulators, ensuing near-circular wear scars, reproducing the basic topographical features of clinically observed wear facets and affords a relatively simple evaluation of wear rates. The antagonist was allowed to directly strike the specimens with a mean force of 30 N at a rate of 30 rpm in order to conduct wear simulation experiments [47]. Periods of 1, 2, and 4 h were chosen. In order to resemble an oral lubrication environment, a 33% glycerin solution was used to mimic stimulated saliva. Tests were run at room temperature [48].

The sliding distance L across each scar at cumulative test duration t was determined from tetrahedral geometry as in the formula (5):

$$L = 2\pi Rft\sin\theta \quad (5)$$

where the angle between the line from the sphere center to the specimen contact and the rotation axis is $\theta = 37^\circ$.

Resulted sliding distances were $L = 43.22$ m (1 h), 86.44 (2 h), and 172.88 (4 h).

Low magnification micrographs were taken to analyze the shape of the wear facet/scar. Scar radii r were measured optically both parallel and perpendicular to the sliding direction, and average values were calculated (**Figures 23–26**).

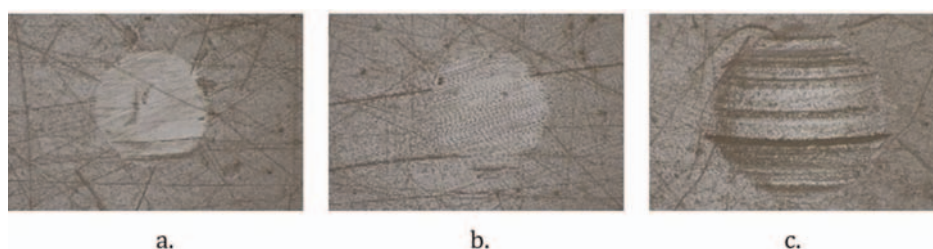


Figure 23.
 Optical images of the wear scars for pressed BioHPP after different periods of time: (a) 1 h, (b) 2 h, and (c) 4 h.

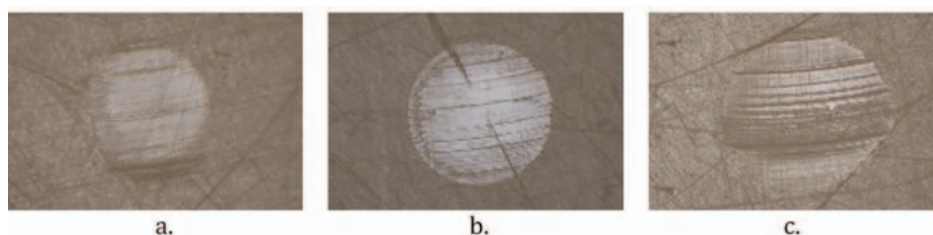


Figure 24.
 Optical images of the wear scars for milled BioHPP after different periods of time: (a) 1 h, (b) 2 h, and (c) 4 h.

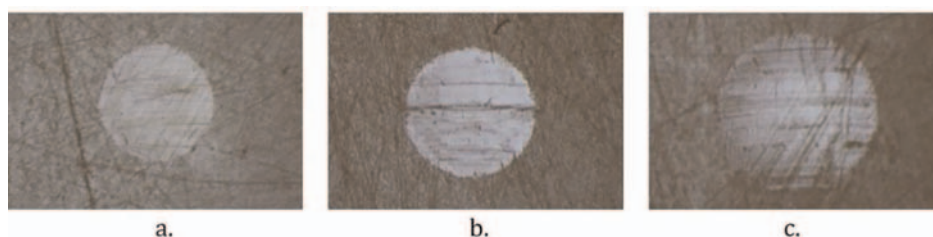


Figure 25.
 Optical images of the wear scars for Juvora after different periods of time: (a) 1 h, (b) 2 h, and (c) 4 h.

After the wear simulation tests, the specimens were ultrasonically cleaned in distilled water for 3 min and then investigated.

Near-circular wear scars on the plates were examined by optical microscopy under 4x magnification. Volumetric wear and wear surface area data were analyzed.

Scar volumes V were computed from the simple conformational relation (6) (Figure 27) [47]:

$$V = \pi r^4 / 4R \quad (6)$$

The maximum depth of wear h (μm) was determined, and mean values were calculated with the formula (7) (Figure 28):

$$h = R - (R^2 - r^2)^{1/2} \quad (7)$$

where R is the radius of the counter ball and r the radius of the wear scar [49].

The rate of material loss can be expressed as the wear rate [50]. Wear rate ($\mu\text{m}/1000$ cycles) can be calculated (Figure 29) as in the formula (8).

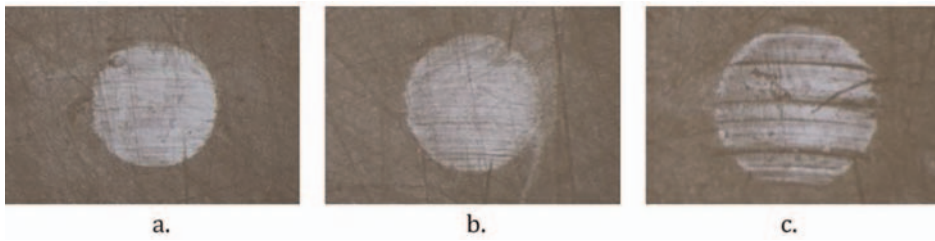


Figure 26.
Optical images of the wear scars for Pekkton after different periods of time: (a) 1 h, (b) 2 h, and (c) 4 h.

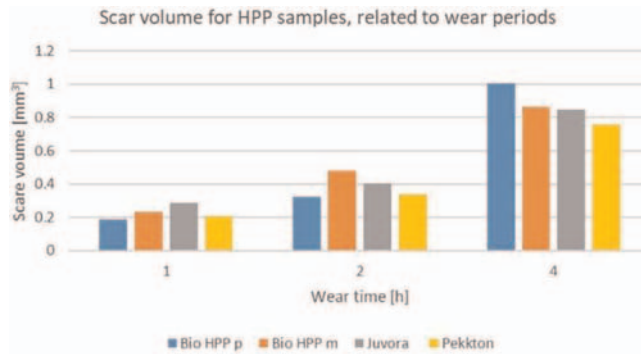


Figure 27.
Scar volume of the HPP samples.

$$\text{Maximum depth of wear } (\mu\text{m}) \times 10^3 / \text{number of cycles} \quad (8)$$

Wear rates gradually declined with an increasing number of cycles due to the increased contact surface area. In terms of the number of cycles the test was conducted under simulations of 1800–7200 cycles. The primary cause of tooth wear is tooth-to-tooth contact brought on by bruxism, clenching, and parafunctional forces, which have been found to happen at an average rate of roughly 8.1 cycles per hour. Assuming this mastication rate, periods of approximately 10, 20, and 40 days were simulated.

The target material's characteristics, antagonists, and experimental parameters including loading force on materials, cycle count, masticatory cycle reproduction method, and lubricant all affect how much wear occurs. Therefore, the amount of material loss caused by the ball material used in the present study cannot easily be compared with other reported in the literature [44].

According to Archard's law specific wear rates were calculated with the formula (9) [47] (**Figure 30**):

$$\text{Specific wear rate} = V/PL \left[\times 10^{-3} \text{mm}^3 / \text{Nm} \right] \quad (9)$$

Volumetric loss indicates the overall surface wear, while vertical loss is limited to linear measurements. Adopting both vertical and volumetric loss measurements would help to understand better the wear dynamics [51].

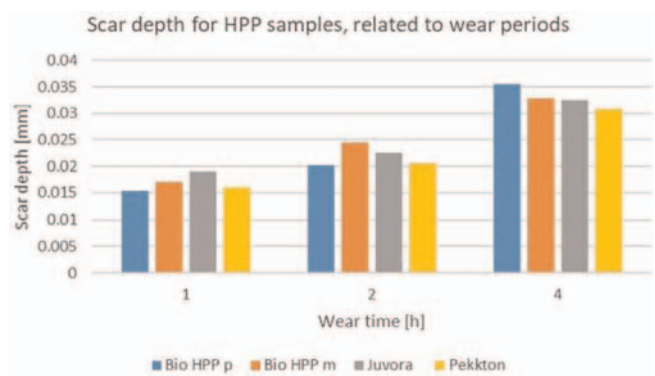


Figure 28.
Scar depth of the HPP samples.

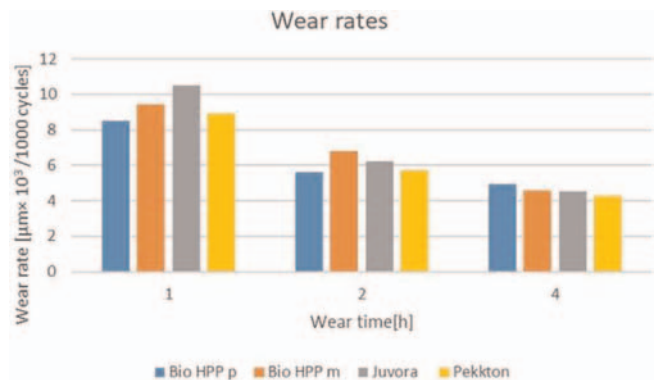


Figure 29.
Wear rates of the HPP samples (maximum depth of wear/1000 cycles).

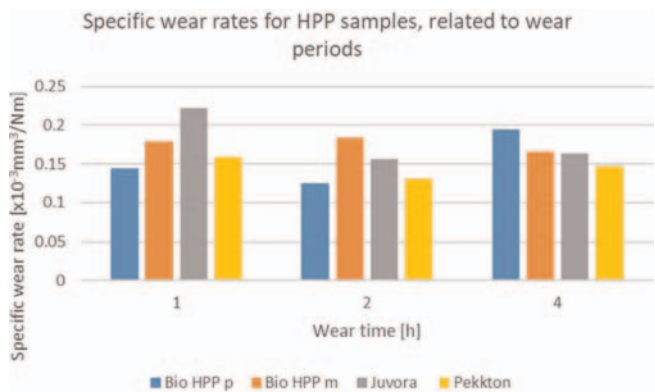


Figure 30.
Specific wear rates of the HPP samples.

For further studies the introductions of clinical relevant wear parameters that can be applied for in vitro studies is an opportunity, like materials, loading force, frequency rate, number of cycles, and environment. Reproducibility and time-efficiency are advantages of these in vitro studies. In vivo studies reflect the multifactorial nature of wear in the oral environment, with all its biological and behavioral variables.

8. Conclusions

The following conclusions summarize the content of this topic.

High-performance polymers (HPPs), which are substantially more expensive and challenging to produce, are in the top class of plastics according to the polymer pyramid. Among all these materials, PEEK is the most used in practice. It is well-known for its excellent mechanical qualities, low specific weight, low plaque affinity, low temperature resistance, chemical stability, high polishing potential, low specific weight, low wear resistance, and good bond strength with luting cements and veneering composites. They may be processed with different manufacturing techniques including milling, vacuum pressing from pellets or granules, and additive manufacturing.

Study observed promising results for PEEK materials with regard to their potential use as RPD frameworks. For fixed restorations, the recorded marginal gap mean values were all within a clinically acceptable range. Their surface processing and finishing should be a challenge. Artificial aging damages the color stability and roughness of PEEK. Water absorption was associated with a decrease in microhardness. The wear resistance of dental restorative materials is an important factor for clinical decisions and the success in maintaining the vertical dimension. Adopting wear quantification methods and finding new correlations would help to understand better the wear dynamics of HPP.

All studies and investigations leads to state that HPPs offer new perspectives for prosthetic and restorative applications in dentistry. Therefore, different applications and specific designs have to be assessed and taken into consideration.

Acknowledgements

We would like to acknowledge VICTOR BABES UNIVERSITY OF MEDICINE AND PHARMACY TIMISOARA for their support in covering the costs of publication for this paper.

Conflict of interest

The authors declare no conflict of interest.

Author details

Liliana Porojan^{1*}, Flavia Roxana Bejan¹, Roxana Diana Vasiliu¹ and Anamaria Matichescu²

1 Department of Dental Prostheses Technology (Dental Technology), Center for Advanced Technologies in Dental Prosthodontics, Faculty of Dentistry, Victor Babeş University of Medicine and Pharmacy, Timișoara, Romania

2 Department of Preventive, Community Dentistry and Oral Health, Center for Advanced Technologies in Dental Prosthodontics, Faculty of Dentistry, Victor Babeş University of Medicine and Pharmacy, Timișoara, Romania

*Address all correspondence to: sliliana@umft.ro

IntechOpen

© 2025 The Author(s). Licensee IntechOpen. This chapter is distributed under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/4.0>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited. 

References

- [1] Zol SM, Alauddin MS, Said Z, Mohd Ghazali MI, Hao-Ern L, Mohd Farid DA, et al. Description of poly(aryl-ether-ketone) materials (PAEKs), polyetheretherketone (PEEK) and polyetherketoneketone (PEKK) for application as a dental material: A materials science review. *Polymers*. 2023;**15**(9):2170. DOI: 10.3390/polym15092170
- [2] Divya PD, Dubey S. Can high performance polymers replace traditional alloys in dentistry? *Acta Scientific Dental Sciences*. 2023;**7**(9): 64-68. DOI: 10.31080/ASDS.2023.07.1697
- [3] Alqurashi H, Khurshid Z, Syed AUY, Rashid Habib S, Rokaya D, Zafar MS. Polyetherketoneketone (PEKK): An emerging biomaterial for oral implants and dental prostheses. *Journal of Advanced Research*. 2021;**28**:87-95. DOI: 10.1016/j.jare.2020.09.004
- [4] Bächle J, Merle C, Hahnel S, Rosentritt M. Bacterial adhesion on dental polymers as a function of manufacturing techniques. *Materials*. 2023;**16**(6):2373. DOI: 10.3390/ma16062373
- [5] Micovic D, Mayinger F, Bauer S, Roos M, Eichberger M, Stawarczyk B. Is the high-performance thermoplastic polyetheretherketone indicated as a clasp material for removable dental prostheses? *Clinical Oral Investigations*. 2021;**25**(5):2859-2866. DOI: 10.1007/s00784-020-03603-y
- [6] Porojan L, Toma FR, Vasiliu RD, Topală FI, Porojan SD, Matichescu A. Optical properties and color stability of dental PEEK related to artificial ageing and staining. *Polymers*. 2021;**13**(23): 4102. DOI: 10.3390/polym13234102
- [7] Benli M, Eker Gümüş B, Kahraman Y, Huck O, Özcan M. Surface characterization and bonding properties of milled polyetheretherketone dental posts. *Odontology*. 2020;**108**(4): 596-606. DOI: 10.1007/s10266-020-00484-1
- [8] Nascimento AS, Rodrigues JFB, Torres RHN, Santos KO, Fook MVL, Albuquerque MSD, et al. Physicomechanical and thermal analysis of bulk-fill and conventional composites. *Brazilian Oral Research*. 2019;**33**:e008. DOI: 10.1590/1807-3107bor-2019
- [9] Alshali RZ, Salim NA, Satterthwaite JD, Silikas N. Post-irradiation hardness development, chemical softening, and thermal stability of bulk-fill and conventional resin-composites. *Journal of Dentistry*. 2015; **43**(2):209-218. DOI: 10.1016/j.jdent.2014.12.004
- [10] Qin L, Yao S, Zhao J, Zhou C, Oates TW, Weir MD, et al. Review on development and dental applications of polyetheretherketone-based biomaterials and restorations. *Materials*. 2021;**14**(2): 408. DOI: 10.3390/ma14020408
- [11] Polychronakis N, Lagouvardos P, Polyzois G, Sykaras N, Zoidis P. Color changes of polyetheretherketone (PEEK) and polyoxymethylene (POM) denture resins on single and combined staining/cleansing action by CIELab and CIEDE2000 formulas. *Journal of Prosthodontic Research*. 2020;**64**(2): 159-166. DOI: 10.1016/j.jpjor.2019.06.005
- [12] Papathanasiou I, Kamposiora P, Papavasiliou G, Ferrari M. The use of PEEK in digital prosthodontics: A narrative review. *BMC Oral Health*. 2020;**20**(1):217. DOI: 10.1186/s12903-020-01202-7

- [13] Alsadon O, Wood D, Patrick D, Pollington S. Fatigue behavior and damage modes of high performance poly-ether-ketone-ketone PEKK bilayered crowns. *Journal of the Mechanical Behavior of Biomedical Materials*. 2020;**110**:103957. DOI: 10.1016/j.jmbbm.2020.103957
- [14] Dua R, Rashad Z, Spears J, Dunn G, Maxwell M. Applications of 3D-printed PEEK via fused filament fabrication: A systematic review. *Polymers*. 2021; **13**(22):4046. DOI: 10.3390/polym13224046
- [15] Porojan L, Toma FR, Bîrdeanu MI, Vasiliu RD, Uțu ID, Matichescu A. Surface characteristics and color stability of dental PEEK related to water saturation and thermal cycling. *Polymers*. 2022;**14**(11):2144. DOI: 10.3390/polym14112144
- [16] Skirbutis G, Dzingutė A, Masiliūnaitė V, Šulcaitė G, Žilinskas J. A review of PEEK polymer's properties and its use in prosthodontics. *Stomatologija, Baltic Dental and Maxillofacial Journal*. 2017;**19**:19-23
- [17] Aydın N, Karaoğluoğlu S, Oktay EA, Ersöz B. Superficial effects of different finishing and polishing systems on the surface roughness and color change of resin-based CAD/CAM blocks. *Odovtos - International Journal of Dental Sciences*. 2021;**23**(3):87-97. DOI: 10.15517/ijds.2021.46679
- [18] Liebermann A, Wimmer T, Schmidlin PR, Scherer H, Löffler P, Roos M, et al. Physicomechanical characterization of polyetheretherketone and current esthetic dental CAD/CAM polymers after aging in different storage media. *The Journal of Prosthetic Dentistry*. 2016;**115**(3):321-328.e2. DOI: 10.1016/j.prosdent.2015.09.004
- [19] Fonseca ASQS, Labruna Moreira AD, De Albuquerque PPAC, De Menezes LR, Pfeifer CS, Schneider LFJ. Effect of monomer type on the CC degree of conversion, water sorption and solubility, and color stability of model dental composites. *Dental Materials*. 2017;**33**(4):394-401. DOI: 10.1016/j.dental.2017.01.010
- [20] Bathala L, Majeti V, Rachuri N, Gedela S. The role of polyether ether ketone (PEEK) in dentistry – A review. *Journal of Medicine and Life*. 2019;**12**(1): 5-9. DOI: 10.25122/jml-2019-0003
- [21] Maloo LM, Toshniwal SH, Reche A, Paul P, Wanjari MB. A sneak PEEK toward polyaryletherketone (PAEK) polymer: A review. *Cureus*. 2022;**14**(11): e31042. DOI: 10.7759/cureus.31042
- [22] Alsadon O, Wood D, Patrick D, Pollington S. Comparing the optical and mechanical properties of PEKK polymer when CAD/CAM milled and pressed using a ceramic pressing furnace. *Journal of the Mechanical Behavior of Biomedical Materials*. 2019;**89**:234-236. DOI: 10.1016/j.jmbbm.2018.09.039
- [23] Ligon SC, Liska R, Stampfl J, Gurr M, Mülhaupt R. Polymers for 3D printing and customized additive manufacturing. *Chemical Reviews*. 2017; **117**(15):10212-10290. DOI: 10.1021/acs.chemrev.7b00074
- [24] Prechtel A, Stawarczyk B, Hickel R, Edelhoff D, Reymus M. Fracture load of 3D printed PEEK inlays compared with milled ones, direct resin composite fillings, and sound teeth. *Clinical Oral Investigations*. 2020;**24**(10):3457-3466. DOI: 10.1007/s00784-020-03216-5
- [25] Priester M, Müller WD, Beuer F, Schmidt F, Schwitalla AD. Performance of PEEK based telescopic crowns, a comparative study. *Dental Materials*.

2021;**37**(11):1667-1675. DOI: 10.1016/j.dental.2021.08.020

[26] Gerogianni P, Lien W, Bompolaki D, Verrett R, Haney S, Mattie P, et al. Fracture resistance of pressed and milled lithium disilicate anterior complete coverage restorations following endodontic access preparation. *Journal of Prosthodontics*. 2019;**28**(2):163-170. DOI: 10.1111/jopr.12798

[27] Lee YK. Translucency of human teeth and dental restorative materials and its clinical relevance. *Journal of Biomedical Optics*. 2015;**20**(4):045002. DOI: 10.1117/1.jbo.20.4.045002

[28] Sen N, Us YO. Mechanical and optical properties of monolithic CAD-CAM restorative materials. *The Journal of Prosthetic Dentistry*. 2018;**119**(4): 593-599. DOI: 10.1016/j.prosdent.2017.06.012

[29] Kim HK, Kim SH, Lee JB, Han JS, Yeo IS. Effect of polishing and glazing on the color and spectral distribution of monolithic zirconia. *The Journal of Advanced Prosthodontics*. 2013;**5**(3): 296. DOI: 10.4047/jap.2013.5.3.296

[30] Porojan L, Roxana Toma F, Diana Vasiliu R, Matichescu A. Surface roughness and color changes of dental PEEK related to staining beverages and cleaning methods. *Materials Today Proceedings*. 2023;**78**:221-226. DOI: 10.1016/j.matpr.2022.10.174

[31] Gao S, Gao S, Xu B, Yu H. Effects of different pH-values on the nanomechanical surface properties of PEEK and CFR-PEEK compared to dental resin-based materials. *Materials*. 2015;**8**(8):4751-4767. DOI: 10.3390/ma8084751

[32] Taymour N, Abd El-Fattah A, Kandil S, Fahmy AE, Al-Qahtani NH,

Khaled A, et al. Revolutionizing dental polymers: The versatility and future potential of polyetheretherketone in restorative dentistry. *Polymers*. 2025; **17**(1):80. DOI: 10.3390/polym17010080

[33] Müller JA, Rohr N, Fischer J. Evaluation of ISO 4049: Water sorption and water solubility of resin cements. *European Journal of Oral Sciences*. 2017; **125**(2):141-150. DOI: 10.1111/eos.12339

[34] Taşın S, Ismatullaev A. Comparative evaluation of the effect of thermocycling on the mechanical properties of conventionally polymerized, CAD-CAM milled, and 3D-printed interim materials. *The Journal of Prosthetic Dentistry*. 2022;**127**(1):173.e1-173.e8. DOI: 10.1016/j.prosdent.2021.09.020

[35] Mayinger F, Micovic D, Schleich A, Roos M, Eichberger M, Stawarczyk B. Retention force of polyetheretherketone and cobalt-chrome-molybdenum removable dental prosthesis clasps after artificial aging. *Clinical Oral Investigations*. 2021;**25**(5):3141-3149. DOI: 10.1007/s00784-020-03642-5

[36] Tannous F, Steiner M, Shahin R, Kern M. Retentive forces and fatigue resistance of thermoplastic resin clasps. *Dental Materials*. 2012;**28**(3):273-278. DOI: 10.1016/j.dental.2011.10.016

[37] Zoidis P, Papathanasiou I, Polyzois G. The use of a modified poly-ether-ether-ketone (PEEK) as an alternative framework material for removable dental prostheses. A clinical report. *Journal of Prosthodontics*. 2016; **25**(7):580-584. DOI: 10.1111/jopr.12325

[38] Mously HA, Finkelman M, Zandparsa R, Hirayama H. Marginal and internal adaptation of ceramic crown restorations fabricated with CAD/CAM technology and the heat-press technique. *The Journal of Prosthetic Dentistry*.

2014;**112**(2):249-256. DOI: 10.1016/j.prosdent.2014.03.017

[39] Toma FR, Moleriu LC, Porojan L. Micro-CT marginal and internal fit evaluation of CAD/CAM high-performance polymer onlay restorations. *Polymers*. 2023;**15**(7):1715. DOI: 10.3390/polym15071715

[40] Donovan TE. Factors essential for successful all-ceramic restorations. *Journal of the American Dental Association* (1939). 2008;**139**:S14-S18. DOI: 10.14219/jada.archive.2008.0360

[41] Hamza TA, Ezzat HA, El-Hossary MMK, El Megid Katamish HA, Shokry TE, Rosenstiel SF. Accuracy of ceramic restorations made with two CAD/CAM systems. *The Journal of Prosthetic Dentistry*. 2013;**109**(2):83-87. DOI: 10.1016/s0022-3913(13)60020-7

[42] Attia MA, Shokry TE. Effect of different fabrication techniques on the marginal precision of polyetheretherketone single-crown copings. *The Journal of Prosthetic Dentistry*. 2020;**124**(5):565.e1-565.e7. DOI: 10.1016/j.prosdent.2020.04.003

[43] Beuer F, Naumann M, Gernet W, Sorensen JA. Precision of fit: Zirconia three-unit fixed dental prostheses. *Clinical Oral Investigations*. 2009;**13**(3):343-349. DOI: 10.1007/s00784-008-0224-6

[44] Meshreky M, Halim C, Katamish H. Vertical marginal gap distance of CAD/CAM milled BioHPP PEEK coping veneered by HIPC compared to zirconia coping veneered by CAD-on lithium disilicate “in-vitro study”. *Advanced Dental Journal*. 2020;**2**(2):43-50. DOI: 10.21608/adjc.2020.21032.1043

[45] Grymak A, Aarts JM, Ma S, Waddell JN, Choi JJE. Wear behavior of

occlusal splint materials manufactured by various methods: A systematic review. *Journal of Prosthodontics*. 2022;**31**(6):472-487. DOI: 10.1111/jopr.13432

[46] Bogdan DN. License Work: Wear Behaviour of HPP Restorations. Romania: Victor Babes University of Medicine and Pharmacy Timisoara; 2024

[47] Borrero-Lopez O, Guiberteau F, Zhang Y, Lawn BR. Wear of ceramic-based dental materials. *Journal of the Mechanical Behavior of Biomedical Materials*. 2019;**92**:144-151. DOI: 10.1016/j.jmbbm.2019.01.009

[48] Shah K, Lawson NC, Sayed Ahmed A, Nizami B, Lawson TJ, Kee E, et al. Wear of lithium disilicate opposed by various ceramic materials. *Journal of Esthetic and Restorative Dentistry*. 2024;**36**(2):356-362. DOI: 10.1111/jerd.13115

[49] Amanov A, Pyun YS, Kim JH, Sasaki S. The usability and preliminary effectiveness of ultrasonic nanocrystalline surface modification technique on surface properties of silicon carbide. *Applied Surface Science*. 2014;**311**:448-460. DOI: 10.1016/j.apsusc.2014.05.089

[50] Namura Y, Uchida Y, Inaba M, Kaetsu R, Utsu A, Takamizawa T, et al. Influence of masticating cycles and chewing patterns on inadvertent enamel wear caused by zirconia brackets. *European Journal of Oral Sciences*. 2022;**130**(1):e12831. DOI: 10.1111/eos.12831

[51] Grymak A, Aarts JM, Cameron AB, Choi JJE. Evaluation of wear resistance and surface properties of additively manufactured restorative dental materials. *Journal of Dentistry*. 2024;**147**:105120. DOI: 10.1016/j.jdent.2024.105120

Evaluation of Mechanical and Optical Properties of Monolithic Zirconia for Restorative Dentistry

Flavia Roxana Bejan, Liliana Porojan, Roxana Diana Vasiliu and Anamaria Matichescu

Abstract

The continuous development and promotion of dental ceramic materials for computer-assisted design (CAD)/computer-assisted manufacturing (CAM) technologies have led to significant advancements in dentistry. Due to their excellent mechanical and aesthetic properties, biocompatibility, chemical stability or aging behavior in the oral environment, the new generations of zirconia for monolithic dental restorations, processed using CAD/CAM subtractive technologies, offer multiple prospects in prosthetic applications. Yttria-stabilized tetragonal zirconia (3Y-TZP) contains 3 mol% Y_2O_3 and exhibit opacity but high strength and fracture toughness. To obtain a material with high translucency and also resistant, the crystal structure of the conventional material was modified. The increase in the yttria content to 4 or 5 mol% and of the cubic phase to 15 to over 50% results in two polycrystalline zirconia (4Y- and 5Y-TZP) with superior aesthetics at the expense of mechanical properties. These compositional differences are decisive and influence the individual characteristics of each dental zirconia system. Alongside factors as the processing and sintering method or surface treatment, they have an impact on clinical properties such as surface roughness, toughness/microhardness, translucency and resistance to the aging process. In this context, the present study aims to summarize and update the data regarding the classification, mechanical and optical properties, applications, and future perspectives in the use of monolithic translucent zirconia. It provides clinicians with information to find a balance between aesthetics and strength, to preserve properties of material over time, and to extend the lifespan of dental restorations, for the benefit of patients.

Keywords: translucent zirconia, microroughness, surface topography, optical properties, color changes, microhardness, artificial aging

1. Introduction

Zirconia has become one of the most demanded and used materials, with numerous indications in restorative dentistry. Monolithic zirconia manufactured by CAD/

CAM technology is known as the most commonly prescribed material for posterior crowns, and multilayer zirconia as the second most used material for anterior crowns [1]. These metal-free restorations have considerable advantages: high flexural strength, satisfactory aesthetics, accurate milling and chipping complications are avoided, minimal wear of antagonists. They require more conservative dental preparation, fewer dental sessions and less laboratory time. Through successive changes in the microstructure, several generations of monolithic zirconia have been developed over time, aiming to obtain a more aesthetic material with increased flexural strength and fracture toughness [2].

Silicate ceramics are aesthetically impeccable, but in terms of mechanical properties, they are obviously weaker than polycrystalline ceramics and resin-based ceramics. Polycrystalline ceramics are less translucent, but their optical properties can be favorably compared with those of other non-ceramic materials [3].

The biaxial flexural strength of monolithic zirconia can vary from 688 ± 159 MPa to 1194 ± 111 MPa, depending on the type and content of the dopant, significantly exceeding the strength of lithium disilicate (460 ± 53 MPa) [4, 5]; however, it decreases with increasing yttria content.

3Y-TZP is mainly composed of the tetragonal phase (over 85% content), with the surface being almost completely made up of this phase, resulting in increased strength due to a more pronounced transformation toughening (t to m). However, a high content of the tetragonal phase makes zirconia more susceptible to the aging process. Although the tetragonal phase and transformation toughening provide zirconia with excellent mechanical properties, they also restrict the translucency and aging resistance [2, 6].

Achieving greater translucency of zirconia can be targeted with several strategies: Enhancing the amount of dopant and cubic phase and refining the microstructure by considerably increasing the grain size and, implicitly, reducing residual porosity so that there are fewer boundaries to interfere with light [6].

These microstructural variations not only induce significant improvements in the optical performance of zirconia but also inevitably generate substantial changes in its mechanical properties, influencing long-term stability [7]. Debates related to the balance between mechanical and aesthetic properties require additional experimental studies to successfully implement them in dental practice.

In addition, processing and finishing methods, different surface treatments, can impact color stability over time and affect the quality and, at the same time, the longevity of dental restorations [8]. Surface treatments (polishing, glazing) not only improve aesthetics but also prevent wear of opposing teeth and reduce bacterial adhesion and inflammatory reactions [9, 10].

It is known that these materials are differently susceptible to the aging process or so-called “low-temperature degradation,” which can occur, depending on the composition, microstructure and local stress state, when the surface is exposed to moderate temperatures in a humid environment [11–14]. According to some meta-analyses and recent studies, monolithic zirconia restorations on natural teeth have a high survival rate of 91–100% [15]. It has been observed that the chipping rate of monolithic zirconia crowns was significantly lower (0%) compared to that of metal-ceramic crowns (7.61%) [16]. Additionally, a success rate of over 80% was reported over a period of 3–10 years for single-unit resin-bonded dental prostheses [17], and regarding implant-supported prostheses on a complete arch, a high survival rate of 97.23% was documented over a period of 4 years [18].

Material	Manufacturer	Yttria content	Flexural strength
Bruxir 16 shaded plus	Glidewell direct, USA	3 mol %	> 1000 MPa
Katana HTML plus	Katana, Kuraray Noritake Dental, Tokyo, Japan	3 mol %	1150 MPa
IPS e.max ZirCad LT	Ivoclar Vivadent, Schaan, Liechtenstein	3 mol %	1200MPa
Katana STML	Katana, Kuraray Noritake Dental, ToKyo, Japan	4 mol % (7–10.wt%)	750 MPa
IPS e.maxZirCad Medium translucency (MT) Multi	Ivoclar Vivadent, Schaan, Liechtenstein	4 mol % cervical 4+5 mol %transition 5 mol % incisal	850 MPa dentin 650 MPa incisal
Ceramill Zolid fx Multi-layer (ML)	Amman Girschbach, Koblach, Austria	5 mol %	700 MPa
Katana UTML	Katana, Kuraray Noritake Dental, Tokyo, Japan	5 mol %	555 MPa
IPS e.max ZirCad Prime	Ivoclar Vivadent, Schaan, Liechtenstein	3 mol % dentin 3+5 mol % gradient 5 mol % incisal	650-1200 MPa

Table 1.
Monolithic dental zirconia is used in the dental field (according to the manufacturer's indications).

There are still insufficient studies on how the specific characteristics, resistance and aging behavior of these materials are influenced throughout their functional life. Several commercial materials with different compositions and various mechanical and optical properties are presented in **Table 1** [19–22].

2. The role of composition and microstructure on mechanical and optical properties for different types of monolithic zirconia

The starting powders contain additives and a binder that are pressed together using the isostatic method. Metal oxides are also added: Yttrium oxide (Y_2O_3) to stabilize the tetragonal phase, aluminum oxide (Al_2O_3) to prevent water corrosion, and hafnium oxide to prevent and reduce pore development and color defects [23]. Some components are removed by heating, leading to the formation of the material in a pre-sintered (or “green”) state. Zirconia remains soft enough to be easily machined, yet hard enough to preserve its shape. The final shape of the dental restoration is obtained by milling a disk or block of partially sintered zirconia, followed by complete sintering, accompanied by a shrinkage of approximately 20% [2, 24].

There are two types of zirconia blanks. Fully sintered blanks—with high hardness and strength—are machined with diamond rotary tools, known as hard milling. The pre-sintered blanks—which are soft-milled into a chalk-like state using hard metal rotary tools, and then sintered to achieve the final hardness. During this procedure, the pre-sintered zirconia shrinks by 20–30% of its volume, and the software can correlate the shrinkage of the restoration obtained after sintering. The milling process can be performed by two methods: Wet milling—for fully sintered blanks, the system uses a special liquid to cool the rotating instruments, and dry milling—for pre-sintered blocks (**Figure 1**).



Figure 1.
Zirconia blocks and disks in the pre-sintered state after milling the dental restorations.

Monolithic zirconia in the shape of blocks or disks can be processed using the computer-aided design/computer-aided manufacturing (CAD/CAM) system, which performs the scanning, computer-aided design, and milling process of dental restorations.

With CAD/CAM technology, a half-arch digital impression can be obtained in 40 seconds, and clinicians can examine the accuracy of the restoration before starting the milling process. In addition, this system is designed to allow the individualized manufacture of dental restorations (inlay/onlay, veneers, crowns), in the dental office or in the dental laboratory. The quality of restorations is extremely high due to the accurate data obtained during scanning and the precision of manufacturing. Additionally, their appearance is very natural, as the material is available in a very wide range of shades, with translucency similar to that of natural enamel [25].

Zirconia is a polymorphic material, meaning it can exist in three crystalline phases (structures), depending on temperature and pressure: Monoclinic (m), tetragonal (t) and cubic (c). After final sintering, all three phases coexist in varying percentages. This results in a variety of material options with different optical and mechanical properties

By incorporating different amounts of stabilizers (Y_2O_3 —yttrium oxide, CaO —calcium oxide, MgO —magnesium oxide), partially or fully stabilized zirconia results. The most common dopant used is Y_2O_3 . By adding 8 mol% Y_2O_3 or 16 mol% MgO or CaO , the dopants can almost completely stabilize the cubic phase and *fully stabilized zirconia* is achieved. Smaller amounts of these dopants induce the formation of *partially stabilized zirconia* (PSZ) with mainly tetragonal and cubic metastable phases [2, 6, 26].

The adjustment of the cooling procedure and a quantity of 3–5 mol% Y_2O_3 results in a zirconia composed mainly of cubic phase and a tetragonal phase of a defined size, homogeneously distributed in the cubic matrix, known as *yttrium stabilized tetragonal zirconia polycrystals* (Y-TZP). The quantity and name of the dopant are indicated in front of the abbreviation.

Due to the incorporation of stabilizers, zirconia with remarkable properties, such as high hardness, flexural strength and chemical resistance, can be obtained. Parameters such as the amount of dopant, particle size and temperature can influence the tetragonal to monoclinic transformation [23, 27].

2.1 Transformation toughening

Zirconia types can be differentiated by the tetragonal/cubic phase ratio, which is influenced by the yttria content. It has been established that the mechanical properties (flexural strength, toughness) of zirconia increase proportionally with the tetragonal phase content, and a large amount of monoclinic and cubic phase determines inferior mechanical properties. Thus, three major properties of zirconia are influenced by these microstructural differences: Translucency, toughness and aging behavior [28].

The transformation of t into m generates a local increase in strength and flexural toughness, being an important advantage in partially stabilized zirconia. Transformation toughening represents the ability of zirconia to stop and resist crack propagation, associated with increasing fracture toughness (**Figure 2**).

The microstructure characteristics and particle size determine and influence the transformation ability at the appropriate temperature. If the grains of the tetragonal phase are too small or too large, zirconia loses its transformation ability during crack formation. At a particle size of less than 0.3 μm , zirconia loses its t-m transformation capacity when cracks occur, and therefore, the fracture toughness decreases. If the particles are larger than 1 μm , zirconia can undergo a spontaneous tetragonal to monoclinic (t to m) transformation, which can lead to different failures [29, 30].

The cubic phase of the material cannot undergo transformation toughening. A study analyzed the capacity of 3Y-, 4Y- and 5Y-TZP to undergo transformation toughening: 3Y- was able to undergo transformation, 4Y- (with 75% tetragonal phase) underwent some transformation, and 5Y- (with 50% tetragonal phase) underwent almost no transformation [26, 29].

2.1.1 Generations of zirconia

Dental zirconia can be classified into four categories/generations based on the yttria content and according to their optical and mechanical properties (**Table 2**).

First generation 3Y-TZP (known as conventional zirconia): For additional stabilization of the tetragonal phase (98 %), this high-strength zirconia contains 3 mol% yttria and 0.25% alumina, which was a source of opacity. The material has the highest mechanical strength (1200 MPa) at the expense of optical properties, which are lower. The high refractive index is created by the many very small grains and implicitly by the large number of boundaries and interfaces through which light does not

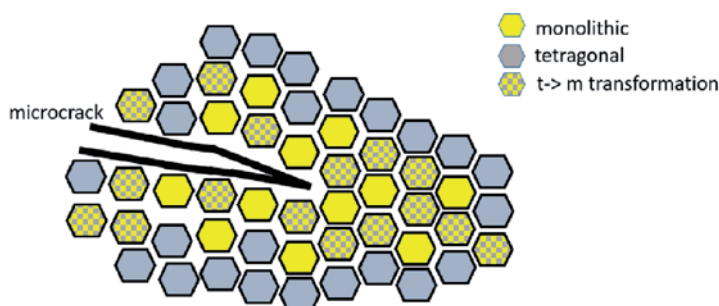


Figure 2.
Schematic representation of transformation toughening in Y-TZP.

	<i>Reducing in Al₂O₃ and repositioning</i>	<i>Increase in Y₂O₃</i>	<i>Decrease in Y₂O₃</i>
<i>1st Generation</i>	<i>2nd Generation</i>	<i>3rd Generation</i>	<i>4th Generation</i>
1995	2013	2015	2017
~ 3 mol% Y ₂ O ₃ ~ 0.25 w% Al ₂ O ₃	~ 3 mol% Y ₂ O ₃ ~ 0.05 w% Al ₂ O ₃	~ 5 mol% Y ₂ O ₃ ~ 0.05 w% Al ₂ O ₃ up to 53% cubic	~ 4 mol% Y ₂ O ₃ ~ 0.05 w% Al ₂ O ₃ 25% cubic phase
<i>3Y-TZP: Opaque</i>	<i>3Y-TZP: Optical improved</i>	<i>5Y-TZP: Most translucent</i>	<i>4Y-TZP: Largely opaque</i>
Highest mechanical properties	Highest mechanical properties	Lower mechanical properties	High mechanical properties
White opaque	Some translucency	Most translucency	Moderate translucency
Mainly tetragonal phase	Mainly tetragonal phase	More cubic, less tetragonal phase	Tetragonal and cubic phases

Table 2.
Chronological overview of zirconia generations and their characteristics.

pass. Multi-unit dental restorations with minimal wall thicknesses can be fabricated from these materials.

Second generation 3Y-TZP: In the material structure, the yttria content of 3 mol% was maintained, but the alumina content was reduced from 0.25 to 0.05%. The excellent mechanical properties were preserved, and in addition, the translucency was improved, as the alumina particles were placed at the boundaries of the zirconia particles, allowing a higher level of light transmission.

Third generation: 5Y-TZP (known as high-translucent zirconia): The crystalline structure of zirconia was modified by increasing the dopant amount to 5 mol% yttria and, at the same time, the cubic phase content up to 50%. This implies an increase in the size of the cubic particles, reducing porosity and increasing light transmission by 43–45%. All these changes led to a significant improvement in translucency but also to a reduction in fracture toughness and flexural strength with a negative impact on the mechanical properties. The translucency of 5Y-TZP is slightly lower compared to that of lithium silicate, while the mechanical properties are superior.

Fourth generation: 4Y-TZP: In the fourth generation, the Y₂O₃ content was reduced to 4 mol% to stabilize around 25% of the cubic phase. Compared to the third generation, it is characterized by lower optical properties and higher mechanical strength. 4Y-TZP is recommended for performing monolithic restoration with three units, including molar restorations, while 5Y-TZP is recommended for individual monolithic crowns in the anterior and posterior regions and for three-unit restorations in the anterior region [26, 31].

A certain disadvantage of these two new generations (third and fourth) is the lower strength and fracture toughness compared to 3Y-TZP, as they contain lower amounts of the tetragonal phase, leading to a reduced possibility of t-m transformation, which means less transformation toughening [26, 32].

2.2 The multilayered zirconia

To overcome the aesthetic limitations of monochromatic materials, multilayered zirconia blanks have been introduced. For different zirconia generations,

gradient-shaded disks or blocks are available. Multilayer zirconia contains three or four pre-colored, polychromatic layers that simulate different translucencies and shades of natural teeth, with decreasing chroma and opacity toward the incisal area. The arrangement varies from the most opaque layer in the cervical area, followed by one or two transition layers, to the translucent occlusal/incisal area. The dentin layer is more colored and opaque, while the enamel layer is more transparent, due to its considerable light permeability (**Figure 3**) [33, 34]. The invisible transition between the differently colored layers is obtained through a specific process of crystal distribution during the pre-sintering stage, and it was shown that the interfaces between the layers were not weak links [35]. This material is the ideal choice for restoration in the anterior area, where aesthetic requirements prevail: Veneers, single crowns and three-unit fixed dental prostheses, suprastructure on implants.

Previous studies showed that the first multilayer zirconia that was introduced to the market (Katana, Kuraray Noritake), contained the same amount of cubic phase and yttrium in the layers of the material, and only the composition of the pigments created the color difference between the layers [28]. The layers may contain mixtures of phases with different distributions of particle size and boundaries [14]. Polychromatic layers have various formulations depending on the chemical composition and amount of dopants; therefore, there may be possible dissimilarity between layers in terms of physical properties, combining high translucency with high strength [34, 36]. A thorough understanding of the local composition is necessary for a complete characterization of the materials.

When two different commercial materials were tested: STML (Katana Kuraray Noritake Dental) described by the manufacturers as being composed of four layers (enamel, transition 1 and 2, dentin), entirely containing 4Y-TZP, and IPS e.max ZirCad Prime (Ivoclar AG), composed of three layers (incisal 5Y-, gradient zone 3Y+5Y-, dentin 3Y-). From top to bottom, no substantial differences in yttria (9.6%–9.8) and tetragonal phase (30.6–35.3%) content were found among the layers in STML, but certain differences were identified within Prime (10.1–5.9%) and (61.8–73.3%) respectively [37].

In many studies and most comparisons of the layers, the materials showed differences in terms of light transmission and biaxial strength, depending on the elemental composition and the overall composition of the phases in the tested areas. In addition,

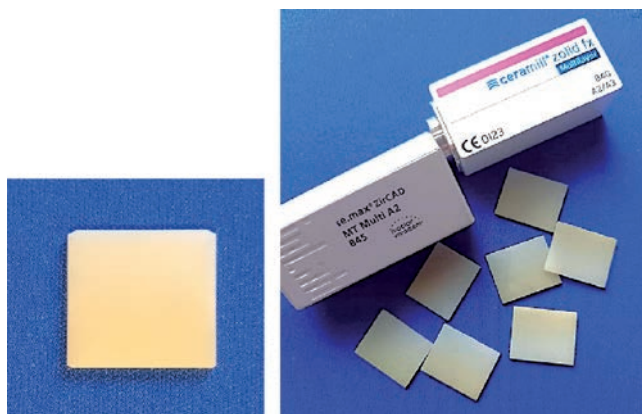


Figure 3.
Samples obtained from multilayer zirconia blocks.

these parameters define the optical and mechanical properties of zirconia [35, 38, 39]. Recent studies reveal that multilayered zirconia with a content of 8.5–9.5% mol yttria surpasses traditional monolithic multilayer zirconia in terms of translucency and color rendering value, thus demonstrating a significant optical improvement of this new type of material [4]. Due to its reduced surface hardness, it protects opposing teeth, yet it has shown superior wear resistance [16]. A great advantage of using multilayer zirconia is that after the sintering procedure, the restorations are almost complete. Staining is accomplished when specific individualization is required.

3. Surface characteristics and mechanical properties

Flexural strength is an indicator for estimating the strength of brittle materials. Fracture toughness characterizes the ability of a material to resist crack propagation, developed as a result of machining or finishing procedures, or the existence of defects and pores; it is an indicator for assessing the failure of brittle materials at the moment of fracture. Lower toughness could induce more bulk fractures and chipping during their functional service. Regarding the performance of monolithic zirconia, the following values were reported: For 3Y-TZP (opaque zirconia)—fracture toughness of 7–9 MPa m^{1/2} and flexural strength of 900–1200 MPa; for 5Y-TZP (translucent zirconia)—fracture toughness of 2.2–4 MPa and flexural strength of 700–800 MPa; respectively for 4Y-TZP, fracture toughness of 2.5–3.5 MPa m^{1/2} and flexural strength of 600–900 MPa [7, 23].

By comparison of color-graded (4Y or 5Y) and strength and color-graded (3Y+5Y) zirconia, the intaglio (bottom) zone of the strength-graded material was significantly stronger, in terms of flexural strength, than the other areas [37].

It was observed that the difference in wear patterns induces more severe wear on translucent multilayer zirconia compared to conventional (3Y-) material, showing a greater wear depth and a higher volume loss; due to the probable greater proportion of cubic phase in the upper layer [36, 40].

When the amount of dopant and implicitly the cubic phase content is high, the surface roughness is increased, which means that it is higher for 5Y-TZP than for 3Y-TZP, and the mechanical properties in high-translucent zirconia are lower [5].

Surface treatments, such as polishing and glazing, enhance the aesthetics of dental restorations and reduce bacterial accumulation and inflammatory response of periodontal tissue. They have a relevant impact on optical and mechanical parameters, both before and after material aging [41].

Glazing is a dental laboratory procedure and consists of applying a layer of a mixture of powder and colorless glass liquid, which evenly covers the surface and smoothens it, seals pores, reduces roughness and maintains color stability. The appearance of the glazed surface can be affected by the layer deposition technique, its thickness, adhesion capacity, and the characteristics of the layer-zirconia interface, which can result in a wavy surface with small defects and irregular areas. The glaze layer can wear off after six months in an *in vivo* environment, allowing exposure of the underlying material [42]. The glazed layer of translucent monolithic zirconia has been found to be the most abrasive to the opposing enamel. Beneath the glazed layer, the material has a rough surface and, when exposed, induces more wear on the enamel of the opposing teeth than a polished surface [43].

Glazed surfaces were the smoothest compared to sintered ones and those processed with diamond burs. In the case of sintered zirconia, grinding causes a

significant increase in surface roughness, whereas polishing significantly reduces it. Studies have shown that polished-glazed surfaces exhibit better wear resistance than glazed surfaces, inducing long-term retention of the glaze layer [44]. Glazing can reduce the strength of high-translucency zirconia (5Y-), while polishing and glass infiltration may lead to achieving a balance between aesthetic and strength [45]. Other research has revealed that polished surfaces were smoother than the glazed or sintered ones, and the roughness of polished material belonging to some brands of monolithic zirconia was lower than that of feldspathic ceramics, and higher than that of lithium-disilicate pressed ceramics [43, 46].

The polishing ability of monolithic zirconia is influenced by the microstructure, the amount of stabilizer and cubic phase, the particle size, and the polishing protocols. Due to the resulting residual stress, polishing induces t to m transformation zones around the scratches, causing an increase in the monoclinic phase. This results in increased surface roughness and a reduction of translucency. It is also shown that polished monolithic zirconia causes less wear on antagonist teeth than glazed ones, and it presents the smoothest surface [47].

Gentle polishing, performed with a low-speed handpiece associated with small-grit instruments (15–30 μm), induces a less extensive t to m transformation, without or with minor defects in zirconia with different yttria amount [10].

Polished surfaces tend to be more resistant than as-machined ones, and air-abrasion surface conditioning of restorations obtained using CAD/CAM technology can improve cement adhesion and also increase its resistance to hydrothermal degradation [48]. According to previous studies, the polished surface of zirconia exhibited lower biofilm adhesion, while its texture (roughness) remained minimally affected by acidic media, thanks to its remarkable hardness, proving significant advantages for long-term use [49].

Nondestructive tests (**Figure 4**) are used to evaluate surface roughness, nano-roughness, porosity and defects that could influence the durability and quality of dental restorations. The assessment of surface roughness can be carried out using a contact profilometer, a device that enables the calculation of R_a (μm) and R_z (μm) parameters. R_a is the average surface roughness, and R_z is the maximum surface roughness.

For the analysis of the nanosurface characteristics, an atomic force microscope is used. Atomic Force Microscopy (AFM) provides three-dimensional images and enables the calculation of S_a (nm) and S_q (nm) nanoroughness parameters. S_a —is the arithmetical mean height, and S_q —is the root mean square height. Additionally, for investigating the changes of surface resulting from various treatments, a scanning

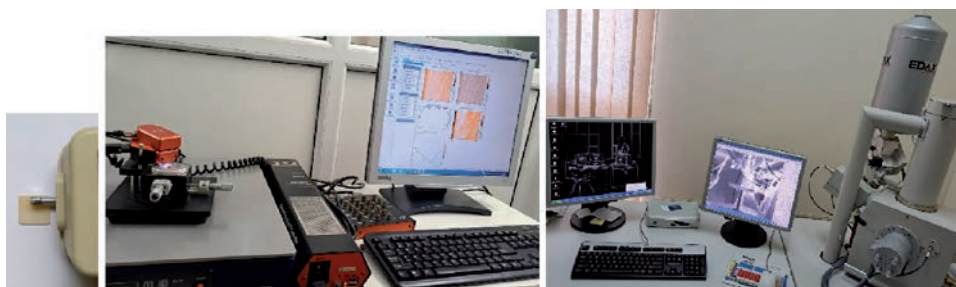


Figure 4.
Devices for assessing surface characteristics through different technologies (profilometry, AFM, SEM).

electron microscope—with high resolution field emission can be used. The method is known as Scanning Electron Microscopy (SEM).

For the evaluation of surface microhardness and the measurement of Vickers hardness number (VN), a microhardness tester is commonly used. A diamond pyramid indenter applies a load of 0.3 Kg for 10 sec. on the surface of the material, and the size of the indentation provides data about its hardness. Smaller indentations in area and depth indicate harder materials.

4. Optical properties

Color and aesthetic changes are important factors in achieving high-quality dental restorations. People have different perceptions of a certain color. In order to have a concrete way to distinguish and characterize colors, as well as to quantify the differences between them, the CIE $L^*a^*b^*$ system was developed.

It is based on the use of three independent values: L^* - the lightness coordinate (brightness-darkness), a^* - the chromatic coordinate on the green/red axis, b^* - the chromatic coordinate on the blue/yellow axis [50, 51].

The perception of tooth color can be influenced by the following factors: Light scattering, transparency, lighting conditions, gloss and the human eye. For the optical assessment of a surface, in addition to the three primary color characteristics (chroma, lightness, hue), other parameters must be taken into account, such as translucency, fluorescence, opalescence, opacity and metamerism.

Scattering defines the passage of light through an object and the changes in direction of the beam. This phenomenon is explained by the fact that secondary waves with various directions from the primary wave result. It depends on the grain size and the boundaries between them, the presence of impurities and pores in zirconia [52].

The factors that can affect light scattering in dental zirconia are:

Crystalline phase and particle size. A greater yttria content and a higher sintering temperature produce larger particles, increased density and better elimination of porosity, resulting in a zirconia with a more compact microstructure and higher translucency. The particles of the cubic phase are larger with fewer boundaries and less residual porosity than the tetragonal ones. They are in an isotropic arrangement, which allows a more uniform passage of incident light in all directions, resulting in greater translucency [6, 52].

The greatest scattering occurs when the crystals or flows have similar sizes (350–780 nm) to the visible wavelength. Therefore, 3Y-TZP (conventional zirconia) is more opaque than 4Y- or 5Y-TZP (translucent zirconia). Following several studies, it was found that super-translucent zirconia (4Y-TZP) contains crystals with a size of 0.5–1 μm (500–1000 nm) and an amount of cubic phase of 25–53% by weight, and super-high translucent zirconia (5Y-TZP) incorporates crystals larger than 1 μm , dispersed differently, and a content of 60–71% cubic phase by weight, which makes these materials more transparent but also more susceptible to fractures [34, 53].

Composition. Alumina (Al_2O_3) contributes to the formation of a fine-grained microstructure, increases the densification rate, delays the aging process, but due to its segregation at particle boundaries, reduces translucency. In conventional zirconia (3Y-TZP), alumina inclusions constitute significant scattering centers. Reducing the alumina concentration to 0.05% by weight and increasing the yttria content in new generations of zirconia has led to a significant increase in translucency [7]. There are different views on the impact of oxide pigments on the stability of tetragonal particles

and on the optical characteristics of zirconia. They have a different refractive index, inducing a decrease in translucency.

Porosity. Pores, defects, and impurities contribute to reducing translucency and can negatively affect optical properties, because there is a difference between the refractive index of air ($n=1$) and that of zirconia ($n=2.1-2.2$). Pores and defects can be intergranular—located between particles and having various orientations, or intragranular—within a particle. In the case of translucent zirconia, an extremely low porosity (<0.01 vol%) is indicated. Pores larger than 50 nm induce considerable scattering, altering light transmission [54].

Sintering. Sintering parameters such as temperature and holding time have an impact on the optical properties of zirconia. Some studies have shown that a high sintering temperature (1400–1550°C) causes an increase in translucency, associated with an increase in grain size and density, as a result of solid-state diffusion and pore elimination [55]. Depending on the geometry and size of the restoration, the sintering time can be reduced to only about 30 minutes (speed or super-speed sintering) [56]. This technology can only be applied to zirconia that is specifically developed for this procedure. However, scientific data supporting rapid sintering is still insufficient.

Translucency defines the relative amount of light transmission through a medium, and its value depends on the permittivity of this medium through which the light passes. The translucency of 5Y-TZP is positioned between that of conventional zirconia and lithium disilicate [5]. Subsequently, ultra-high translucent zirconia (UHTZ) was introduced, with translucency comparable to that of lithium disilicate while maintaining a flexural strength similar to that of 5Y [57].

Opalescence is the optical parameter that defines a dispersion of wavelengths of the visible light spectrum and exhibits the blue of reflected light and the orange of transmitted light. It has been observed that dental restoration is optimal aesthetically and optically if the opalescence of the zirconia is similar to that of the adjacent teeth. When there are particles of the same size or larger than the visible wavelength at the boundaries between different phases, it induces scattering and opalescence, respectively [58, 59]. According to some studies, the opalescence value for 3 Y-TZP ranges from 1.25 to 2.83, and for human teeth ranges from 4.8 to 7.4 [59, 60]. At a thickness of 10 mm, the opalescence (OP) values of zirconia were 19, and for human teeth ranged from 19.8 to 27.6 [59].

The total color change (ΔE^*) defines the color difference between two evaluation steps and is determined using the CIE $L^*a^*b^*$ color system.

The color parameters and appearance of a material can be affected by extrinsic factors such as beverages, foods, smoking and by intrinsic factors such as surface treatments, microstructure (density, amount of yttria, phase content, grain size, type of pigments), surface roughness, water sorption and aging behavior. Several studies have revealed that factors such as surface condition and texture, water content of samples, finishing procedures and lighting can considerably influence translucency values. The surface finishing procedure could alter the surface topography and thus the light scattering. Surface treatments such as polishing and glazing decreased lightness. Perceptible color changes occurred after polishing, and an increase in yellowness was observed after glazing. It has also been found that polished surfaces provide a more natural, realistic appearance than the glazed ones, as the glaze layer causes a decrease in opalescence, but without influencing translucency [28, 47]. A study revealed that zirconia was not affected by remarkable discoloration ($\Delta E^* < 0.5$) after immersion in various solutions for 4 weeks, while lithium disilicate materials and composite resin showed evident discoloration (in rhodamine B, $\Delta E^* > 0.5$) [57].

However, it is relevant to note that although zirconia demonstrates good resistance to discoloration, its color may change after the aging process.

Color parameters are recorded against a white and black background, and there are several types of shade matching devices, such as spectrophotometers, colorimeters, spectroradiometers, digital cameras and software.

5. Aging behavior of zirconia for monolithic dental restoration

Hydrothermal aging or low temperature degradation (LTD) is defined as an aging phenomenon that alters dental materials after a period of their functional use in the humid, moderate temperature conditions of the oral environment, adversely affecting their mechanical and optical properties. It depends on the microstructure and composition of the zirconia or the state of residual stress, and can be influenced by oral hygiene, periodontal condition, smoking and loading. Zirconia is susceptible to aging, which can be seen as a limitation for these materials [61, 62].

Hydrothermal aging is accompanied by a slow t to m transformation of the grains, starting from the surface that is exposed to the moisture of the oral environment. Due to a stress-induced mechanism, aging degradation begins with the transformation of a single grain, accompanied by its volume increase, the formation of microcracks and water penetration (**Figure 5**). Then, the conversion of other grains follows, which results in the expansion of the transformed area. After water penetrates through microcracks, it progressively advances into the bulk, causing pull-outs and particle detachment. That leads to an increase in surface roughness and implicitly to a decrease in density and mechanical strength with the alteration of optical properties [63, 64].

It is known that mechanical (polishing, milling) and hydrothermal impact can cause stress followed by unexpected t to m phase transformation on the zirconia surface, which increases susceptibility to aging. A rough area causes wear of the

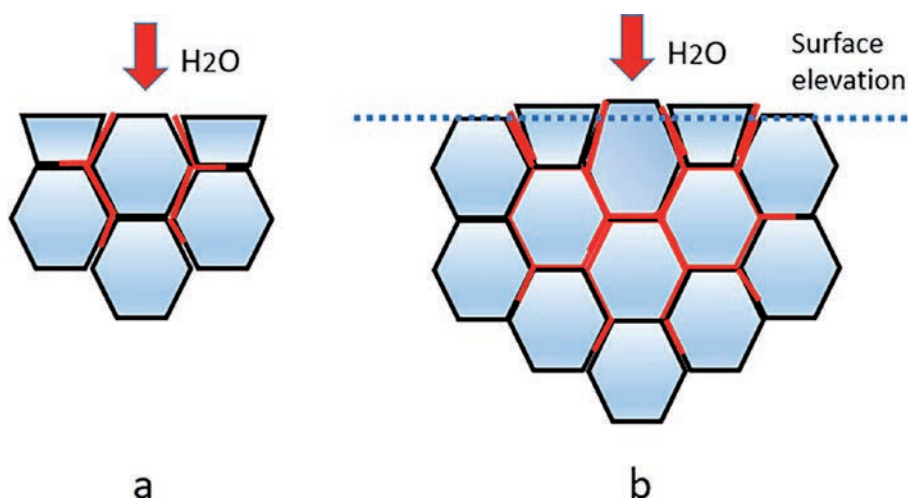


Figure 5.
The aging course starts from a single particle on the surface (a), followed by a sequence of damage from one particle to another (b).

antagonist teeth, accumulation of food debris and bacterial plaque. Therefore, the surface treatment procedure should be rigorously applied to obtain a smoother surface [9].

Translucent zirconia with higher cubic content experienced almost no monoclinic transformation and hydrothermal degradation. Several studies revealed that translucent zirconia (5Y-TZP) was less altered than conventional zirconia (3Y-TZP). The level of degradation is different between various types of translucent zirconia, as the aging behavior is related to several factors such as microstructure characteristics, impurities and defects, manufacturing processes, loading and exposure time to the aging medium [6, 54].

With the increase in yttria content, a technological advancement was recorded from multilayer zirconia (ML) to super-translucent multilayer zirconia (STML) and then to ultra-translucent multilayer zirconia (UTML), which induced an improvement in translucency and aesthetic performance, as well as a significant enhancement in aging resistance [65]. UTML contains the highest percentage of cubic phase, with the largest particle size, and demonstrates the best aging resistance. In comparison, ML showed an increase in the monoclinic phase content after hydrothermal degradation (12 h), while STML and UTML were not affected [41].

To evaluate the long-term stability of various dental materials during clinical service and to initiate and simulate the accelerated aging process, the most commonly used laboratory procedures are:

- Hydrothermal treatment in an autoclave: t to m phase transformation and degradation are induced and accelerated at elevated temperature (120–140°C), under steam pressure (0.2 MPa). It was observed that one hour of autoclave treatment under these conditions would produce the same effects on the material as 3–4 years *in vivo* at 37°C. According to ISO 13356-2008, zirconia (Y-TZP) is admissible for clinical use if its composition includes less than 25% of the monoclinic phase as a result of the t to m transformation after 5-hour autoclave degradation (134°C, 0.2 MPa) [66].
- Thermocycling: t to m phase transformation and degradation are caused by cycles of standardized temperature variations in alternating baths of 5–55°C. It has been found that 10,000 cycles are equivalent to one year *in vivo* [67].

5.1 Effect of hydrothermal degradation on surface characteristics

Many studies have compared the impact of autoclave-aging on the crystalline microstructure and composition of different types of zirconia after various periods of time. For conventional zirconia, an increase in the monoclinic phase was observed. After 5 hours of hydrothermal degradation, the increase ranged from 2 to 14%, and after 20 hours, it ranged from 50 to 81% [68], and other studies have reported an increase ranged from 25 to 50% [6]. For the third generation (5Y-TZP—with the cubic phase content up to 50%), previous studies revealed an increase in the monoclinic phase of less than 1% after several aging stages or even no changes were reported after 5, 10 or 54 hours [69]. This highlights the resistance of these materials to hydrothermal aging compared to those of the first two generations. After 18 hours of autoclave degradation, conventional zirconia (3Y-TZP) showed the highest flexural strength, with insignificant differences. Super-high translucent zirconia (5Y-TZP)

demonstrated lower flexural strength but no tendency for tetragonal to monoclinic transformation or susceptibility to aging [61].

However, there have also been situations where highly translucent zirconia (4Y-TZP) has shown higher strength than 3Y-TZP. The reason being that although for 4Y-, the t to m transformation is reduced, the microstructure is finer and processing defects are smaller, maintaining an even higher strength than some 3Y-TZP zirconias [29].

Three types of monolithic multilayered dental zirconia, with different microstructures were investigated: STML (Katana, Kurraray Noritake Dental)—noted STM, IPS e.max ZirCad MT Multi (Ivoclar Vivadent AG)—noted IPS and Ceramill Zolid fx ML (Amman Girrbach AG)—noted CER. Sixty plate samples (20 from each material) were prepared according to the instructions of each manufacturer, and each specimen was polished on both sides (with a low-speed device, polishing brush+diamond paste). The samples were evaluated on both sides in each of the three areas corresponding to the layers: Dentin (cervical), medium and incisal; both before (control group) and after hydrothermal degradation (aging group). For the assessment of surface roughness—Ra (arithmetic average surface roughness), a contact profilometer was used. The nanosurface characterization and surface modifications were analyzed by Atomic Force Microscopy (AFM) and Scanning Electron Microscopy (SEM).

Before aging, the lowest surface roughness was recorded for STM (4Y-) and the highest for CER (5Y-), with values almost similar between the three areas of a material. For IPS (4Y+5Y-), the values have increased from cervical to incisal. After artificial aging, there is a noticeable increase in Ra(μm) values for STM and an imperceptible increase for CER, the situation being almost similar for all three areas of a material. For IPS, a downward trend from cervical to incisal was registered (Figure 6).

Insignificant differences (two-way Anova, $\alpha = 0.05$) were reported when comparing the surface roughness between dentin-medium-incisal areas, individual on each side of samples, for a material, in the before and after aging stage. Significant differences (paired T-test $\alpha = 0.05$) among specimens before-after aging, for STM ($p_{\text{dentin}} = 0.046$, $p_{\text{medium}} = 0.02$, $p_{\text{incisal}} = 0.44$)

The AFM investigation reported no significant differences (two-way Analysis of Variance (ANOVA)) regarding Sa (arithmetical mean height) among the three areas

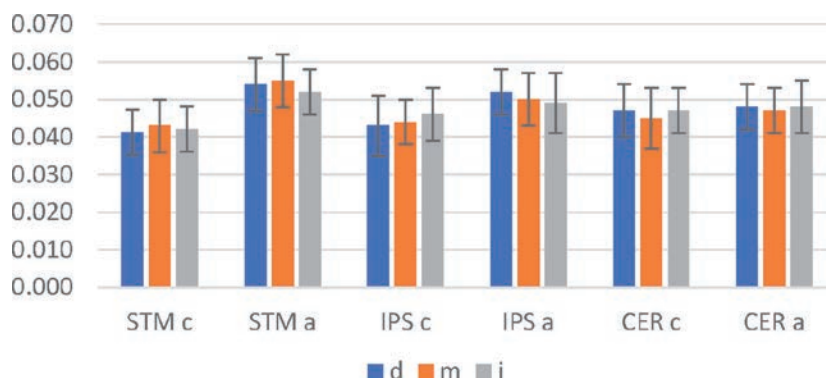


Figure 6.

Mean Ra values (with standard deviation), for all groups (before and after aging). STM = STML, IPS = IPS e.max ZirCad MT Multi, CER=CeramillZolid fx ML, c = control group, a = aging group, d = dentin (cervical), m = medium, i = incisal.

for a material, both in the before and after aging stage. After LTD, there is an increase in Sa values and significant differences (paired t-Test, $p < 0.05$) among the same areas, for the material was calculated.

Before LTD, the surface topographic analysis (SEM), revealed fine interconnecting striations, small flows and irregularities; for STM and IPS (both medium areas), porosities and small defects can be observed. After aging, there is noticeable damage and impairment in all areas, for all materials. 3D AFM images, SEM images and particle size distribution for dentin (cervical) area are illustrated in **Figures 7–9**.

The existence of different oxides (Er_2O_3 , Fe_2O_3) in pre-colored zirconia improves the resistance to the aging process more than in the uncolored one, even after 100 hours. Fe_2O_3 and Er_2O_3 , associated with Y_2O_3 , function as trivalent dopants contributing to further stabilize the tetragonal phase [70].

For measurement of Vickers hardness number (VN), in all three areas of the samples, both before and after the LTD stage (**Figure 10**), a microhardness tester (HVS 10A1, Huatec, Beijing, China) was used.

Before LTD, the highest VN values were registered for STM (d, m areas), followed by IPS (d area). Among materials, the lowest microhardness was recorded for CER. No significant differences (two-way ANOVA test, $p > 0.05$) among dentin-medium-incisal areas, in one stage, were observed. After aging, a minor increase in VN values for all materials was observed. No significant differences (paired t-Test, $p > 0.05$) concerning VN values, among the same areas of before-after aging groups, for a material.

To maintain the mechanical properties of zirconia during its clinical service, it is relevant to apply the most suitable surface treatment and finishing procedure. A negative correlation was found between flexural strength and roughness when coarse diamond burs were used for surface machining and the specimens were subjected to accelerated aging for 20 hours. The lowest surface roughness values and the highest strength values were recorded for the samples ground with extra-fine diamond burs. The correlation between strength and roughness depends on the ability of the surface and underlying material to initiate transformation toughening. This correlation

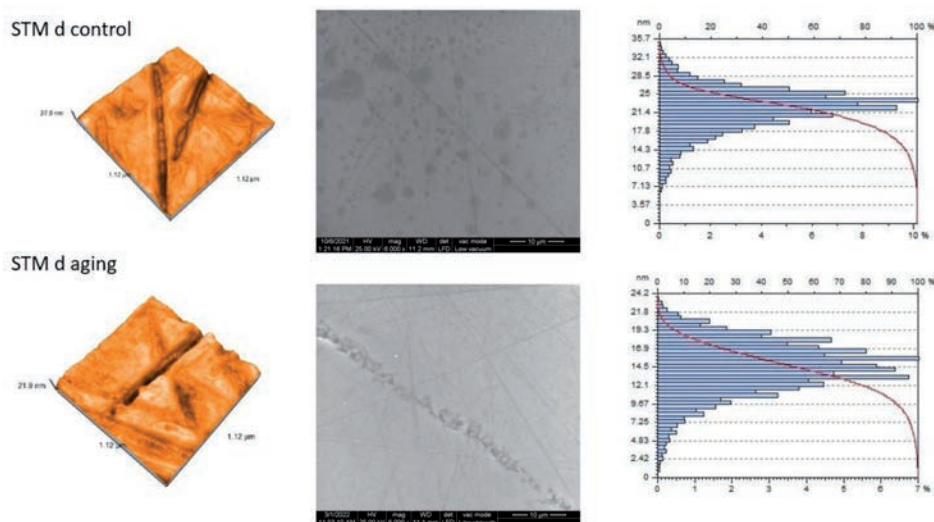


Figure 7.
3D AFM images, SEM images and particle size distribution for STM dentin area; STM = STML, d = dentin (cervical).

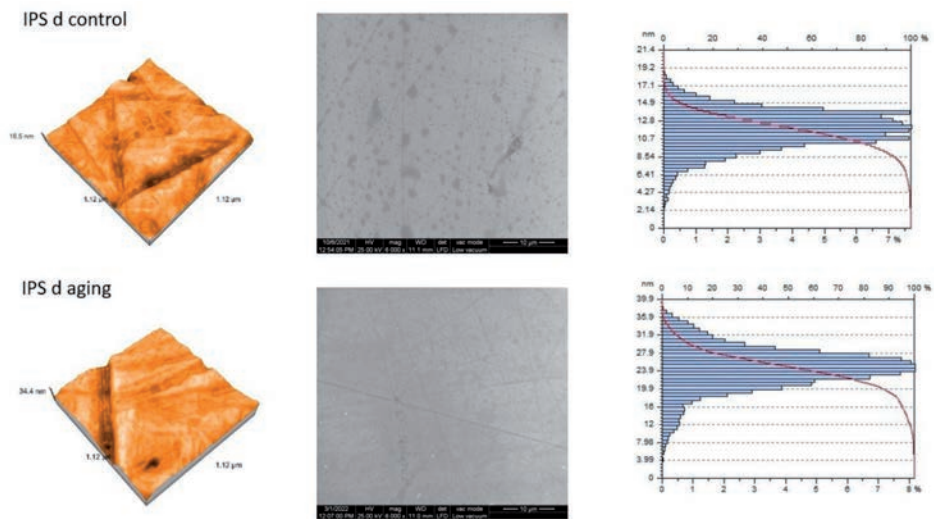


Figure 8.
3D AFM images, SEM images and particle size distribution for IPS dentin area; IPS = IPS e.max ZirCad MT Multi, d = dentin (cervical).

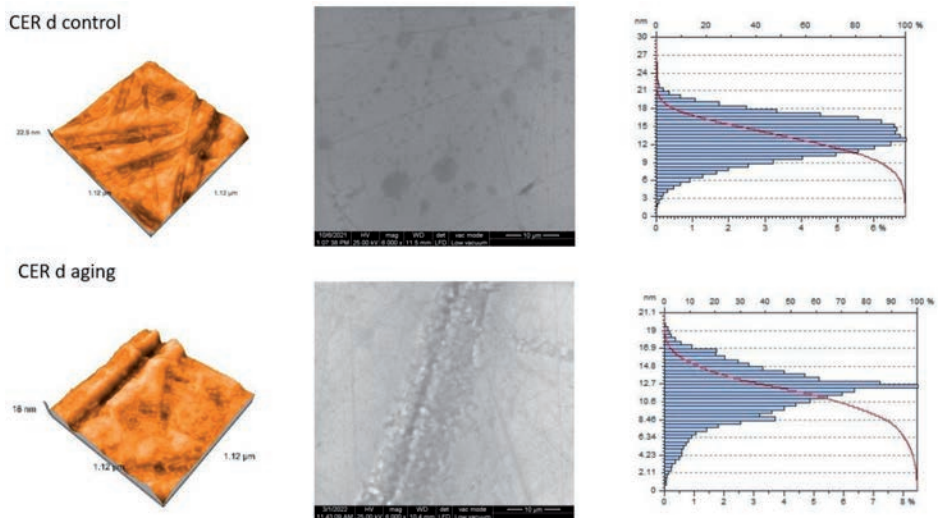


Figure 9.
3D AFM images, SEM images and particle size distribution for IPS dentin area; CER-CeramillZolid fx ML, d = dentin (cervical).

could be strong and positive if the grinding procedure creates defects and cracks that are deeper than the pre-existing ones. In order to increase the aging resistance of zirconia, after surface processing, polishing with extra-fine instruments is indicated, rather than glazing the surface [71]. The aging process may not affect the glaze layer, which has a protective role, or it may be directly damaged, either due to alteration of the underlying zirconia, appearing thinned, chipped, cracked or separated from the material, with a great impact on the optical and mechanical properties of dental restorations [63].

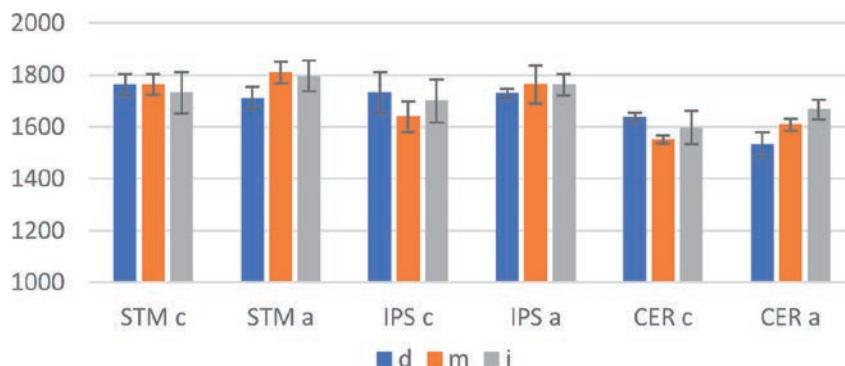


Figure 10.
Mean Vickers hardness values (with standard deviation), for all groups (before and after aging). STM = STML, IPS = IPS e.max ZirCad MT Multi, CER=CeramillZolid fx ML, c = control group, a = aging group, d = dentin (cervical), m = medium, i = incisal.

An atomic force microscope (AFM, scan size 1.2x1.2µm) was used to comparatively analyze the characteristics of the glazed and polished nanosurface (**Figure 11**) of 4Y-TZP and 5Y-TZP samples. It was reported that the nanoroughness of the glazed surfaces was higher than that of the polished ones, and after aging, it increased significantly for 5Y-TZP. Before LTD, the surface irregularities, striation or sharp peaks are more evident for 5Y-, both in the glaze group and polished ones. Significant differences ($p < 0.05$) in terms of Sa values among the same areas of before-after aging groups, on glazed or polished surfaces of a material, were found.

According to other SEM analysis, a perfect glazing, which uniformly covers 100% of the surface, is difficult or impossible to obtain. This situation will lead to the existence of localized areas on the surface of the material that will inevitably be affected by LTD. The degradation will expand from the vulnerable point in various radial directions into the bulk, under the glazed region and into the subadjacent area, leading to damage to the material under the glaze layer through subsurface micro-cracking. This increases the risk of chipping of the affected zirconia, especially if a mechanical load is applied to the damaged surface [72].

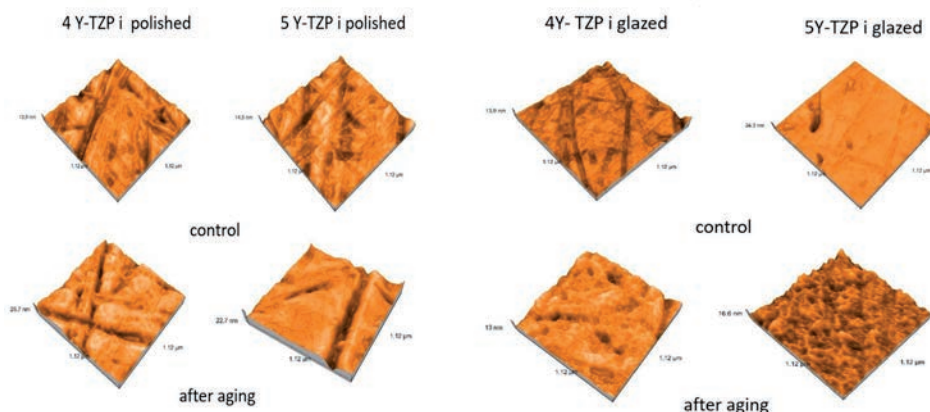


Figure 11.
The AFM 3D images in the incisal area of the glazed and polished samples, for 4Y-TZP and 5Y-TZP, before and after aging.

5.2 Effect of hydrothermal degradation on the optical properties

Making a synthesis of data from previous research, it was reported for the first two generations of zirconia, a decrease in translucency and opalescence, and an increase in opacity after different aging periods (1, 3, 5, 10 hours), and it was demonstrated that the material becomes more opaque with increasing exposure period to hydrothermal degradation [73]. The translucency values of third- and fourth-generation monolithic translucent zirconia were significantly affected by several factors, such as composition, microstructure, sintering time and staining techniques, surface treatments, thickness, and different aging protocols [28].

Cubic zirconia is known to be less susceptible to hydrothermal aging. The fourth and mostly the third generation have proven to be completely resistant to the degradation process. But significant changes in translucency values have also been recorded as a consequence of the interaction of various factors and the hydrothermal degradation. The aging process causes an increase in the volume of the cubic phase, accompanied by a separation of the tetragonal and cubic phases. The material becomes more susceptible to changes in temperature and humidity, and less stable [6].

For super-high translucent zirconia, obtained from blanks processed using a CAD/CAM system, the highest translucency was recorded when the material was dry-milled, with lower values for wet milling. After hydrothermal degradation, dry-milled specimens preserve a high translucency, and for wet-milled specimens, translucency increases; however, the aesthetic performance is still lower [29].

Optical and color measurements were recorded in each area (dentin-medium-incisal) on polished surfaces, before and after LTD, using a spectrophotometer Easyshade Advance IV (Vita Zahnfabrik, Bad Sackingen, Germany). The highest translucency (TP) values were registered for CER, and the lowest for STM. The trend of translucency relative to areas is in the following order: $d < m < i$ (STM, CER) and $d > m < i$ (IPS). After LTD, the translucency decreased for CER and increased (less incisal) for STM and IPS. However, the highest TP was recorded for CER and the lowest for STM, with close values between dentin and medium areas. For IPS, the order of values between areas was maintained. The incisal areas of the three materials undergo fewer changes (**Figure 12**).

Significant differences (two-way ANOVA, $p < 0.05$) among TP values of the three areas (d-m-i), for an IPS and CER before and after the aging stage, were found. Additionally, significant differences (increases) were recorded regarding TP for control-autoclaving groups, in dentin and medium areas for IPS and STM.

Previous research has reported that the translucency values of translucent zirconia decreased as the thickness increased. For example, an increase in material thickness from 0.5 mm to 1 mm induced a significant reduction in translucency values [74]. After accelerated aging (autoclaving, thermocycling), translucency values decreased for all thicknesses, and significant differences were recorded between the 0.5 mm specimens and those of 1, 1.5 and 2 mm. The color change was maximum for the 0.5 mm thick specimens and minimum for those of 2 mm thick [75].

Translucency values can also be influenced by aging related to sintering time. Prolonged sintering followed by hydrothermal degradation for 2 hours led to a surface with a generalized irregular appearance and micro-retentive areas, significantly reducing translucency. This consequence could be observed already after 1 hour, becoming more evident later. High-speed sintering can induce a decrease in the optical properties of 3Y- and 4Y-TZP. The translucency of industrially preshaded 4Y-zirconia was not influenced by the aging process, showing higher color stability than that stained manually [76].

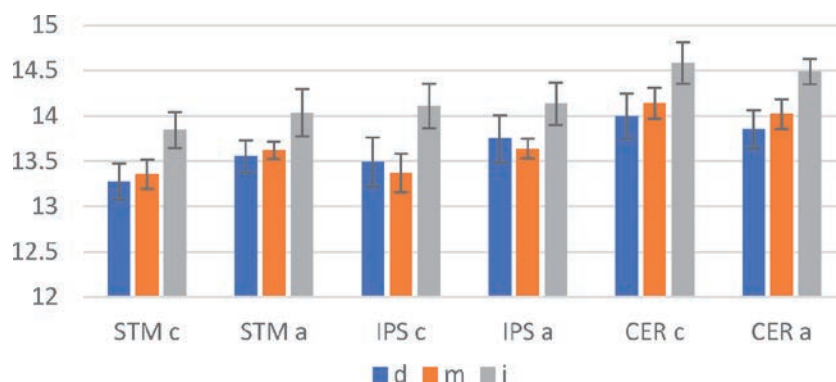


Figure 12. Mean TP values (with standard deviation) for all groups (before and after aging). STM = STML, IPS = IPS e.max ZirCad MT Multi, CER=CeramillZolid fx ML, c = control group, a = aging group, d = dentin (cervical), m = medium, i = incisal.

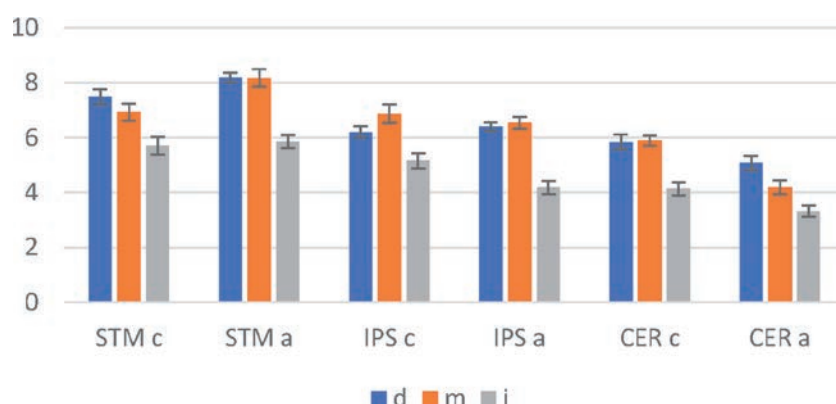


Figure 13. Mean opalescence (OP) values (with standard deviation) for all groups (before and after aging). STM = STML, IPS = IPS e.max ZirCad MT Multi, CER=CeramillZolid fx ML, c = control group, a = aging group, d = dentin (cervical), m = medium, i = incisal.

After the artificial aging process, the opalescence decreased for IPS (medium) and CER, and increased for IPS (dentinal, incisal). The highest mean OP was recorded for STM and the lowest for CER, with intermediate values for IPS. Following the aging process, the statistical test reported significant differences among the specimens before and after LTD for STM (medium), IPS (incisal) and CER. Mean OP values measured before and after the LTD stage are illustrated graphically in **Figure 13**.

According to the NBS system (The National Bureau of Standards), ΔE^* was converted to NBS units to express the level of color changes. After artificial aging, the levels of color change were perceivable (1.5–3.0) for STM and IPS; and for CER ranged from slight change (0.5–1.5—dentinal, medium) to extremely slight change (0.0–0.5—incisal).

6. Conclusions

The difference between the generations of zirconia is given by the tetragonal phase-cubic phase ratio, which is determined by the amount of Yttria added to the

material composition. The properties and lifespan of zirconia restorations can also be affected, on the one hand, by the correctness of the preparation and application of indications, occlusal concepts and luting procedures, and on the other hand by the particularities strictly related to the material: particle size, incorporation of pores and defects, milling and sintering procedures, finishing methods. These microstructural changes can influence mechanical properties (surface roughness, microhardness, flexural strength), optical properties (translucency, opalescence), as well as aging behavior. The innovative development of zirconia types and CAD/CAM technology requires good knowledge for optimal use of all available options

The conclusions below summarize the content of this topic regarding the new generations of monolithic translucent zirconia:

- Insignificant differences among the layers, regarding surface roughness and topography, were recorded in the before and after LTD stage
- The surface roughness increased for 4Y-TZP more than for 5Y-TZP after aging process; the 4Y+5Y-TZP material showed similarities for each layer related to microstructure
- There were significant differences (increase) in terms of surface nanoroughness for all zirconia –after LTD
- Related to microhardness, hydrothermal degradation does not have a significant influence
- Surface treatments (polishing/glazing) have a significant effect on surface topography
- Significant difference among layers, regarding translucency for 4Y- and 5Y- were found in before and after LTD stage
- The translucidity for 4Y-TZP significantly increased after hydrothermal degradation
- The level of color changes was perceivable for 4Y- and 4Y+5Y- zirconia.

Acknowledgements

We would like to acknowledge Victor Babeş University of Medicine and Pharmacy Timișoara, for their support in covering the costs of publication for this paper.

Conflict of interest

The authors declare no conflict of interest.

Author details

Flavia Roxana Bejan^{1*}, Liliana Porojan¹, Roxana Diana Vasiliu¹
and Anamaria Matichescu²

1 Department of Dental Prostheses Technology (Dental Technology),
Center for Advanced Technologies in Dental Prosthodontics, Faculty of Dentistry,
Victor Babeș University of Medicine and Pharmacy Timișoara, Romania

2 Department of Preventive, Community Dentistry and Oral Health, Center for
Advanced Technologies in Dental Prosthodontics, Faculty of Dentistry,
Victor Babeș University of Medicine and Pharmacy Timișoara, Romania

*Address all correspondence to: flavia.toma@umft.ro

IntechOpen

© 2025 The Author(s). Licensee IntechOpen. This chapter is distributed under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/4.0>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited. 

References

- [1] Makhija SK, Lawson NC, Gilbert GH, et al. Dentist material selection for single-unit crowns: Findings from the National Dental Practice – Based Research Network. *Journal of Dentistry*. 2016;**55**:40-47. DOI: 10.1016/j.jdent.2016.09.010
- [2] Zhang Y, Lawn BR. Novel zirconia materials in dentistry. *Journal of Dental Research*. 2018;**97**:140-147. DOI: 10.1177/0022034517737483
- [3] Yu SH, Runxuan P, Jing Y, Di Cai F, Xin H, Bo JH, et al. Overview of several typical ceramic materials for restorative dentistry. *Bio Med Research International*. 2022;**8451445**, 18 pages. DOI: 10.1155/2022/84551445
- [4] Ban S. Classification and properties of dental zirconia as implant fixtures and superstructures. *Materials*. 2021;**14**(17):4879. DOI: 10.3390/ma14174879
- [5] Kwon SJ, Lawson NC, McLaren EE, Nejat AH, Burgess JO. Comparison of the mechanical properties of translucent zirconia and lithium disilicate. *The Journal of Prosthetic Dentistry*. 2018;**120**(1):132-137. DOI: 10.1016/j.prosdent.2017.08.004
- [6] Camposilvan E, Leone R, Gremillard L, Sorrentino R, Zarone F, Ferrari M, et al. Aging resistance, mechanical properties and translucency of different yttria-stabilized zirconia ceramics for monolithic dental crown applications. *Dental Materials*. 2018;**34**(6):879-890. DOI: 10.1016/j.dental.2018.03.006
- [7] Zhang F, Inokoshi M, Batuk M, et al. Strength, toughness and aging stability of highly-translucent Y-TZP ceramics for dental restorations. *Dental Materials*. 2016;**32**:327-337. DOI: 10.1016/j.dental.2016.09.025
- [8] Toma FR, Birdeanu MI, Utu ID, Vasiliu RD, Moleriu LC, Porojan L. Surface characteristics of high translucent zirconia related to aging. *Materials (Basel)*. 2022;**15**(10):2606. DOI: 10.3390/ma15103606
- [9] Hjerpe J, Narhi TO, Valittu PK, Lassila LV. Surface roughness and flexural and bend strength of zirconia after different surface treatments. *The Journal of Prosthetic Dentistry*. 2016;**116**:577-583. DOI: 10.1016/j.prosdent.2016.02.018
- [10] Park C, Vang MS, Park SW, Lim HP. Effect of various polishing system on the surface roughness and phase transformation of zirconia and the durability of the polishing systems. *The Journal of Prosthetic Dentistry*. 2017;**117**:430-437. DOI: 10.1016/j.prosdent.2016.10.005
- [11] Hajhamid B, Bozec L, Tenenbaum H, et al. Effect of artificial aging on optical properties and crystalline structure of high-translucency zirconia. *Journal of Prosthodontics*. 2024;**33**:61-69. DOI: 10.1111/jopr.13648
- [12] Kim SH, Choi YS, Kang KH, Att W. Effects of thermal and mechanical cycling on the mechanical strength and surface properties of dental CAD-CAM restorative materials. *The Journal of Prosthetic Dentistry*. 2022;**128**:79-88. DOI: 10.1016/j.prosdent.2020.11.014
- [13] Pereira GKR, Venturini AB, Silvestri T, Dapieve KS, Montagner AF, Soares FZM, et al. Low-temperature degradation of Y-TZP ceramics: A

systematic review and meta-analysis. The Journal of the Mechanical Behavior of Biomedical Materials. 2015;**55**:151-163. DOI: 10.1016/j.jmbbm.2015.10.017

[14] Harada A, Shishido S, Barkarmo S, Inagaki R, Kanno T, Ortengren U, et al. Mechanical and microstructural properties of ultra-translucent zirconia ceramic stabilized with 5 mol%yttria. Journal of the Mechanical Behavior of Biomedical Materials. 2020;**111**:103974. DOI: 10.1016/j.jmbbm.2020.103974

[15] Leitao CIMB, Fernandes GVO, Azevedo LPP, et al. Clinical performance of monolithic CAD/CAM tooth-supported zirconia restorations: systematic review and meta-analysis. Journal of Prosthodontic Research. 2022;**66**:374-384. DOI: 10.2186/jpr.JPR_D_21_00081

[16] Tajti P, Solyom E, Czumbel LM, et al. Monolithic zirconia as a valid alternative to metal-ceramic for implant-supported single crowns in the posterior region: A systematic review and meta-analysis of randomized controlled trials. The Journal of Prosthetic Dentistry. 2023;**S0022-3913**(23):00336-00340. DOI: 10.1016/j.prosdent.2023.05.006

[17] Al-Bermani ASA, Quigley NP, Ha WN. Do zirconia single-retainer resin-bonded fixed dental prostheses present a viable treatment option for the replacement of missing anterior teeth? A systematic review and meta-analysis. The Journal of Prosthetic Dentistry. 2023;**130**:533-542

[18] Vozzo LM, Azevedo L, Fernandes JCH, et al. The success and complications of complete-arch implant-supported fixed monolithic zirconia restorations: A systematic review. Prosthesis. 2023;**5**:425-436. DOI: 10.3390/prosthesis5020029

[19] Kuraray Noritake—Technical Guide Katana Zirconia Multi-Layered Series.

201805-brochure-katana-zirconia-technical-guide-web-en_2.pdf. Available from: <https://www.kuraraynoritake.eu/> [Accessed: August 30, 2025]

[20] Ivoclar-Vivadent IPS e.max ZirCAD Labside Gebrauchsinformation 2019-06-27, Rev3a. 2019. Available from: <https://www.cadstar.dental/download/87/materialdokumentation-de/5667919/ipse-maxzircadlabside.pdf> [Accessed: August 30, 2025]

[21] Ceramill Zirconia User Manual-Zolid FX, Zolid FX Multilayer INT. Available from: <https://media.amanngirrbach.com/share/ro6aGRB5wgTqayA11Zjb/assets/8775> [Accessed: August 30, 2025]

[22] BruxZir Material: BruxZir Shaded 16 PLUS. Available from: https://glidewellldirect.com/collection/milling-blanks?constraint=bruxzir-material_shaded-16-plus [Accessed: August 30, 2025]

[23] Chen YW, Moussi J, Drury JL, Wataha JC. Zirconia in biomedical applications. Expert Review of Medical Devices. 2016;**13**:945-963. DOI: 10.1080/17434440.2016.1230017

[24] Malkondu O, Tinastepe N, Akan E, Kazazoglu E. An overview of monolithic zirconia in dentistry. Biotechnology and Biotechnological Equipment. 2016;**30**:644-652. DOI: 10.1080/13102818.2016.1177470

[25] Solis Pinargote NW, Yanushevich O, Krokheli N, Smirnov A, Savikin S, Grigoriev SN, et al. Materials and methods for all-ceramic dental restorations using computer-aided design (CAD) and computer-aided manufacturing (CAM) technologies-a brief review. Dental Journal. 2024;**12**:47. DOI: 10.3390/dj12030047

- [26] Stawarczyk B, Keul C, Eichberger M, Figge D, Edelhoff D, Lumkemann N. Three generations of zirconia: From veneered to monolithic. Part I. Quintessence International. 2017;**48**:369-380. DOI: 10.3290/j.qi.a38057
- [27] Stawarczyk B, Lümkmann N, Eichberger M, Edelhoff D. Werkstoffkunde update: Monolithisches Zirkonoxid. Die Quintessenz der Zahntechnik. 2017;**43**:980-991
- [28] Kolakarnprasert N, Kaiser MR, Kim DK, Zhang Y. New multi-layered zirconias: Composition, microstructure and translucency. Dental Materials. 2019;**35**:797-806. DOI: 10.1016/j.dental.2019.02.017
- [29] Zhang F, Reveron H, Spies BC, Van Meerbeek B, Chevalier J. Trade-off between fracture resistance and translucency of zirconia and lithium-disilicate glass ceramics for monolithic restorations. Acta Biomaterialia. 2019;**91**:24-34. DOI: 10.1016/j.actbio.2019.04.043
- [30] Lucas TJ, Lawson NC, Janowski GM, Burgess JO. Effect of grain size on the monoclinic transformation, hardness, roughness, and modulus of aged partially stabilized zirconia. Dental Materials. 2015;**31**(12):1487-1492. DOI: 10.1016/j.dental.2015.09.014
- [31] Jerman E, Lümkmann N, Eichberger M, Zoller C, Nothelfer C, Kienle A, et al. Evaluation of translucency, Marten's hardness, biaxial flexural strength and fracture toughness of 3Y-TZP, 4Y-TZP and 5Y-TZP materials. Dental Materials. 2021;**37**(2):212-222. DOI: 10.1016/j.dental.2020.11.007
- [32] Stawarczyk B, Frevert K, Ender A, Roos M, Sener B, Wimmer T. Comparison of four monolithic zirconia materials with conventional ones: Contrast ratio, grain size, four-point flexural strength and two-body wear. Journal of the Mechanical Behavior of Biomedical Materials. 2016;**59**:128-138. DOI: 10.1016/j.jmbbm.2015.11.040
- [33] Elsaka SE. Optical and mechanical properties of newly developed monolithic multilayer zirconia. Journal of Prosthodontics. 2019;**28**(1):e279-e284. DOI: 10.1111/jopr.12730
- [34] Strasser T, Wertz M, Koenig A, Koetzsch T, Rosentritt M. Microstructure, composition, and flexural strength of different layers within zirconia materials with strength gradient. Dental Materials. 2023;**39**(5):463-468. DOI: 10.1016/j.dental.2023.03.012
- [35] Inokoshi M, Liu H, Yoshihara K, et al. Layer characteristics in strength-gradient multilayered yttria-stabilized zirconia. Dental Materials. 2023;**39**:430-441. DOI: 10.1016/j.dental.2023.03.015
- [36] Vardhaman S, Borba M, Kaizer MR, Kim D, Zhang Y. Wear behavior and microstructural characterization of translucent multilayer zirconia. Dental Materials. 2020;**36**(11):1407-1417. DOI: 10.1016/j.dental.2020.08.015
- [37] Maharishi A, McLaren EA, White SN. Color- and strength-graded zirconia: Strength, light transmission, and composition. The Journal of ProstheticDentistry. 2024;**131**(6):1236.e1-1236.e9. DOI: 10.1016/j.prosdent.2024.03.015
- [38] Čokić SM, Córdor M, Vleugels J, et al. Mechanical properties-translucency- microstructure relationships in commercial monolayer and multilayer monolithic zirconia ceramics. Dental Materials. 2022;**38**:797-810. DOI: 10.106/j.dental.2022.04.011

- [39] Maruo Y, Yoshihara K, Irie M, et al. Flexural properties, bond ability, and crystallographic phase of highly translucent multi-layered zirconia. *Journal of Applied Biomaterials and Functional Materials*. 2020;**18**:2280800020942717. DOI: 10.1177/2280800020942717
- [40] De Angelis F, Buonvivere M, Sorrentino E, Rondoni GD, D'Arcangelo C. Wear properties of conventional and high-translucent zirconia-based materials. *Materials*. 2022;**15**(20):7324. DOI: 10.3390/ma15207324
- [41] Fathy SM, Al-Zordk W, Grawish ME, Swain MV. Flexural strength and translucency characterization of aesthetic monolithic zirconia and relevance to clinical indications: A systematic review. *Dental Materials*. 2021;**37**(4):711-730. DOI: 10.1016/j.dental.2021.01.022
- [42] Kaizer MR, Bano S, Borba M, Garg V, Dos Santos MBF, Zhang Y. Wear behavior of graded glass/zirconia crowns and their antagonists. *Journal of Dental Research*. 2019;**98**(4):437-442. DOI: 10.1177/0022034518820918
- [43] Lai X, Si W, Jiang D, Sun T, Shao L, Deng B. Effects of small-grit grinding and glazing on mechanical behaviours and aging resistance of a super-translucent dental zirconia. *Journal of Dentistry*. 2017;**66**:23-31. DOI: 10.1016/j.jdent.2017.09
- [44] Alves LMM, Rodrigues CDS, Ramos NDC, Buizastrow J, Campos TMB, Bottino MA, et al. Silica infiltration on translucent zirconia restorations: effects on the antagonist wear and survivability. *Dental Materials*. 2022;**38**(12):2084-2095. DOI: 10.1016/j.dental.2022.11.015
- [45] Mao L, Kaizer MR, Zhao M, Guo B, Song YF, Zhang Y. Graded ultra-translucent zirconia (5Y-PSZ) for strength and functionalities. *Journal of Dental Research*. 2018;**97**(11):1222-1228. DOI: 10.1177/0022034518771287
- [46] Kim H-K, Kim S-H, Lee J-B, Ha S-R. Effects of surface treatments on the translucency, opalescence, and surface texture of dental monolithic zirconia ceramics. *The Journal of Prosthetic Dentistry*. 2016;**115**:773-779. DOI: 10.1016/j.jjoule.2020.22.020
- [47] Wu Z, Tian J, Wei D, Zhang Y, Lin Y, Di P. Effects of thickness and polishing treatment on the translucency and opalescence of six dental CAD-CAM monolithic restorative materials: An in vitro study. *BMC Oral Health*. 2023;**23**(1):579. DOI: 10.1186/s12903-023-03299-y
- [48] McLaren EA, Maharishi A, White SN. Influence of yttria content and surface treatment on the strength of translucent zirconia materials. *The Journal of Prosthetic Dentistry*. 2023;**129**:638-643. DOI: 10/1016/j.prosdent. 2021.07.001
- [49] Elraggal A, Afifi RR, Alamoush RA, Raheem IA, Watts DC. Effect of acidic media on flexural strength and fatigue of CAD-CAM dental materials. *Dental Materials*. 2023;**39**(1):57-69. DOI: 10.1016/j.dental.2022.11.019
- [50] Cie CIE. 15: 2004 COLORIMETRY. Vienna, Austria: Commission Internationale de l'Eclairage; 2004
- [51] Lee YK. Translucency of human teeth and dental restorative materials: Their clinical relevance. *Journal of Biomedical Optics*. 2015;**20**(4):045002. DOI: 10.1117/1.JBO.20.4.045002
- [52] Kontonasaki E, Rigos AE, Ilia C, Istantos T. Monolithic zirconia:

An update to current knowledge. optical properties, wear and clinical performance. *Dentistry Journal*. 2019;7:90. DOI: 10.3390/dj7030090

[53] Zhang Y. Making Yttria-stabilized tetragonal zirconia translucent. *Dental Materials*. 2014;30:1195-1203. DOI: 10.1016/j.dental.2014.08.375

[54] Pekkan G, Pekkan K, Bayindir BÇ, Ozcan M, Karasu B. Factors affecting the translucency of monolithic zirconia ceramics: A review from materials science perspective. *Dental Materials Journal*. 2020;39(1):1-8. DOI: 10.4012/dmj.2019-098

[55] Sabet H, Wahsh M, Sherif A, Salah T. Effect of different immersion times and sintering temperatures on translucency of monolithic nanocrystalline zirconia. *The Future Dental Journal*. 2018;4:84-89. DOI: 10.1016/j.fdj.2017.09.003

[56] Cho MH, Seol H-J. Effect of high-speed sintering on the optical properties, microstructure, and phase distribution of multilayered zirconia stabilized with 5 mol% yttria. *Materials*. 2023;16(16):5570. DOI: 10.3390/ma16165570

[57] Ban S. Development and characterization of ultra-high translucent zirconia using new manufacturing technology. *Dental Materials Journal*. 2023;42(1):1-10. DOI: 10.4012/dmj.2022-243

[58] Sen N, Us YO. Mechanical and optical properties of monolithic CAD-CAM restorative materials. *The Journal of Prosthetic Dentistry*. 2018;119(4):593-599. DOI: 10.1016/j.prosdent.2017.06.012

[59] Shirani M, Savabi O, Mosharraf R, Akhavankhaleghi M, Hebibkhodaei M, Isler S. Comparison of translucency and opalescence among different dental monolithic ceramics. *The Journal of*

Prosthetic Dentistry. 2021;126(3):446.e1-446.e6. DOI: 10.1016/j.prosdent.2021.04.030

[60] Lee YK. Translucency of human teeth and dental restorative materials and its clinical relevance. *Journal of Biomedical Optics*. 2015;20:45002. DOI: 10.1117/1JBO.21.4.045002

[61] Nistor L, Gradinaru N, Rîcã R, Mărășescu P, Stan M, Manolea H, et al. Zirconia use in dentistry - Manufacturing and properties. *Current Health Sciences Journal*. 2019;45(1):28-35. DOI: 10.12865/chsj.45.01.03

[62] Mourouzis P, Tolidis K. Effects of milling method and artificial ageing on optical properties of high translucent zirconia for chairside restorations. *Dental Materials*. 2022;38(1):108-120. DOI: 10.1016/j.dental.2021.10.015

[63] Hajhamid B, Alfrisany N, Somogyi-Ganss E. The effect of accelerated aging on crystalline structures and optical properties of different monolithic zirconia: A qualitative systematic review. *Dental Materials*. 2022;38(4):569-586. DOI: 10.1016/j.dental.2022.02.005

[64] Furuya K, Takemoto S, Yamashita S, Sekine H, Yajima Y, Yoshinari M. Low-temperature degradation of high-strength Y-TZP (yttria-stabilized tetragonal zirconia polycrystal). *Dental Materials Journal*. 2020;39(4):577-586. DOI: 10.4012/dmj.2019-090

[65] Winter A, Schurig A, Odenthal A-L, M. Schmitter M. Impact of different layers within a blank on mechanical properties of multi-layered zirconia ceramics before and after thermal aging. *Dental Materials*. 2022;38(5):e147-e154. DOI: 10.1016/j.dental.2022.03.009

[66] Standard ISO. 13356:2015. *Implants for surgery-Ceramic*

materials based on yttria-stabilized tetragonal zirconia (Y-TZP). 3rd ed. 2015. Technical committee: ISO/TC 150/SC1ICS:11.040.40. Available from: <https://www.iso.org/cms/render/live/en/sites/isoorg/contents/data/standard/06/23/62373.html>

[67] de Araújo-Júnior ENS, Bergamo ETP, Campos TMB, Jalkh EB B'a, ACO L, Monteiro KN, et al. Hydrothermal degradation methods affect the properties and phase transformation depth of translucent zirconia. *Journal of the Mechanical Behavior of Biomedical Materials*. 2020;**112**:104021. DOI: 10.1016/j.jmbbm.2020.104021

[68] Guilardi LF, Pereira GKR, Wandscher VF, Rippe MP, Valandro LF. Mechanical behavior of yttria-stabilized tetragonal zirconia polycrystal: Effects of different aging regimens. *Brazilian Oral Research*. 2017;**31**:e94. DOI: 10.1016/j.jmbbm.2018.05.029

[69] Kou W, Garbriellsson K, Borhani A, Carlborg M, Molin TM. The effects of artificial aging on high translucent zirconia. *Biomaterial Investigations in Dentistry*. 2019;**6**:54-60. DOI: 10.1080/26415275.2019.1684201

[70] Nakamura K, Harada A, Ono M, Shibasaki H, Kanno T, Niwano Y, et al. Effect of low-temperature degradation on the mechanical and microstructural properties of tooth-colored 3Y-TZP ceramics. *Journal of the Mechanical Behavior of Biomedical Materials*. 2016;**53**:301-311. DOI: 10.1016/j.jmbbm.2015.08.031

[71] Guilardi LF, Pereira GKR, Gundel A, Rippe MP, Valandro LF. Surface micro-morphology, phase transformation, and mechanical reliability of ground and aged monolithic zirconia ceramic. *Journal of the Mechanical Behavior of Biomedical Materials*. 2017;**65**:849-856. DOI: 10.1016/j.jmbbm.2016.10.008

[72] Mohammadi Bassir M, Babasafari M, Rezvani MB, Jamshidian M. Effect of coarse grinding, overglazing, and 2 polishing systems on the flexural strength, surface roughness, and phase transformation of yttrium-stabilized tetragonal zirconia. *The Journal of Prosthetic Dentistry*. 2017;**118**:658-665. DOI: 10.1016/j.prosdent.2016.12.019

[73] Kang C-M, Peng T-Y, Shimoe S. Color accuracy of different types of monolithic multilayer precolored zirconia ceramics. *The Journal of Prosthetic Dentistry*. 2020;**124**(6):789.e1-789.e7. DOI: 10.1016/j.prosdent.2020.04.026

[74] Sulaiman TA, Abdulmajeed AA, Donovan TE, Ritter AV, Vallittu PK, Närhi TO, et al. Optical properties and light irradiance of monolithic zirconia at variable thicknesses. *Dental Materials*. 2015;**31**:1180-1187. DOI: 10.1016/j.dental.2015.06.016

[75] Cho MH, Seol HJ. Optical properties, microstructure, and phase fraction of multi-layered monolithic zirconia with and without yttria-gradient. *Materials (Basel)*. 2022;**16**:41. DOI: 10.3390/ma16010041

[76] Shin HJ, Kwon YH, Seol HJ. Effect of superspeed sintering on translucency, opalescence, microstructure, and phase fraction of multilayered 4 mol% yttria-stabilized tetragonal zirconia polycrystal and 6 mol% yttria-stabilized partially stabilized zirconia ceramics. *The Journal of Prosthetic Dentistry*. 2023;**130**(254):e1-e10

Assessment of the Mechanical and Optical Characteristics of Hybrid Dental Ceramics in Dental Prosthetics

*Roxana-Diana Vasiliu, Bejan Flavia Roxana
and Liliana Porojan*

Abstract

The continuous development of new dental materials for computer-aided design/computer-aided manufacturing (CAD/CAM) technologies has significantly expanded the range of options available to clinicians for rehabilitating their prosthetic patients. Subtractive CAD/CAM dental technologies have permitted the processing of ceramic materials with better mechanical and optical properties. Hybrid ceramics, which combine the strengthening properties of two different materials, have been developed to simulate the mechanical and optical properties of a natural tooth. The main types of hybrid ceramics are polymer-infiltrated ceramics and resin nanoceramics. Hybrid ceramics stand out for their remarkable esthetic appeal, exceptional durability, and impressive flexibility, making them an outstanding choice for various restorative procedures. As dental technology advances, hybrid ceramics become indispensable in providing patients with high-quality and enduring dental restorations. Hybrid ceramic materials greatly enhance dental restorations by combining the best characteristics of ceramics and resin composites. Several *in vitro* research studies found in the literature provide helpful information regarding their optical and mechanical behavior. In conclusion, the experimental part and the results from previous research and original studies revealed that the microstructure of ceramic materials significantly influences their topographical features and microhardness. Different categories display unique microstructural arrangements that affect their response to mechanical stress and environmental factors. Water sorption impacts the long-term clinical performance of resin matrix ceramics.

Keywords: hybrid ceramics, optical properties, mechanical behavior, microstructure, biocompatibility

1. Introduction

Dental ceramics possess excellent mechanical and optical properties, as well as being biocompatible. Despite their great esthetics, they are fragile, rigid, and challenging to repair. In contrast, composites are easier to manipulate and repair, more flexible, and less abrasive on opposing teeth [1, 2]. Nonetheless, their poor wear resistance and difficulty achieving a good polish put them at a disadvantage compared to ceramics. The rising demand for natural restorations has prompted manufacturers to explore innovative methods to enhance ceramic materials, ensuring they have both esthetic appeal and sufficient strength for use in posterior regions [3, 4].

Hybrid ceramics blend ceramic and polymer components to produce improved properties. They are commonly used in obtaining dental restorations where strength and esthetic appeal are essential. Unlike traditional ceramics, the polymer-infiltrated resin materials can be milled and polished in a single step, simplifying the fabrication process. Some hybrid ceramics can also be glazed using a thin layer of photopolymerizable material. These aspects depend on the manufacturer's instructions for use.

The polymeric CAD/CAM materials are classified depending on their microstructure and the industrial polymerization manufacturing mode for polymer-infiltrated ceramic networks (PICNs) and resin-based composites (RBCs) with dispersed fillers.

Material	Type	Manufacturer	Composition
Lava Ultimate	Nanoceramic resin	3M ESPE, Germany	SiO ₂ , ZrO ₂ , aggregated ZrO ₂ /SiO ₂ cluster 80%
Vita Enamic	Hybrid ceramic	Vita Zahnfabrik, Germany	Feldspar ceramic enriched with aluminum oxide 86%
Cerasmart	Composite resin	GC, SUA	Silica, barium glass 71%
Shofu HC	Composite resin	Shofu, Japan	Silica, silicate, zirconium silicate 61%
Hyramic	Composite resin	Upcera, China	Inorganic filler 55–85%

Table 1.
Resin matrix ceramics are used in the dental field [12].



Figure 1.
Different types of resin matrix ceramics are used in the dental field.

These are new CAD/CAM materials, which feature a composite resin matrix and are referred to as resin-matrix ceramics (RMCs) [5]. The rationale behind introducing this category of materials was to combine the advantages of polymers (low wear and improved flexural properties) and ceramics (color stability and structural durability) [6–8].

Polymer-infiltrated ceramic networks (PICNs) are characterized by their porous feldspar ceramic framework that is saturated with a cross-linked polymer. This dual-network structure effectively reduces crack propagation and improves the mechanical properties of the feldspar ceramic. Several studies have shown that PICNs demonstrate promising clinical performance, with a 3-year survival rate ranging from 97.0% to 97.4% for partial coverage restorations [9–11].

The typical resin matrix ceramics are listed in **Table 1** and **Figure 1**.

2. The role of the microstructure and surface topography of hybrid ceramics (resin matrix ceramics) on optical and mechanical properties

The *information* in this chapter was searched in the literature using PubMed and Google Scholar engines, and also new information that was not published before was added.

The microstructural examination of resin matrix ceramics enables both qualitative and quantitative assessments of surface characteristics.

Microstructural dental ceramics have two key phases: a glassy phase that enhances their esthetic appeal and a crystalline phase that provides mechanical strength. Grain size is crucial for ceramics' performance, as it directly affects surface friction and the material's wear resistance. The emergence of polycrystalline ceramics (silicon-free ceramics), hybrid ceramics, and nano-ceramics has necessitated the development of a new classification system [13].

The microstructure of hybrid ceramics plays a significant role in determining both their optical and mechanical properties. Ceramics with a glassy matrix exhibit enhanced optical qualities but often exhibit lower mechanical strength. Conversely, reinforced glass ceramics possess higher mechanical strength. Additionally, certain resin ceramics can be polished more easily due to their nanoscale crystal content, which affects their microstructure.

Resin matrix ceramics are hybrid ceramics of an organic matrix loaded with ceramic particles [14, 15]. Since 2013, the American Dental Association has included these ceramics in its ceramic classifications, defining them as “milled, and easily polished materials that contain inorganic refractory compounds, such as porcelain, glass, and ceramics” [16]. According to the last classifications, two CAD/CAM hybrid materials classes can be found in the literature. The first consists of materials with dispersed fillers, including Cerasmart (GC), Shofu Block HC (Shofu), and Lava Ultimate (3M). The second class is composed of PICN materials such as Enamic from Vita.

Lava Ultimate from 3M ESPE consists of nano-ceramic particles constrained in a polymer matrix. The nanocluster particles have a diameter of 0.6–10 μm and are composed of 20-nm silica nanomers and 4–11 nm zirconia nanomers. The particle's nano-dimension enables a high proportion of ceramic to be assimilated into the resin matrix. The non-requirement for firing after milling is a significant advantage of these ceramics [17].

Nano-ceramics consist of grains smaller than 100 nm. The size of these crystalline grains is crucial in functional ceramics, such as zirconia, alumina, and glass-ceramics. Shofu Block (Shofu, SHOFU Dental GmbH, Ratingen, Germany) contains silica

powder, zirconium silicate, ethylenediamine, and triethylene glycol dimethacrylate (TEGDMA). Vita Enamic (Vita Zahnfabrik, Germany) features a fine structure feldspar matrix infused with polymer materials, including UDMA and TEGDMA [18].

The roughness of a prosthetic restoration can change after adjustments are made inside the mouth. To avoid inaccurate results, roughness measurements can be performed using a 3D scanner microscope. This type of testing allows for repeated measurements while minimizing surface scratching, which can lead to inconsistent results. A potential drawback of this system is that it may be influenced by the surface reflections of the materials being investigated. However, examinations conducted with scanning electron microscopy and atomic force microscopy can provide accurate visualizations of surface roughness.

A widely used and more straightforward method for evaluating surface roughness is surface profilometry (**Figure 2**). A surface profilometer enables the calculation of three surface roughness parameters: Ra (average surface roughness), Rz (maximum surface roughness), and Rq.

A more suitable method for studying the surface features of ceramics is atomic force microscopy (AFM). The advantages of this method include high-resolution analysis, the avoidance of previous treatments for the tested samples, and its suitability for use in both vacuum and liquid environments. Disadvantages include a significant amount of time required for analysis and the inability to measure large samples [19]. The non-contact type measuring instruments are standardized by ISO 25178 [20, 21].

A sharp tip is used to register the surface of the sample. Scanning the tip over the sample surface can be performed in contact, non-contact, or tapping mode. In contact mode, the tip follows the topography, and the force between the tip and the sample is kept at a constant level using a feedback curve. In tapping mode, the tip remains in contact with the sample for only a brief moment. This mode is advantageous for analyzing soft surfaces [22].

In the non-contact mode, the distance between the cantilever and the samples ranges from 5 to 15 nm. Using an atomic force microscope (AFM) provides a three-dimensional representation of the surface, making it an essential tool for characterizing materials, particularly in the field of nanoscience. AFM is part of scanning probe microscopy (SPM) tools that are designed to study material surfaces from micron dimensions down to atomic dimensions. Atomic force microscopy has garnered significant attention due to its ability to detect nanoscale changes in material structures.



Figure 2.
Surface profilometer SurfTest SJ-201 (Mitutoyo Japan).

Recent studies have utilized the atomic force microscopy (AFM) method to evaluate the deformation of hybrid ceramic surfaces under cyclic loading. This technique has also aided researchers in understanding the relationship between mechanical properties and surface topography at the nanoscale. In the field of dentistry, the parameters examined include Sa, Sq, and Sz. Sa is an extension of the Ra parameter, which represents the arithmetical mean of height. It is used to express the variation in height of each peak compared to the arithmetic mean. Sq represents the root mean square height, while Sz is defined as the sum of the highest peak height and the deepest pit depth [23, 24]. AFM images of hybrid ceramics are presented in **Figure 3**.

In **Figure 3**, atomic force microscopy images of various hybrid resin ceramics are shown. In each type of hybrid resin ceramic analyzed, the surfaces exhibited a range of minor irregularities alongside distinct sharp spikes. These features not only influenced the tactile quality of the materials but also enhanced the overall esthetic appeal of the product. This differentiation highlights the unique characteristics of the surfaces (**Figure 4**).

A significant factor contributing to superficial abrasion and roughness in dental restorations is daily tooth brushing. When combined with toothpaste, a phenomenon known as 3- or 4-body wear can occur on various types of restorations. Tooth brushing can result in the removal of the characteristic layer, leading to increased surface

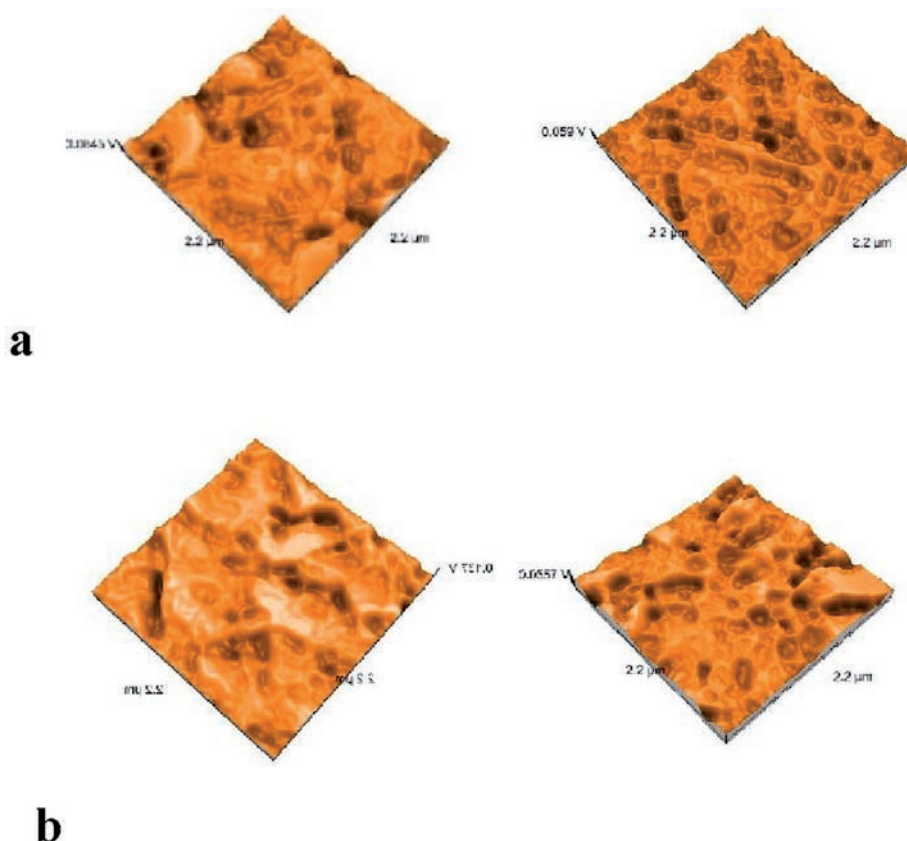


Figure 3.
 AFM pictures of hybrid matrix ceramics. (a) Lava Ultimate (3M ESPE, Germany), (b) Cerasmart (GC, SUA) before and after thermal aging. This data comes from an original experiment and has not been published before.

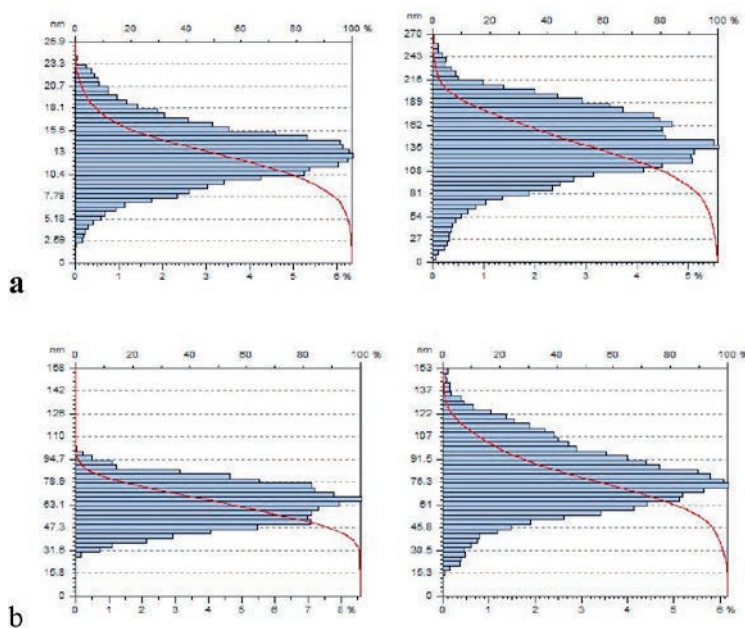


Figure 4.

Particle size distribution of hybrid matrix ceramics. (a) Lava Ultimate (3M ESPE, Germany), (b) Cerasmart (GC, SUA) before and after thermal aging. This data comes from original experiment and has not been published before.

roughness and color changes. In **Figure 5**, the different values of hybrid resin ceramics related to brushing and thermal aging are shown.

Simulating brushing and thermal aging for a total of 5000 cycles revealed that Hyramic hybrid ceramic, followed by Cerasmart, exhibited higher surface roughness values.

The surface texture of dental materials plays a significant role in color perception, as rougher surfaces are known to reflect less light, which can alter the visual appearance of restorative materials. Research has shown that an increase in surface

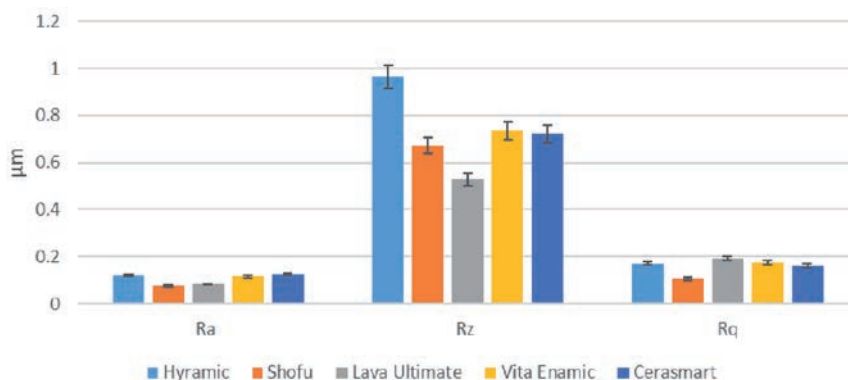


Figure 5.

Mean values for surface roughness parameters a for hybrid ceramics after simulating brushing. This data comes from an original experiment and has not been published before.

roughness exceeding 0.2 mm results in greater plaque accumulation on these surfaces. This accumulation not only heightens the risk of dental caries (cavities) but also contributes to periodontal inflammation, thereby impacting overall oral health.

Moreover, the increased surface roughness of dental materials is correlated with a higher rate of wear on opposing teeth (antagonists), which raises concerns about the longevity and effectiveness of restorations. The wear can compromise the functionality of both the restorative material and the natural teeth over time.

3. Oral environment influence on hybrid ceramics

Over time, the oral environment can significantly impact the properties of hybrid ceramics. *In vitro* studies have partially simulated the oral environment through thermal cycling, involving different cold and warm baths in which ceramic samples were immersed [25].

In the oral cavity, hybrid ceramic restorations are subjected to stresses from high and low temperatures, which can eventually lead to the development of cracks and a loss of material strength. The thermocycling process can alter the failure load of the material to some extent. Thermal aging has a direct impact on the longevity of resin ceramics [26].

Standardized parameters are typically used to replicate the *in vitro* oral environment. The cycles generally range from 500 to 600,000, with 1 year represented by 10,000 cycles (10^4). A standardized thermocycler is used with distilled water baths set to different temperatures and specific dwell times. In some studies, distilled water is substituted with coffee to examine potential color changes [27]. The dwelling time is 30 seconds for each bath, with a 10-second interval between the two immersions of the samples (Figure 6).

In vitro research indicates that resin ceramics are sensitive to degradation within the oral cavity, primarily due to fluctuations in pH [28]. Dietary habits can significantly influence the pH of the oral environment. Over time, this degradation can affect both the strength and surface roughness of these materials, ultimately leading to long-term restoration failure [29].

Coffee, carbonated acidic drinks, black tea, and wine are commonly used in studies to simulate the oral environment and evaluate pH changes. Researchers have found that specific acids, such as acetic, lactic, and propionic, may lead to reduced microhardness [30].

Another method for aging resin matrix ceramics involves ultraviolet (UV) radiation. Studies have shown that the optical properties (ΔE values) exceed clinically acceptable levels after undergoing UV aging. One study found that the properties of resin nano-ceramics changed after UV aging in comparison with those of lithium disilicate, feldspathic, and zirconia-reinforced lithium silicate glass-ceramics. This finding has been supported by additional research indicating that the crystalline structure, polymeric matrix, and filler size influence discoloration [31].

Tooth wear caused by erosive and abrasive influences is currently a significant research focus, partly due to the recent decline in the prevalence of dental caries. The daily consumption of fruit juices, soft drinks, and sour fruits plays a significant role in the development of erosive defects, as these substances can soften the tooth structure, making it more susceptible to abrasion from mechanical forces. Several authors have examined the resistance of various CAD/CAM materials to both abrasive and erosive influences [32].

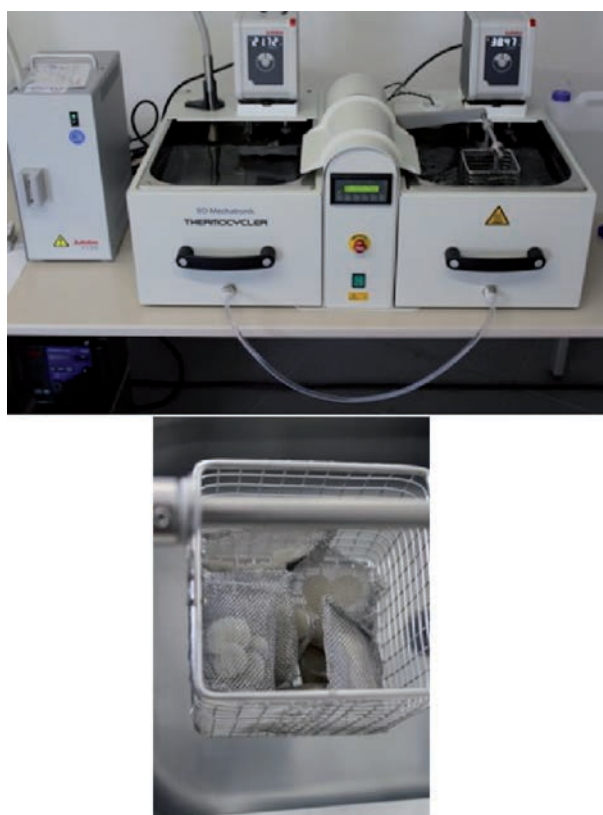


Figure 6.
Thermocycling equipment that contains two water baths, one with hot water at 55°C and the other with cold water at 5°C.

4. Optical properties of hybrid dental ceramics

The information in this chapter was searched in the literature using the PubMed and Google Scholar engines, and also new information that was not published before was added.

The concept of color can sometimes be difficult to grasp and is often more closely associated with art than science [33]. In dentistry, accurately matching the colors of teeth and restorations is essential, yet it can be a challenging and unpredictable process. Munsell was the first to systematically organize dental color. Around the same time, the International Commission on Illumination published standards for color [34]. In 1976, the CIE developed a new system known as CIEL*a*b*. This was the first instance where numbers were assigned to colors, enabling the calculation of differences between them. In this system, L* represents the lightness of an object, a* indicates the balance of redness or greenness, and b* denotes the level of yellowness and blueness [35].

The optical properties of hybrid dental ceramics are significantly influenced by their chemical composition and the sizes of their structures. Understanding these properties is crucial, especially in dentistry and material science applications. Three primary phenomena contribute to determining the optical properties of resin matrix ceramics: refraction, deflection, and total light transmission. Each of these interactions is closely tied to the wavelength of the incident light [36].

Refraction, for instance, is the bending of light as it passes from one medium to another, which is inherently linked to the speed of light in those materials.

Reflection is another important phenomenon that occurs when light encounters the interface between two materials with different optical properties. The reflective index quantifies the amount of light reflected from the surface of a ceramic material into the surrounding environment. Notably, uneven or textured surfaces can scatter light in multiple directions, complicating the predictability of reflection compared to flat surfaces that direct light primarily in one direction [37].

In dentistry, advancements in optical materials did not immediately enhance color matching techniques. The traditional visual matching method prevailed for some time, mainly because the CIEL*a*b* color system, although a significant improvement, can be affected by various factors. These factors include opacity (the degree to which a substance blocks light), transparency (the extent to which light can pass through), translucency (the partial transmission of light), metamerism (the phenomenon where colors appear differently under varying lighting conditions), opalescence (the shifting colors produced by microstructure), and fluorescence (the emission of light by a substance that has absorbed light or other electromagnetic radiation). Understanding these complexities is crucial for achieving accurate and esthetically pleasing results in dental restorations [38].

Translucency is defined as the degree to which light is transmitted through a substrate from its surface to its surrounding environment. While “translucency” is commonly used to describe the optical properties of materials, “transmission” is the corresponding term utilized in physics. Conversely, opacity signifies the absence of transparency [39].

Quantification of translucency can be achieved through three distinct measurements: direct transmission (where light passes through without altering its direction), total transmission (which encompasses both direct and diffuse transmissions), and spectral reflectance (which captures the portion of incident light that is reflected by an interface, such as a textured surface).

The TP parameter value is the color difference between the same specimen viewed against a white and black background, with values ranging from 0 to 100. The formula for calculating TP is as follows [40]:

$$TP = \left[(L^{B*} - L^{W*})^2 + (a^{B*} - a^{W*})^2 + (b^{B*} - b^{W*})^2 \right]^{1/2}, \quad (1)$$

Index B refers to the value of color coordinates against a dark background, and index W refers to those against a white background [41].

$$OP = \left[(a^{B*} - a^{W*})^2 + (b^{B*} - b^{W*})^2 \right]^{1/2} \quad (2)$$

Index B refers to the value of color coordinates against a dark background, and index W refers to those against a white background.

CR values range from 0 (completely transparent) to 1 (completely opaque) [42].

$$CR = Y_b / Y_w = \left[(L^* + 16) / 116 \right]^3 \times 100 \quad (3)$$

The total color change (ΔE^*) can be calculated using the following formula [43]:

$$\Delta E^* = \left[(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2 \right]^{1/2} \quad (4)$$

The color change was then converted to NBS units using the following Equation [44, 45]:

$$NBS = \Delta E^* \times 0.92 \quad (5)$$

The translucency parameter of hybrid dental ceramics (**Figure 7**) closely resembles that of natural teeth, with values ranging from 19 to 24. This indicates that these hybrid resin ceramics are appropriate for anterior restorations. After undergoing thermal aging and brushing—two methods to simulate the oral environment—the Cerasmart ceramic demonstrated the highest translucency parameter values.

Figure 8 results indicate that all the hybrid ceramic materials included demonstrated a significant increase in their opalescence parameters following thermal aging and brushing processes, which underscores their biomimetic qualities—characteristics that closely mimic natural tooth enamel.

The measurements taken to assess the opalescence parameters varied among the different materials. Notably, Hyramic exhibited the highest opalescence parameter, indicating a more natural esthetic resemblance, while Vita Enamic showed the lowest opalescence parameter. This variation highlights the differences in the optical properties of the materials, which may influence their suitability for specific dental applications.

The equation for color difference (ΔE_{ab}) was developed to assess the level of color acceptability. Shade designation and illuminants can influence color differences. The literature reports that the range of color differences falls between 0.8 and 4.8 ΔE units. The perceptible limit of color stability is defined as ΔE greater than 2.6, while the unacceptable limit is defined as ΔE greater than 5.5. The values of color differences can be correlated with visual evaluations [17].

A value of 3.7 ΔE units is associated with acceptable standards based on spectrophotometric evaluations, while values of 2.6 ΔE units are considered clinically

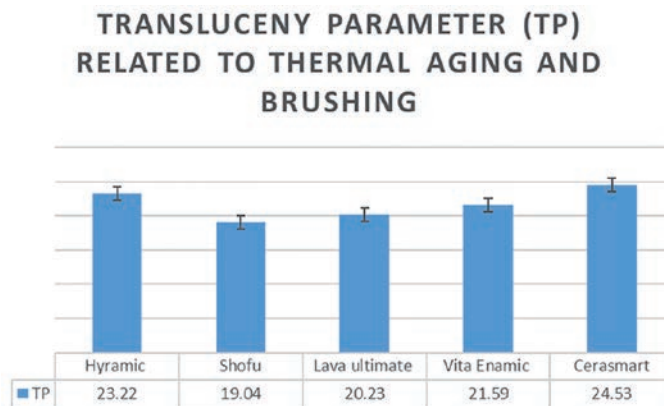


Figure 7. Mean values and standard deviation for the translucency parameter for hybrid resin ceramics [46].

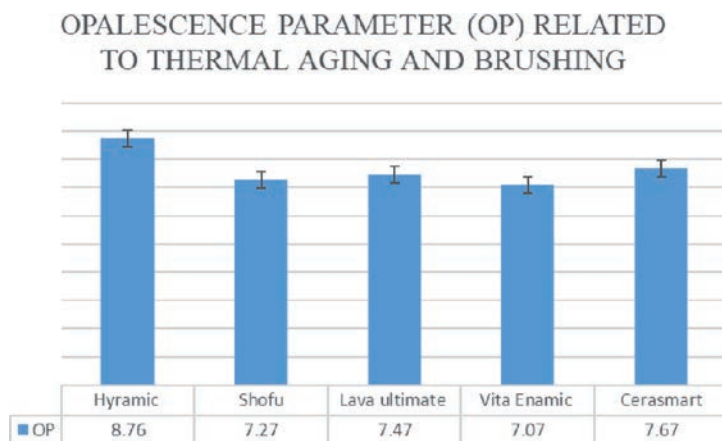


Figure 8.
 Mean values and standard deviation for the opalescence parameter for hybrid resin ceramics [46].

acceptable according to spectroradiometer measurements. The National Bureau of Standards (NBS) describes the color change rating. The ΔE^* values must be converted to NBS units using $NBS = \Delta E^* \times 0.92$. This conversion is necessary to evaluate color differences relative to clinical standards. Based on spectrophotometer measurements, a value of 6.8 ΔE units is considered at the limit of clinical acceptability, while values of 5.5 ΔE units are regarded as the threshold for spectroradiometer measurements [47].

The relative translucency of esthetic materials can affect the masking ability of dental restorations. Several studies have investigated the optical properties of various hybrid ceramics, examining how different factors influence the final color of these restorations. These factors include dental substrates, luting agents, restoration materials, glazes, and laboratory procedures. However, there is limited information on the complex optical behavior of esthetic CAD-CAM materials regarding the color parameters of natural tooth structures.

The masking ability of ceramic materials is notably affected by their thickness. A review of previous research has indicated that the ΔE^*_{ab} value, which measures color difference, decreases as the thickness of the ceramic increases. This finding contrasts with the results reported by Turgut et al., who observed a different trend. In a current study, it was found that, irrespective of the specific material or the background against which it was tested, the mean ΔE^*_{ab} values demonstrated a decrease with increasing material thickness. This suggests that thicker hybrid ceramics may provide better masking properties overall. Notably, this trend was only observed for Lava Ultimate ceramic and Vita Enamic when tested over an amalgam background, as well as for Vita Enamic when placed over enamel [48].

These results provide partial support for the findings of another study, suggesting that while thickness generally enhances masking ability, the relationship can vary significantly depending on the specific ceramic material and the underlying substrate.

The color of the substrate cannot be altered; it can only be masked. Masking is defined as the ability to conceal a colored background. According to some researchers, masking a dental substrate with cements may not be effective because various shades are not available, and the layers of cement are thin.

About the luting material, other studies emphasize its significance in esthetic rehabilitation, indicating that it impacts approximately 10–15% of the optical results

for all-ceramic restorations. To achieve better esthetic predictability, it is recommended to test try-in pastes before cementation.

Considering these factors, the masking ability of the restoration material is crucial. Studies have demonstrated that the masking effect can be correlated with the translucency parameter (TP) values when the TP values of the materials differ. However, when the TP values are similar, the opalescence parameters (OP) may influence the masking effect. Therefore, the contribution of opalescence should be quantitatively confirmed. Opalescence occurs due to the scattering of visible light, resulting in a bluish appearance in reflected light and an orange or brown appearance in transmitted light, as shorter wavelengths are scattered more than longer wavelengths (**Figures 9–11**).

Color changes were assessed for all materials and ranked in order of significance, from most significant to least significant: Hyramic > Cerasmart > Enamic > Shofu > Lava Ultimate. For slight changes, the order of decreasing percentage is: Lava Ultimate > Shofu > Enamic > Hyramic > Cerasmart. In terms of perceivable

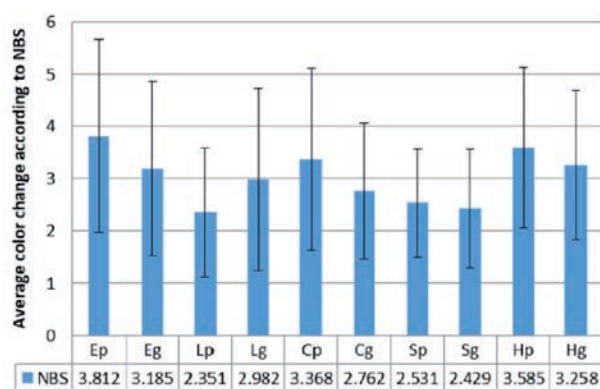


Figure 9.
Average color changes and SD, related to restoration material [46].

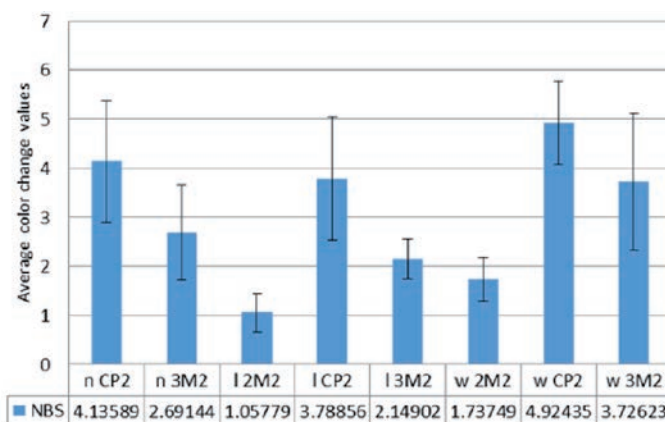


Figure 10.
Average color changes and SD, related to luting material/substrate [46].

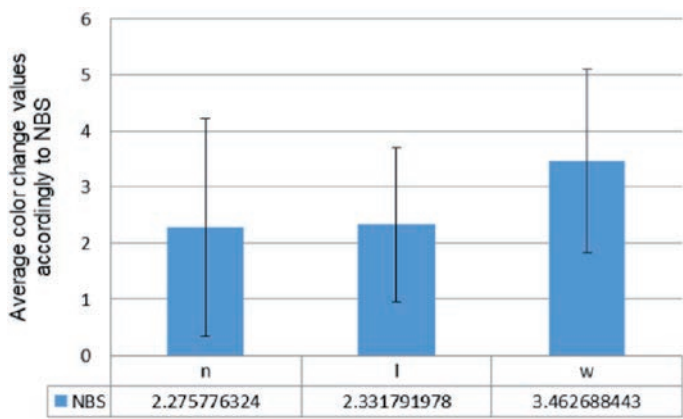


Figure 11.
 Average color changes and SD, related to luting material [46].

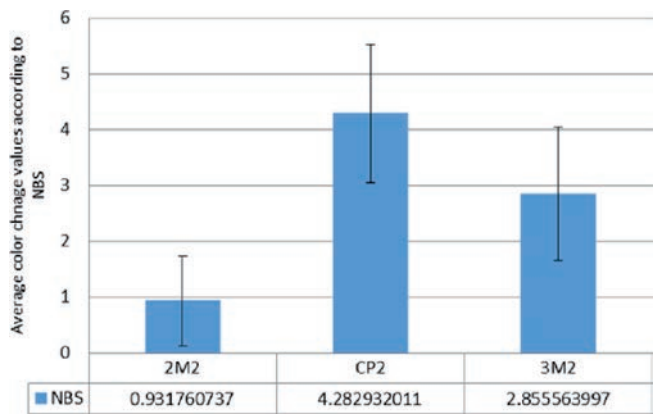


Figure 12.
 Average color changes and standard deviation (SD), related to substrate [46].

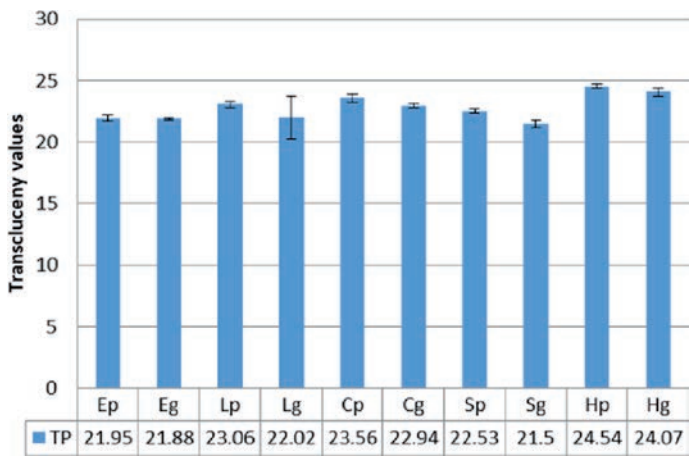


Figure 13.
 Translucency parameter average values of the tested samples with different try-in pastes and substrates [46].

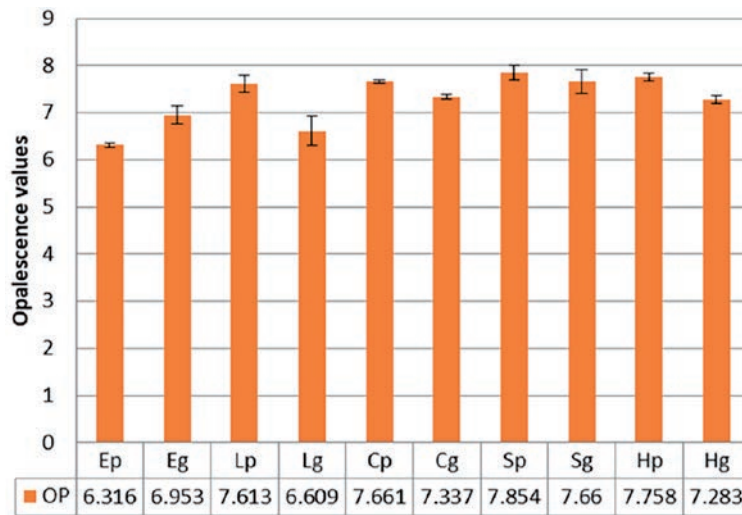


Figure 14.
Opalescence parameter average values of the tested samples with different try-in pastes and substrates [46].

changes, the ranking is: Shofu > Lava Ultimate > Cerasmart > Enamic > Hyramic (Figures 12–14) [46].

The average values for translucency parameter (TP) across all materials ranged from 21.49 to 24.53. The decreasing order of translucency was as follows: H > L > C > S > E. Significant differences were observed ($p < 0.005$) between H and all other materials, as well as between C and both S and E. Polished samples exhibited greater translucency compared to glazed samples [46]. The average values for the opalescence parameter (OP) ranged from 6.31 to 7.85. Both E and L showed similar values and had the lowest opalescence. C and H exhibited similar and higher values,

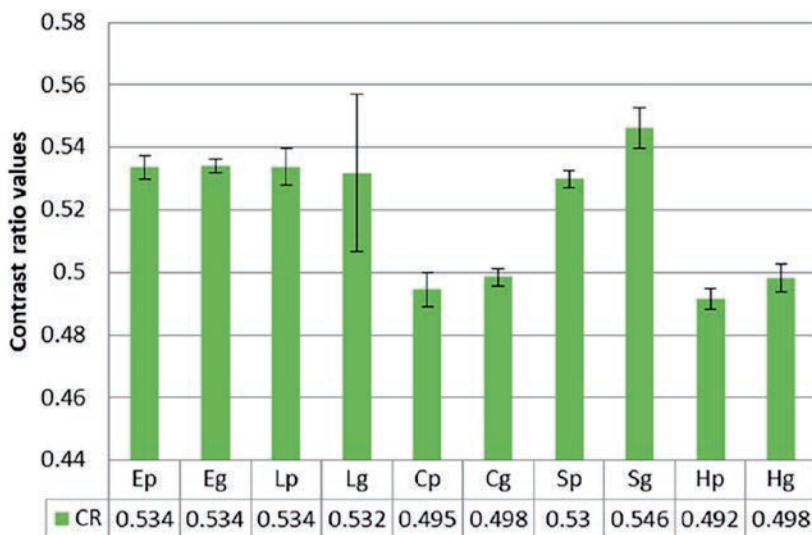


Figure 15.
Contrast ratio parameter average values of the tested samples with different try-in paste and substrate [46].

while S had the highest opalescence. In general, polished samples were more opalescent than glazed samples, except for E. A moderate positive correlation was found between OP and TP ($r = 0.406$), whereas a strong negative correlation was noted between CR and TP ($r = -0.867$) (**Figure 15**) [46].

Using NBS units, perceivable color changes were calculated. The average color changes among the materials decreased in the following order: Enamic > Hyramic > Cerasmart > Lava Ultimate > Shofu, with significant differences observed ($p < 0.05$) between E and S, as well as between H and L, and H and S [46].

5. Mechanical characteristics of hybrid dental ceramics

The information in this chapter was searched in the literature using the PubMed and Google Scholar engines, and also new information that was not published before was added.

Mechanical evaluation is primarily used in dentistry to characterize and assure the quality of newly developed materials. Over time, several academic organizations have developed standards for testing ceramics, including ISO 24370, ISO 23146, and ISO 6872 [49].

One standard test for measuring material hardness is the Vickers hardness test, which is designed for small and thin samples. This test employs a diamond indenter and a specific load to create an indentation in the material. The size of the indentation correlates inversely with the hardness of the tested material: Smaller indentations indicate harder materials. The Vickers test utilizes a pyramidal diamond indenter, and the applied force can range from 1 to 1000 grams force (gf). In contrast, microhardness analysis typically employs a force of 2 N, equivalent to approximately 200 gf. Indentation results generally measure around 50 micrometers (μm) [50].

In comparison with glass-ceramics, which possess a Martens hardness of 3843 N/mm², a Vickers hardness between 592 and 622, and an elastic modulus of 74–95 GPa for lithium disilicate, resin-based composites (RBCs) are characterized by lower elastic modulus and hardness values. This distinction facilitates easier milling and intraoral adjustment, reduces the likelihood of fracture and chipping, and minimizes wear on opposing dentition. Furthermore, unlike resinous composite materials utilized for direct restorations, CAD/CAM RBCs are polymerized under conditions of elevated pressure and temperature. This method enhances polymerization, resulting in increased density, diminished porosity, and a higher degree of monomer conversion, thereby significantly improving their mechanical properties [51, 52].

To ensure accurate indentation measurements, the samples must have smooth surfaces. The indentation is examined microscopically to achieve precise results. This technique involves applying a specific load to an indenter pressed onto a surface for 10 seconds, after which the resulting indentation is analyzed microscopically. Vickers microhardness test results for dental ceramics usually range from 6 to 9 gigapascals (GPa). The lowest hardness values are associated with leucite and feldspathic glass-ceramics, while the highest values are noted in lithium disilicate and zirconia-reinforced lithium silicate glass-ceramics [18]. Surface treatments, such as glazing and polishing, can produce varying results for the tested hybrid ceramic materials (**Figure 16**).

Figure 17 reveals statistically significant differences identified between the glazed and polished samples of hybrid matrix ceramics ($p \leq 0.05$). The application of a glaze layer exerts a considerable effect on the microhardness value. Between the materials, greater microhardness values were registered for glazed Hyramic,

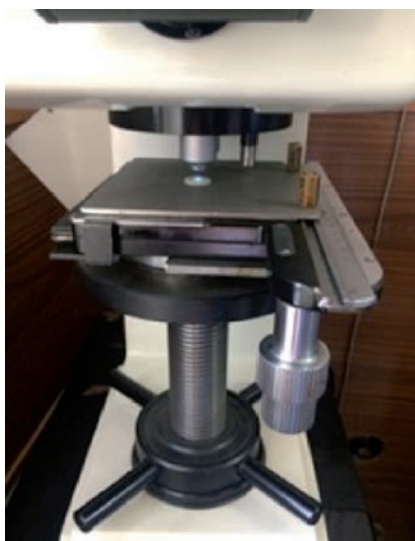


Figure 16.
Vickers microhardness equipment is used for hardness testing.

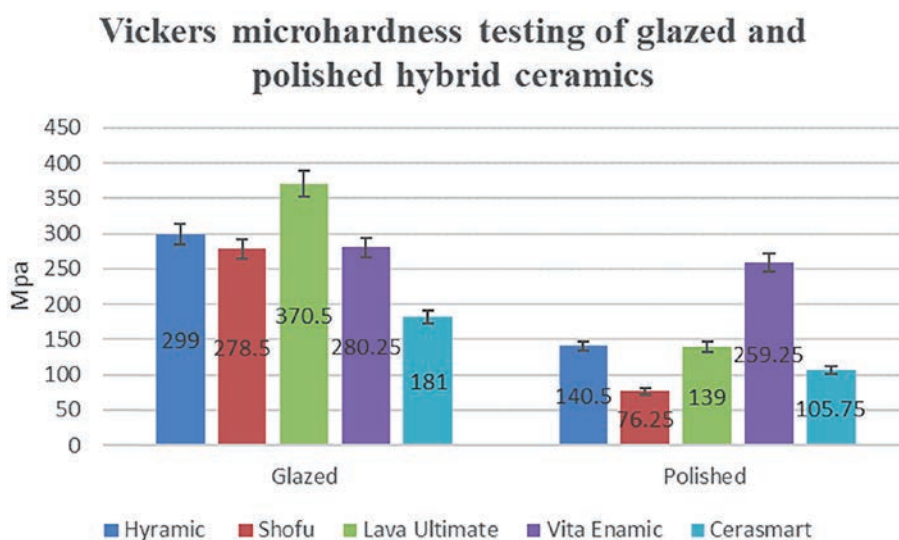


Figure 17.
Mean values and standard deviation for hybrid dental ceramics. This data comes from an original experiment and has not been published before.

followed by Lava Ultimate. In the polished group, higher values were registered for Vita Enamic and Hyramic.

In the field of research, various loading devices are used to evaluate the fracture strength of dental restorations. The mechanical resistance of dental ceramic restorations can be assessed through tests that apply specific loads. One standard method involves static loading until the ceramic crowns fracture. In these tests, the crowns are cemented onto abutments and placed in a testing machine, where a stylus exerts force until the crown breaks [18]. A fractographic analysis is performed to examine the

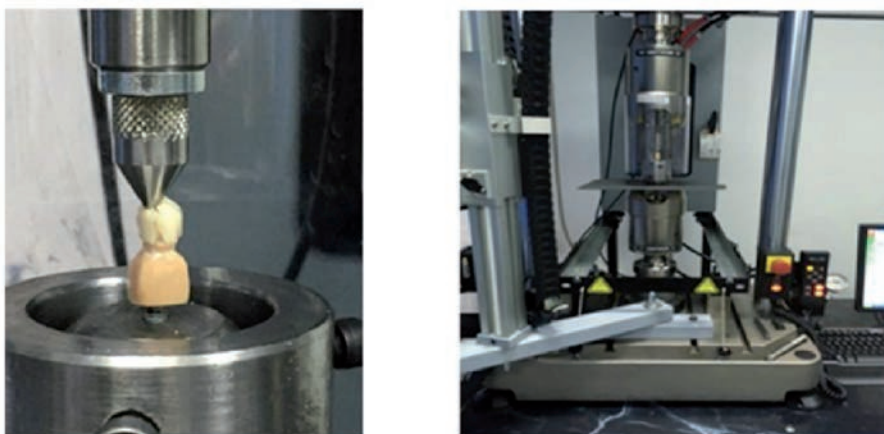


Figure 18.
Fractographic analysis using a static loading device.

resulting fragments and determine the origin and path of the fracture. A key tool for this analysis is the stereomicroscope. This equipment enables the three-dimensional visualization of samples, facilitating the observation of spatial relationships among the fragments. By utilizing various illumination angles, the stereomicroscope can also provide insights into the surface roughness of the samples being examined (**Figure 18**) [53].

Research indicates that the primary cause of failure in crowns is the propagation of a radial crack that extends throughout the material, ultimately leading to a complete bulk fracture.

Fractographic features, such as hackles, wake hackles, and arrest lines, indicate the origins of fractures [54].

Several evaluations of the surfaces can be conducted before and after aging processes to identify changes in the crystal structure that may lead to clinical failures. Non-destructive testing is valuable for detecting, locating, and measuring defects within hybrid resin ceramic structures. Measuring and assessing defects and porosity is essential, as they can influence the strength and longevity of restorations. Generally, ceramics exhibit some defects and porosity, while hybrid ceramics that incorporate resins may show interlaminar porosity and processing-induced gaps [55].

Examples of nondestructive structural analyses include computed tomography (CT) evaluation, ultrasonic testing, profilometry, atomic force microscopy (AFM), scanning electron microscopy (SEM), and environmental scanning electron microscopy (ESEM). Both computed tomography and ultrasonic analysis provide applicable evaluations of pores and cracks within the ceramic structures.

A study found in research literature investigated the fracture toughness of these ceramics. Fracture toughness was analyzed by the ISO standard ISO 6872. The stress intensity factor, K_{Ic} , was determined using four-point bending with a crosshead speed of 0.5 mm/min on a universal testing machine [56]. To calculate the mean depth of each notch, measurements were taken at three points on the fracture surfaces after K_{Ic} testing.

The analysis of fracture surfaces provided valuable insights into the varying microstructures of the materials that were tested. Each material exhibited distinct

roughness patterns on its fracture surfaces, which were influenced by its unique microstructural properties.

For the CAD/CAM resin composite materials, notable features included visible crack paths that traversed the matrix and the interfaces between the matrix and the filler particles. These observations were made at a microscale, highlighting the complex interactions within the composite. Additionally, microcracks, which are smaller than typical cracks, were identified, indicating the materials' susceptibility to stress at a finer level [55].

Interestingly, although crack bridging—a phenomenon in which the surrounding material holds cracks together—was not directly observed on the fracture surfaces, the findings still suggested that the material's structure might influence crack behavior. Furthermore, solid particle breaks were uniformly absent in all tested materials. However, specifically for Lava Ultimate and the experimental CAD/CAM composite, cut and fractured filler agglomerates were observed at the prepared notches, indicating that the mechanical processing and formulation of these composites significantly influence their fracture behavior. This detailed examination underscores the importance of understanding the microstructural characteristics in predicting the performance and durability of dental materials [55].

6. Marginal adaptability assessment of hybrid matrix dental ceramics

Excellent marginal adaptation positively influences percolation and plaque buildup, limiting them to some extent. The term “marginal gap” refers to the space between a restoration's crown and the tooth's preparation line. There are also inner gaps, which are the spaces between the inner part of the restoration and the tooth structure. The gap at the edge is referred to as the marginal demarcation gap. Typically, these gaps arise from morphological discrepancies between the tooth and the restoration [57].

The finish line configuration is essential in achieving a good marginal fit. Comparisons between chamfer finish lines and straight finish lines showed that the former had lower marginal gap values. Another study compared shoulder margins with rounded internal angles to chamfer lines and found no significant differences. However, it was noted that chamfered finish lines led to wider marginal gaps compared to rounded shoulders [24].

The space created by cement between the crown and the abutment of the teeth also affects the marginal fit of ceramic crowns. If this space is too small, it may hinder the evacuation of excess cement, thereby increasing the marginal gap. A study concluded that cementation could negatively impact adaptation, and fine-grained cement yielded better long-term results. Some research has suggested that the marginal gap can significantly increase after cementation due to hydraulic pressure and the evacuation of cement [58].

Different measuring methods have been developed, which can affect the final values for the marginal adaptability of all-ceramic crowns. Impression techniques and visual examinations rely on the researcher's experience, often influenced by subjectivity. The location of the demarcation line also impacts the assessment; it is typically more challenging to evaluate marginal gaps objectively when the line is subgingival. The most commonly used method is the replica technique, which employs low-viscosity silicone; however, it may produce inaccurate results due to potential damage when the silicone impression is removed from the die. Other measurement methods

include profilometry, scanning electron microscopy (SEM), optical stereomicroscopy, and micro-computed tomography (micro-CT).

Resin matrix ceramics (RMCs) comprise a highly infiltrated organic matrix containing ceramic particles, resulting in a modulus of elasticity that is closer to that of dentin than that of conventional ceramics. Due to their excellent properties, these CAD/CAM resins are also suitable for endocrowns in endodontically treated teeth. Both the marginal and internal adaptations of endocrowns significantly affect their clinical outcomes. When the marginal adaptation of restorations is poor, the dissolution of the cement over time can lead to endodontic and periodontal inflammation due to bacterial microleakage, failing the prosthesis.

A research study in the literature regarding the internal adaptability of resin matrix ceramics, revealed a wide range of values, from 7.5 to 206.3 μm . This variation can be attributed to several factors, including the methods used to assess adaptation, the materials selected, the nature of the dental preparation, the impression materials and techniques employed, the type of cement, and the cementation process [59].

7. Water sorption impact on optical and mechanical properties of hybrid resin ceramics

A key consideration in the performance of resin composites is their water sorption rate, which directly affects their mechanical, physical, and optical properties.

Water sorption in dental composites primarily occurs within the resin matrix and is influenced by the resin's chemical composition, the polymerization process, and the concentration of fillers. This process involves water molecules diffusing into the polymer matrix, filling spaces between the molecular chains, which can lead to swelling and dimensional changes [60].

The type of dental composite and its specific formulation significantly determine the degree of water sorption. For instance, composites with a higher filler content generally exhibit lower water sorption because there is less available volume in the resin matrix for water molecules to occupy. Additionally, the choice of resin monomer is critical; specific monomers, like Bis-GMA (bisphenol A-glycidyl methacrylate), are more prone to water sorption due to the presence of hydroxyl groups in their structures.

Water sorption in hybrid resin ceramics predominantly occurs in the resin matrix, depending on the resin's chemical composition, polymerization, and filler concentration. Water sorption is the process by which water molecules diffuse into the polymer matrix, filling the gaps between polymer chains, which can cause swelling and dimensional changes [61].

The type of hybrid dental ceramic and its composition influence the extent of water sorption. For example, composites with a higher filler content tend to have lower water sorption, as the volume of the resin matrix available for water sorption is lower. The type of resin monomer also plays a crucial role; due to the nature of the hydroxyl groups in the monomer structure, monomers such as Bis-GMA (bisphenol A-glycidyl methacrylate) are more susceptible to water sorption [62].

The clinical performance of dental materials is significantly influenced by their ability to absorb water, known as water sorption. In resin composites, excessive water absorption can lead to various detrimental effects on restorative materials. For instance, it can cause noticeable color changes, compromising the esthetic appeal of dental restorations. Furthermore, this absorption can weaken the mechanical properties of the materials, making them more susceptible to fractures or wear over time.

Reduced wear resistance can ultimately shorten the lifespan of a restoration. Simultaneously, the breakdown of chemical bonds at the interface between the resin and filler can further undermine the material's structural integrity. In addition to these concerns, the solubility of materials plays a crucial role in their biocompatibility. Increased solubility can lead to decreases in both volume and strength, potentially compromising the restoration's durability. Furthermore, this disruption can cause discoloration as the bond between the filler and resin matrix weakens, detracting from the overall esthetics of dental work. Therefore, understanding and managing water sorption and solubility are essential for enhancing the longevity and performance of dental restorative materials. Hydrophilic materials exhibit a pronounced susceptibility to color changes and staining, predominantly influenced by the volume of water they absorb. This absorption process can lead to significant alterations in mechanical properties, including reductions in strength and elastic modulus, primarily due to the plasticization of the resin matrix. Additionally, as water is absorbed, it may facilitate the leaching of unreacted monomers and various degradation products, posing potential health risks to individuals. From a clinical standpoint, these changes can manifest as visible discoloration, a reduction in bond strength, and an increased likelihood of restoration failure over time [63].

A critical relationship exists between the quantity of absorbed water and the solubility of the materials involved. The presence of absorbed water enables the dissolution of specific components, including unreacted monomers and various additives, which can potentially compromise the material's integrity. The solubility of the polymer network is intricately linked to its crosslink density, as well as the specific type of filler employed. Composites with a higher crosslink density typically exhibit enhanced resistance to dissolution, allowing them to maintain their mechanical strength and structural stability over prolonged periods, thereby improving their longevity and performance in clinical applications.

The clinical performance of dental materials is significantly influenced by water sorption. Water absorption in resin matrix ceramics can negatively impact restorative materials in several ways: it can alter their color, weaken their mechanical properties, reduce wear resistance, and disrupt the chemical bonds at the resin-filler interface. Additionally, solubility can affect the biocompatibility of these materials, decrease their volume and strength, and cause discoloration by interfering with the bond between the filler and resin within the matrix.

8. Biocompatibility of hybrid resin ceramics

Another essential characteristic of hybrid resin ceramics is their excellent biocompatibility. A study in the research literature involving human gingival fibroblasts (HGFs) demonstrated strong adhesion and proliferation on cured pure resin, hydroxyapatite/bioactive glass (HA/BAG) ceramics, and hybrid polymer-ceramic materials after an initial 48-hour culture period. The cells displayed a typical elongated fusiform morphology, indicating a healthy cellular state. Over time, particularly at the 72-hour mark, there was a notable increase in both the number and surface coverage of HGFs. The arrangement of these cells also became more compact. Importantly, no signs of cellular distress, such as rounded or floating cells, were observed, suggesting that the culture conditions were conducive to cell survival and growth [64, 65].

9. Conclusions

The following conclusions can be drawn regarding hybrid resin ceramics.

Hybrid resin ceramic materials offer significant esthetic advantages, and continuous development in digital workflows will lead to further advancements. Hybrid resin ceramics are the subject of numerous new research studies, with the primary concerns being the enhancement of mechanical properties while maintaining their excellent esthetic properties.

Recent advancements in resin ceramics materials have opened up numerous avenues for exploration, which could significantly enhance product quality and patient satisfaction. These resin ceramic materials must exhibit critical properties such as optical clarity, structural integrity, mechanical strength, and long-term marginal adaptation.

The optical properties of hybrid dental ceramics are significantly influenced by their chemical composition and the dimensions of their crystalline structures. A comprehensive understanding of these properties is essential, particularly in the fields of dentistry and materials science. Three primary phenomena are instrumental in determining the optical transparency of ceramics: refraction, deflection, and total light transmission. The translucency parameter of hybrid dental ceramics closely resembles that of natural teeth, with values ranging from 19 to 24. This indicates that these hybrid resin ceramics are appropriate for anterior restorations. After undergoing thermal aging and brushing—two methods to simulate the oral environment—the Cerasmart ceramic demonstrated the highest translucency parameter values.

The underlying dental structure, luting agent, and restoration material significantly impact the esthetic quality of the restoration. Warm try-in pastes associated with non-discolored substrates can cause noticeable color changes. However, when used with dark-colored substrates, they can lead to significant color changes. For substrates that are darker in color, warm try-in pastes result in substantial color changes. In contrast, neutral and light try-in pastes produce only minimal noticeable changes when used with resin composite ceramic materials that have demonstrated superior masking abilities.

The microstructure of ceramic materials plays a crucial role in determining the topographical features and microhardness characteristics of these ceramics. Each category exhibits distinct microstructural arrangements, which directly influence how these materials respond to mechanical stress and environmental factors. Understanding these microstructural differences is essential for optimizing the performance and applications of glass-ceramics in various fields, including engineering, dentistry, and electronics.

Long-term clinical performance of is profoundly influenced by water sorption. The absorption of water in resin matrix ceramics can have adverse effects on restorative materials in multiple ways. It can lead to alterations in color, a reduction in mechanical properties, diminished wear resistance, and disruption of the chemical bonds at the resin-filler interface. Furthermore, the solubility of these materials can have implications for biocompatibility, resulting in decreased volume and strength, as well as causing discoloration by interfering with the bond between the filler and the resin within the matrix.

All the studies included in this work with significant results demonstrate that these CAD/CAM hybrid ceramics possess excellent optical and mechanical properties. This behavior makes them suitable for long-term successful restorations.

Original *data* and also *results* found in the literature were added in this chapter about hybrid resin ceramics. The results found in the literature were searched in PubMed and Google Scholar research engines.

Acknowledgements

We would like to acknowledge VICTOR BABES UNIVERSITY OF MEDICINE AND PHARMACY, TIMISOARA, for their support in covering the costs of publication for this paper.

Conflict of interest

The authors declare no conflict of interest.

Author details

Roxana-Diana Vasiliu*, Bejan Flavia Roxana and Liliana Porojan
Department of Dental Prostheses Technology (Dental Technology), Center for Advanced Technologies in Dental Prosthodontics, Faculty of Dentistry, “Victor Babeș” University of Medicine and Pharmacy, Timișoara, Romania

*Address all correspondence to: roxana.vasiliu@umft.ro

IntechOpen

© 2025 The Author(s). Licensee IntechOpen. This chapter is distributed under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/4.0>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited. 

References

- [1] Acar O, Yilmaz B, Altintas S, Chandrasekaran I, Johnston W. Color stability of CAD/CAM and nanocomposite resin materials. *The Journal of Prosthetic Dentistry*. 2016;**115**:71-75. DOI: 10.1016/j.prosdent.2015.06.014
- [2] Argyrou R, Thompson G, Cho S, Berzins D. Edge chipping resistance and flexural strength of polymer infiltrated ceramic network and resin nanoceramic restorative materials. *The Journal of Prosthetic Dentistry*. 2016;**116**:397-403. DOI: 10.1016/j.prosdent.2016.02.014
- [3] Awada A, Nathanson D. Mechanical properties of resin ceramic CAD/CAM restorative materials. *The Journal of Prosthetic Dentistry*. 2015;**114**:587-593. DOI: 10.1016/j.prosdent.2015.04.016
- [4] Della Bona A, Corazza PH, Zhang Y. Characterization of a polymer-infiltrated ceramic-network material. *Dental Materials*. 2014;**30**:564-569. DOI: 10.1016/j.dental.2014.02.019
- [5] Spitznagel F, Boldt J, Gierthmuehlen P. CAD/CAM ceramic restorative materials for natural teeth. *Journal of Dental Research*. 2018;**97**:1082-1091. DOI: 10.1177/0022034518779759
- [6] Aslan Y, Coskun E, Ozkan Y. Clinical evaluation of three types of CAD/CAM inlay/onlay materials after 1-year clinical follow-up. *The European Journal of Prosthodontics and Restorative Dentistry*. 2019;**27**:131-140. DOI: 10.1922/EJPRD_01891Aslan10
- [7] Coşkun E, Aslan Y, Özkan Y. Evaluation of two different CAD-CAM inlay-onlays in a split-mouth study: 2-year clinical follow-up. *Journal of Esthetic and Restorative Dentistry*. 2020;**32**:244-250. DOI: 10.1111/jerd.12541
- [8] Spitznagel F, Scholz K, Strub J. Polymer-infiltrated ceramic CAD/CAM inlays and partial coverage restorations: 3-year results of a prospective clinical study over 5 years. *Clinical Oral Investigations*. 2018;**22**:1973. DOI: 10.1007/s00784-017-2293-x
- [9] Lu T, Peng L, Xiong F. A 3-year clinical evaluation of endodontically treated posterior teeth restored with two different materials using the CEREC AC chair-side system. *The Journal of Prosthetic Dentistry*. 2018;**119**:363-368. DOI: 10.1016/j.prosdent.2017.04.022
- [10] Coldea A, Swain MV, Thiel N. Mechanical properties of polymer-infiltrated-ceramic-network materials. *Dental Materials*. 2013;**29**(419):426. DOI: 10.1016/j.dental.2013.01.002
- [11] Bajraktarova-Valjakova E, Korunoska-Stevkovska V, Kapusevska B, Gigovski N, Bajraktarova-Misevska C, Grozdanov A. Contemporary dental ceramic materials, A review: Chemical composition, physical and mechanical properties, indications for use. *Open Access Macedonian Journal of Medical Sciences*. 2018;**6**(9):1742-1755. DOI: 10.3889/oamjms.2018.378
- [12] Porojan L, Vasiliu RD, Bîrdeanu MI, Porojan SD. Surface characterisation of dental resin composites related to conditioning and finishing. *Polymers (Basel)*. 2021;**13**(23):4236. DOI: 10.3390/polym13234236
- [13] Silva L, Lima E, Miranda R, Favero S, Lohbauer U, Cesar PF. Dental ceramics: A review of new materials and processing methods. *Brazilian*

- Oral Research. 2017;**31**(suppl 1):e58. DOI: 10.1590/1807-3107BOR-2017.vol31.005832. =8
- [14] Griggs JA. Recent advances in materials for all-ceramic restorations. *Dental Clinics of North America*. 2007;**51**(3):713-727, viii. DOI: 10.1016/j.cden.2007.04.006
- [15] Mainjot A. Recent advances in composite CAD/CAM blocks. *International Journal of Esthetic Dentistry*. 2016;**11**(2):275-280
- [16] Munch E, Launey M, Alsem D, Saiz E, Tomsia A, Ritchie R. Tough, bio-inspired hybrid materials. *Science*. 2008;**322**(5907):1516-1520. DOI: 10.1126/science.1164865
- [17] Suárez M, González de Villaumbrosia P, Pradíes G, Lozano J. Comparison of the marginal fit of Procera AllCeram crowns with two finish lines. *The International Journal of Prosthodontics*. 2003;**16**(3):229-232
- [18] Quintas A, Oliveira F, Bottino M. Vertical marginal discrepancy of ceramic copings with different ceramic materials, finish lines, and luting agents: An in vitro evaluation. *The Journal of Prosthetic Dentistry*. 2004;**92**(3):250-257. DOI: 10.1016/j.prosdent.2004.06.023
- [19] Okutan M, Heydecke G, Butz F, Strub JR. Fracture load and marginal fit of shrinkage-free ZrSiO₄ all-ceramic crowns after chewing simulation. *Journal of Oral Rehabilitation*. 2006;**33**(11):827-832. DOI: 10.1111/j.1365-2842.2006.01637.x
- [20] Flury S, Lussi A, Zimmerli B. Performance of different polishing techniques for direct CAD/CAM ceramic restorations. *Operative Dentistry*. 2010;**35**(4):470-481. DOI: 10.2341/09-373-L
- [21] Rueda AO, Seuba J, Anglada M, Jiménez-Piqué E. Tomography of indentation cracks in feldspathic dental porcelain on zirconia. *Dental Materials*. 2013;**29**(3):348-356. DOI: 10.1016/j.dental.2013.01.001
- [22] Lu Y, Tseng H, Shih Y, Lee SY. Effects of surface treatments on bond strength of glass-infiltrated ceramics. *Journal of Oral Rehabilitation*. 2001;**28**(9):805-813. DOI: 10.1046/j.1365-2842.2001.00735.x
- [23] Burgo TAL, Pereira GKR, Iglesias BA, Moreira KS, Valandro LF. AFM advanced modes for dental and biomedical applications. *Journal of the Mechanical Behavior of Biomedical Materials*. 2022;**136**:105475. ISSN 1751-6161. DOI: 10.1016/j.jmbbm.2022.105475
- [24] Bindl A, Mörmann W. Clinical and SEM evaluation of all-ceramic chair-side CAD/CAM-generated partial crowns. *European Journal of Oral Sciences*. 2003;**111**(2):163-169. DOI: 10.1034/j.1600-0722.2003.00022.x
- [25] Jevremovic D, Ajdukovic Z, Stankovic S, Radosavljevic R. Profilometric and SEM analyses of composite surfaces after excess cement removal. *Hemijaska Industrija*. 2012;**66**(1):59-66. DOI: 10.2298/HEMIND110406069J
- [26] Guazzato M, Albakry M, Swain MV, Ironside J. Mechanical properties of In-Ceram alumina and In-Ceram zirconia. *The International Journal of Prosthodontics*. 2002;**15**(4):339-346
- [27] Hurle K, Belli R, Götz-Neunhoeffler F, Lohbauer U. Phase characterization of lithium silicate biomedical glass-ceramics produced by two-stage crystallization. *Journal of Non-Crystalline Solids*. 2019;**510**(42):50. DOI: 10.1016/j.jnoncrysol.2019.01.027

- [28] Mörmann W, Stawarczyk B, Ender A, Sener B, Attin T, Mehl A. Wear characteristics of current aesthetic dental restorative CAD/CAM materials: Two-body wear, gloss retention, roughness and martens hardness. *Journal of the Mechanical Behavior of Biomedical Materials*. 2013;**20**:113-125. DOI: 10.1016/j.jmbbm.2013.01.003
- [29] Dirxen C, Blunck U, Preissner S. Clinical performance of a new biomimetic double network material. *The Open Dentistry Journal*. 2013;**7**:118-122. DOI: 10.2174/1874210620130904003
- [30] Burke F, Crisp R, Cowan A, Lamb J, Thompson O, Tulloch N. Five-year clinical evaluation of zirconia-based bridges in patients in UK general dental practices. *Journal of Dentistry*. 2013;**41**(11):992-999. DOI: 10.1016/j.jdent.2013.08.007
- [31] Buyukkaplan SU, Özarslan MM, Barutçigil Ç, Arslan M, Barutçigil K, Yoldan EE. Effects of staining liquids and finishing methods on translucency of a hybrid ceramic material having two different translucency levels. *Journal of Advanced Prosthodontics*. 2017;**9**(5):387-393. DOI: 10.4047/jap.2017.9.5.387
- [32] Lee YK. Translucency of human teeth and dental restorative materials: Their clinical relevance. *Journal of Biomedical Optics*. 2015;**20**(4):045002. DOI: 10.1117/1.JBO.20.4.045002
- [33] Ahn J, Lee Y. Difference in the translucency of all-ceramics by the illuminant. *Dental Materials*. 2008;**24**(11):1539-1544. DOI: 10.1016/j.dental.2008.03.020
- [34] Jiang Y, Zhang C, Xu J, Xu J, Zhan X-Q, Ma N, et al. An overview of dental glass–ceramics: From material design to the manufacturing process. *International Journal of Ceramic Engineering and Science*. 2024;**4**. DOI: 10.1002/ces2.10224
- [35] Chen Y, Smales R, Yip K, Sung W. Translucency and biaxial flexural strength of four ceramic core materials. *Dental Materials*. 2008;**24**(11):1506-1511. DOI: 10.1016/j.dental.2008.03.010
- [36] Ferracane JL. Resin composite—State of the art. *Dental Materials*. 2011;**27**(1):29-38. DOI: 10.1016/j.dental.2010.10.020
- [37] Kerby RE, Knobloch LA, Schricker S, Gregg B. Synthesis and evaluation of modified urethane dimethacrylate resins with reduced water sorption and solubility. *Dental Materials*. 2009;**25**:302-313
- [38] Alamoush RA, Sung R, Satterthwaite JD, Silikas N. The effect of different storage media on the monomer elution and hardness of CAD/CAM composite blocks. *Dental Materials*. 2021;**37**:1202-1213. DOI: 10.1016/j.dental.2021.04.009
- [39] Alamoush R, Salim N, Silikas N, Satterthwaite J. Long-term hydrolytic stability of CAD/CAM composite blocks. *European Journal of Oral Sciences*. 2022;**130**:e12834. DOI: 10.1111/eos.12834
- [40] Paravina RD, Ontiveros JC, Powers JM. Curing-dependent changes in color and translucency parameter of composite bleach shades. *Journal of Esthetic and Restorative Dentistry*. 2002;**14**(3):158-166. DOI: 10.1111/j.1708-8240.2002.tb00516.x
- [41] Wang YJ, Chu TG, Lin WS. Translucency parameter and color masking ability of CAD-CAM denture base materials against metal substrates. *Journal of Prosthodontics*. 2023;**32**(S1):61-67. DOI: 10.1111/jopr.13581

- [42] Mirică I, Furtos G, Bâldea B, Lucaciu O, Ilea A, Moldovan M. Influence of filler loading on the mechanical properties of flowable resin composites. *Materials*. 2020;**13**:1477. DOI: 10.3390/ma13061477
- [43] Porojan L, Toma F, Uțu I, Vasiliu R. Optical behavior and surface analysis of dental resin matrix ceramics related to thermocycling and finishing. *Applied Sciences*. 2022;**12**:4346. DOI: 10.3390/app12094346
- [44] Douglas R, Steinhauer T, Wee A. Intraoral determination of the tolerance of dentists for perceptibility and acceptability of shade mismatch. *The Journal of Prosthetic Dentistry*. 2007;**97**(4):200-208. DOI: 10.1016/j.prosdent.2007.02.012
- [45] Mahrous A, Alhammad A, Alqahtani F, Aljar Y, Alkadi A, Taymour N, et al. The toothbrushing effects on surface properties and color stability of CAD/CAM and pressable ceramic fixed restorations-An in vitro study. *Materials (Basel)*. 7 Apr 2023;**16**(8):2950. DOI: 10.3390/ma16082950
- [46] Porojan L, Vasiliu RD, Porojan SD. Masking abilities of dental CAD/CAM resin composite materials related to substrate and luting material. *Polymers (Basel)*. 2022;**14**(3):364. DOI: 10.3390/polym14030364
- [47] Taskonak B, Mecholsky JJ Jr, Anusavice KJ. Fracture surface analysis of clinically failed fixed partial dentures. *Journal of Dental Research*. 2006;**85**:277-281. DOI: 10.1177/154405910608500314
- [48] Shenoy A, Shenoy N. Dental ceramics: An update. *Journal of Conservative Dentistry*. 2010;**13**:195-203. DOI: 10.4103/09720707.73379
- [49] Mclean JW. Evolution of dental ceramics in the twentieth century. *The Journal of Prosthetic Dentistry*. 2001;**85**:61-66. DOI: 10.1067/mpr.2001.112545
- [50] Davis S. Color Perception—Philosophical, Psychological, Artistic, and Cognitive Perspectives. New York: Oxford University Press; 2000. pp. 88-90. DOI: 10.2307/40865895
- [51] Mainjot AK, Dupont NM, Oudkerk JC, Dewael TY, Sadoun MJ. From artisanal to CAD-CAM blocks: State of the art of indirect composites. *Journal of Dental Research*. 2016;**95**(5):487-495. DOI: 10.1177/0022034516634286
- [52] Inami T, Tanimoto Y, Minami N, Yamaguchi M, Kasai K. Color stability of laboratory glass-fiber-reinforced plastics for esthetic orthodontic wires. *Korean Journal of Orthodontics*. 2015;**45**(3):130-135. DOI: DOI10.4041/kjod.2015.45.3.130
- [53] Moressi A, D’Amario M, Monaco A. Effect of critical thermal cycling on the flexural strength of resin composites. *Journal of Oral Science*. 2015;**57**:137-143. DOI: 10.2334/josnurd.57.137
- [54] Turgut S, Bagis B. Colour stability of laminate veneers: An in vitro study. *Journal of Dentistry*. 2011;**39**(Suppl 3):e57-e64. DOI: 10.1016/j.jdent.2011.11.006
- [55] Hampe R, Theelke B, Lümekemann N, Eichberger M, Stawarczyk B. Fracture toughness analysis of ceramic and resin composite CAD/CAM material. *Operative Dentistry*. 2019;**44**(4):E190-E201. DOI: 10.2341/18-161-L
- [56] Morresi A, D’Amarino M, Capogreco M, Gatto R, Marzo G, D’Arcangelo C, et al. Thermal cycling

for restorative materials: Does a standardized protocol exist in laboratory testing? A literature review. *Journal of the Mechanical Behavior of Biomedical Materials*. 2014;**29**:29295-29308. DOI: 10.1016/j.jmbbm.2013.09.013

[57] Contrepolis M, Soenen A, Bartala M, Laviole O. Marginal adaptation of ceramic crowns: A systematic review. *The Journal of Prosthetic Dentistry*. 2013;**110**(6):447-454.e10. DOI: 10.1016/j.prosdent.2013.08.003

[58] Mertsöz B, Ongun S, Ulusoy M. In-vitro investigation of marginal adaptation and fracture resistance of resin matrix ceramic endo-crown restorations. *Materials*. 2023;**16**:2059. DOI: 10.3390/ma16052059

[59] Islam MS, Nassar M, Elsayed M, Jameel D, Ahmad T, Rahman MM. In vitro optical and physical stability of resin composite materials with different filler characteristics. *Polymers*. 2023;**15**:2121. DOI: 10.3390/polym15092121

[60] Perdigão J, Araujo E, Ramos RQ, Gomes G, Pizzolotto L. Adhesive dentistry: Current concepts and clinical considerations. *Journal of Esthetic and Restorative Dentistry*. 2021;**33**(1):51-68. DOI: 10.1111/jerd.12692

[61] Araujo E, Perdigão J. Anterior veneer restorations—An evidence-based minimal-intervention perspective. *The Journal of Adhesive Dentistry*. 2021;**23**(2):91-110. DOI: 10.3290/j.jad.b1079529

[62] Ortengren U, Wellendorf H, Karlsson S, Ruyter IE. Water sorption and solubility of dental composites and identification of monomers released in an aqueous environment. *Journal of Oral Rehabilitation*. 2001;**28**(12):1106-1115. DOI: 10.1046/j.1365-2842.2001.00802.x

[63] Al-Bader RM, Ziadan KM, Al-Ajely MS. Water adsorption characteristics of new dental composites. *International Journal of Medical Research and Health Sciences*. 2015;**4**:281. DOI: 10.5958/2319-5886.2015.00052.1

[64] Chen Y, Sun C, Cao J, Wu Y, Cui B, Ma J, et al. Mechanical properties and in vitro biocompatibility of hybrid polymer-HA/BAG ceramic dental materials. *Polymers*. 2022;**14**:3774. DOI: 10.3390/polym14183774

[65] Fathy H, Hamama HH, El-Wassefy N, Mahmoud SH. Clinical performance of resin-matrix ceramic partial coverage restorations: A systematic review. *Clinical Oral Investigations*. 2022;**26**(5):3807-3822. DOI: 10.1007/s00784-022-04449-2

Anxiety Management in Dental Prosthetics

*Gabriela Ciavoi, Alexandra Roxana Cristea
and Sergiu-Mihai Ciavoi*

Abstract

Dental procedures often cause anxiety in patients, and prosthetic procedures are similarly stressful. Both physical and psychological stressors contribute to anxiety in relation to prosthetic treatment. The oral anesthesia needed for pre-prosthetic or pro-prosthetic therapy, as well as the uncertainty surrounding the next treatments (dental preparation, taking impressions, recording occlusion, etc.), are frequently linked to anxiety. The final result of prosthetic therapy, the functional or esthetic aspects of future work, and the change from a fixed denture to a removable one or implant-supported can all be contributing factors to anxiety. Anxiety prevention, communication, relaxation techniques, breathing, music therapy, hypnosis, self-hypnosis, homeopathic and allopathic medication, and sedation are some of the many strategies used to treat patient anxiety. These factors can affect a patient's compliance with therapy and their satisfaction with prosthetic rehabilitation. Therefore, the dentist needs to be knowledgeable about them and take these factors into consideration.

Keywords: anxiety, dentures, prosthetic, stress factors, management

1. Introduction

The main goal of all prosthetic treatments is to obtain an exceptional esthetic and functional result. The effectiveness of prosthetic therapy depends on several circumstances, but the development of materials and treatment techniques makes this objective easier to accomplish. The technical aspect of treatment is sometimes overlooked in favor of the human element in the collection of information in the field of oral rehabilitation, which occurs in both college and professional workshops and congresses.

With daily clinical experience, the dentist notices that there are differences in the success of the treatment depending on the patient. This fact makes him pay more attention to the patient he is treating and differentiate his approach.

One of the factors that can influence the final outcome of a prosthetic treatment is the patient's anxiety. Anxiety can manifest itself regardless of the type of prosthetic restoration (fixed or removable). It can be triggered before, during, or after the completion of the treatment [1]. There are a multitude of stress factors that trigger anxiety related to prosthetic treatment, but their action as well as the coping mechanisms of the patients are strictly individual [2–6].

Why do we need to know these aspects related to anxiety? An anxious patient will avoid prosthetic treatment, which will lead to its complications (bone resorption, tooth migration, extensive edentulism, etc.). Also, the anamnesis, collaboration, and communication during the treatment will be deficient with an anxious patient. Finally, posttreatment, anxiety related to adaptation to the prosthetic work or its resistance over time may appear [1].

The management of anxiety related to prosthetic treatment should be a concern for the dentist because the success of the treatment, the patient's satisfaction and, implicitly, professional success will depend on its management.

Acquiring knowledge related to the patient's psychology, personality, differences related to the environment of origin, sex, age, and notions of effective communication and stress management are mandatory for any prosthodontist today [3–5]. Homeopathic and allopathic methods of reducing anxiety, adapted to each case, should not be omitted either. Also, collaboration with a psychologist or psychiatrist should be considered when necessary.

2. Anxiety, stress factors, coping mechanisms

Anxiety is a common health condition that affects many people. Anxiety is actually a natural emotion that prepares us for a change. It should not normally affect our daily activities but only help us to act appropriately when we are faced with a challenge [7]. When the demands exceed the individual's capacity to act, anxiety becomes a problem that interferes with the person's tasks. Studies [3] suggest that over 70% of the population who present themselves to the dental practice for treatment suffer from anxiety [4].

Anxiety is characterized by an unpleasant and uncertain feeling of discomfort that can be in the form of simple fear or can gradually increase to phobia. The accompanying symptomatology is both physical and psychological. Physical manifestations can be: palpitations, tremors, sweating, abdominal pain, nausea, frequent urination, and diarrhea. Mental manifestations can be: irritability, headaches, and inability to concentrate. Symptoms differ from one person to another and are more or less visible [6, 8].

It is known that anxiety can frequently occur during dental treatment. Prosthetic treatment is the most complex dental treatment. Most often, it is preceded by surgical treatments (extractions, resections, dental implants), orthodontic, endodontic, and odontal therapy, which can trigger anxiety but also the prosthetic treatment itself can be potentially stressful. That is why it is important to consider the management of the patient's anxiety from the first contact with him and even after the completion of the treatment.

Anxiety related to prosthetic treatment is not triggered by the same factors and does not have the same form of manifestation in all patients. It depends on generalized anxiety and depression, age, sex, background, personality, profession, level of education, and previous experience related to treatment, but it can also be influenced by a 'moment factor' in that moment which the patient is [3, 5, 9, 10]. In most cases, the cause of dental anxiety is a combination of predisposing and triggering factors.

Coping mechanisms also vary, ranging from masking anxiety or avoiding treatment to physical and psychological manifestations in various forms. Some patients manage to mask anxiety and deny its existence, but this is not beneficial because the outcome of the treatment can be compromised. Other patients postpone treatment,

or have anxiety manifestations during its course; for some, this anxiety manifests more physically, while for others it manifests predominantly psychologically [10]. It has been found that anxious patients who go to treatment have adaptive coping mechanisms, while those who avoid treatment tend to adopt an attitude of catastrophizing and despair [11, 12].

3. Anxiety in partial and total edentulism treatments

3.1 Anxiety before treatment

The decision for prosthetic rehabilitation frequently comes after a long deliberation on the part of the patient. In the case of partial or total edentulism, the patient has a history of more or less traumatic dental extractions and in the vast majority of cases a history of neglected complicated dental diseases that have caused suffering [1]. In the case of tooth loss due to periodontal diseases, the patient's history is marked by physical and mental suffering in trying to keep the remaining teeth in the arch for as long as possible. Moreover, single-tooth prosthodontics, even in the absence of prior dental extractions, do not come without anxiety; the tension associated with esthetic restoration exists.

At this stage, the factors that can trigger anxiety are [13]:

- the search process for an 'ideal' dentist
- the financial factor
- the time factor
- the perspective of pain
- erroneous information
- feeling embarrassed or ashamed

When presenting to the dental practice, before treatment, the following stress factors can be added:

- the waiting room or the dental practice itself
- the staff

With the increase and diversification of the offer of dental services, patients, especially those in urban areas, find it increasingly difficult to choose an 'ideal' doctor. The patient has several requirements that the doctor should meet, but the search is not always done in accordance with these. The patient is guided by the dental practice advertisement, general advice received from certain groups on the Internet, and recommendations from acquaintances. All this information, often contradictory, makes the patient postpone the visit to the dentist even more and increases anxiety [13]. Often, erroneous information and unapproved sources are the ones that potentiate a predisposition to anxiety. An anxious, dissatisfied, frustrated, dissatisfied patient will spread erroneous information related to a prosthetic treatment.

The prospect of pain, especially in patients with a history of pain, can be a major factor in triggering anxiety and postponing dental treatment. Studies show that over 70% of anxious patients have the prospect of pain as their main stress factor [14].

The patient may avoid treatment precisely because he is anxious about what the doctor will say about his dental situation. Paradoxically, there are patients who fear either being scolded by the doctor or the verdict regarding the treatment (nothing can be done, it involves complicated procedures).

The financial factor is also a trigger for anxiety for the vast majority of patients, prosthetic rehabilitation is financially expensive and difficult to estimate in terms of costs, especially before presenting for a consultation.

In an era of speed, in which patients who have financial possibilities, especially have limited time at their disposal and the schedule is often unpredictable, time can be a stress factor [14, 15].

After the patient has nevertheless made the decision to undergo prosthetic rehabilitation, the above-mentioned factors can act in the sense of finding excuses for postponing the appointment or starting the treatment. Also, if incidents occur during the prosthetic treatment, which we know is long-term (e.g., the impossibility of showing up for a session without establishing a firm rescheduling), the process can resume with increased anxiety levels and treatment postponement [16].

From the moment of presentation at the dental practice, other factors that trigger or enhance anxiety may appear: the appearance of the dental practice and the waiting room (color, order, crowding, noise, smell, etc.), as well as a factor related to the staff (receptionist, nurse, doctor) and the way they relate and communicate with the patient [13, 15, 17]. All these stress factors, present even before the start of the prosthetic treatment itself, can make prosthetic treatment more difficult or compromise it because the anxious patient will present late, will tend to interrupt the treatment, and will tend to have a behavioral coping based on dysfunctional and maladaptive irrational beliefs.

3.2 Anxiety during prosthetic treatment

Prosthetic treatment can follow a recent dental treatment, which if managed from the point of view of anxiety, will be much easier to achieve. The patient may be 'cured' of anxiety or during the treatment a deconditioning occurred in relation to stress factors. If this does not happen or the patient comes for rehabilitation after a previous negative experience or a long time has passed since the previous treatment, anxiety can be high.

The stress factors during prosthetic treatment are not the same for all patients but the most frequently encountered during this treatment are [4, 5, 7, 18, 19]:

- fear of pain
- fear of anesthesia before dental grinding
- impression
- occlusion registration
- noise, smell, dust
- sight of certain instruments

- fear of losing control
- fear of accidents
- fear of the unknown
- fear of the final result of the treatment

The most common cause of anxiety is the fear of pain [5]. Patients often have a history of this, with dental treatment being perceived as painful by the vast majority of patients, especially those over 40–50 years of age [5, 6] who have undergone traumatic dental treatments without anesthesia. There are patients who are afraid of pain after the effect of anesthesia wears off (dental or at the level of damaged mucosa). Also, patients over 40 years of age are mostly afraid of anesthesia, have a history of incomplete anesthesia, with traumatic needles, or have suffered postanesthesia accidents (hematoma, persistent paresthesia, etc.).

Dental grinding causes anxiety in many patients due to the noise, the smell of ‘burnt teeth’ when cooling is not provided, and the dust that triggers a choking reflex [20]. The same choking reflex can also occur during impression taking [21]. Studies show [5] that anxiety triggered by these factors is much more common in patients from rural areas and with low education (72%), compared to patients with university education in urban areas (9%).

The sight of certain instruments (those for removing prosthetic works, heating wax, and recording occlusion) can trigger patient anxiety [22]. These fears can often be the fear of pain, of unpleasant sensations, of the unknown. In connection with the recording of occlusion, in addition to the anxiety triggered by the use of intraoral devices, the patient also experiences anxiety related to the fact that he did not “bite” correctly. This is especially true when the patient has a history of inadequate prosthetic restorations and for which he was accused by the dentist of not knowing how to achieve the occlusion in the required position. Even if he is not at fault, the patient may assume it and be afraid of making a mistake again.

We often encounter patients with a fear of losing control. Starting from the moment the treatment plan is established, continuing with the horizontal position in the dental chair and the instrument table above the chest, and even the treatment itself, the patient feels at certain moments that they are not the one who decides that they have no control. There are patients who sometimes negotiate the treatment plan without meaning to, others who cannot stand the horizontal position in the dental chair, which they perceive as a constraint. There are also patients who want to see/feel with their tongue how much we are grinding off the tooth. Some ask more timidly or more categorically if we have more or if we have not polished too much and the prosthetic work will be okay [4, 7, 21].

Fear of the final outcome of the treatment is common in prosthetics and can influence the perception of it. It is particularly important for the doctor to identify this anxiety during prosthetic treatment because, if in a dental extraction or dental treatment the outcome is predictable and does not worry about the outcome of the treatment, a prosthetic restoration can completely change the patient’s appearance. The patient has an image in his mind about his appearance at the end of prosthetic rehabilitation and if reality does not coincide with the patient’s mental image (and there is little chance of this happening), a patient who has anxiety in this regard will be dissatisfied with the result [23].

3.3 Anxiety post prosthetic treatment

Fear of prosthetic treatment may appear or continue after the completion of rehabilitation. Usually, after the patient has paid for the prosthetic work, the doctor does not think about his anxiety. The most common fears after the completion of a prosthetic treatment are [5, 7, 21, 24, 25]:

- Fear of not being able to adapt to the new situation in the oral cavity
- Fear of choking with the removable prosthetic work
- Fear that a fixed prosthetic work will come loose and be swallowed
- Fear that the rehabilitation will not be durable over time
- Fear of not changing the perception of the environment toward the person in an undesirable way.

Whether it is a removable or fixed prosthesis, the patient must face a new situation in the oral cavity. The wearer of a removable prosthesis will not think too much about this aspect until the completion of the treatment, being excited and focused on the advantages that the new one will bring him work. Once the treatment is completed, the patient may experience fear or even panic when applying the work in the oral cavity. He may have feelings of choking or nausea, especially in the case of bimaxillary edentulous patients who have not been prosthetically treated for a long time [21]. There is also a fear that the work is too large, that it will not be stable in the prosthetic field during chewing or daily activities, or that he will not be able to speak. Another stress factor present in these patients is the fear of using the prosthetic work at night in order not to suffocate [25, 26].

In prosthetic patients, studies show that esthetic rehabilitation increases self-esteem, improves social relationships, and decreases depression [25, 27, 28]. However, the patient may experience anxiety related to the fact that the new situation will change the way he is viewed by others. We meet patients with successful, esthetic removable prostheses, the patient is delighted with the result but still tries to hide the prosthetic work (covers his mouth with his hand while talking, and does not wear dentures in public). This aspect is frequently found in patients with low self-esteem, introverts who think that they will be judged by others or will stand out too much [28, 29].

The same anxiety related to the change in facial appearance also occurs in patients wearing fixed prosthetic works. Although they want an improvement in their facial appearance, they are satisfied with the result but are afraid of the reaction of their relatives. That is why they will frequently ask: Are not my teeth too white/big? Are not they embarrassing? The patient will seek the approval/disapproval of those around them with fear and a negative comment could dramatically influence the patient's satisfaction.

There are also patients who, either have had previous experiences/heard that the work can be unluted, or who have provisionally luted work, are afraid that it might happen to them, especially during the night, to swallow the work [5, 7]. After completing prosthetic treatment, many patients ask or are concerned about the durability of a prosthetic work. Some patients ask right from the first session and insist, after completing the treatment, on obtaining a document that provides them

with a guarantee over time. Many patients are disappointed when the guarantee of a prosthetic work is conditional (maintaining rigorous hygiene, avoiding certain foods), considering that these are just excuses on the part of the doctor to evade in case of damage to the prosthetic work [26, 29, 30]. There are also many patients so anxious about preserving the integrity of the work that they impose major restrictions on themselves in their daily lives. Often, due to a lack of information, they avoid cold or hot foods so as not to 'crack' the ceramic, they choose only soft or very soft foods, they sanitize excessively, etc.

4. Anxiety prevention

Knowing the aspects related to anxiety in the prosthetically rehabilitated patient will lead to improved collaboration with him and obtaining a treatment that satisfies both the doctor and the patient. This goal is not difficult to achieve, but the doctor must be open to accepting these aspects and allocate the necessary time to identify and remove anxiety-provoking factors for the patient.

4.1 Effective communication

The dentist takes some time, especially during the first consultation, to obtain the necessary data to make a diagnosis and approach a treatment plan. Usually, this communication with the patient is limited to aspects strictly related to treatment, labor, and cost. Especially with the introduction of telecommunication technologies, there is a tendency for aspects related to direct doctor-patient communication to be increasingly reduced. It is often assumed that the patient, having easy access to online information, is informed and involved as a partner in his own treatment [31–33].

Many dentists have the impression that their communication style is efficient, but feedback questionnaires applied to patients show that the patient often does not understand the information transmitted and feels neglected in the relationship with the dentist [33]. This is often the reason for the patient's anxiety. To help doctors, several associations have developed patient communication guides, which describe a list of main points that the dentist should touch upon throughout the entire collaboration with the patient [34].

In 1967, Nathan Friedman introduced the term 'iatrosedation'. The term "iatrosedation" is formulated by combining the prefix "iatros" (healer) with sedation (calming) and literally means calming through the doctor's behavior [6]. This emphasizes the major importance of communication in reducing anxiety.

Self-assessment [35]:

- Do you take the time to explain the agenda for each patient's visit?
- Do you feel rushed with each appointment?
- During the dental exam do you explain what you are seeing and looking for?
- When an exam is over, do you ask the patient if they have any questions?
- Do you discuss the pros and cons of treatment options?

- Have you expressed, as the expert, your preferred option of treatment?
- Do you supply patients with information they can take home with them?
- Do you take the time to discuss fees for treatment directly with your patient?
- Do you inform the patient of payment options?

Starting from the first contact with the patient, which may be the dental practice website or the appointment, continuing throughout the treatment, and after its completion, the dentist must ensure that he/she has communicated effectively with the patient, provided the necessary information and the patient has understood this information.

Prosthetic treatment is so complex due to the fact that it extends over a prolonged period of time, and the dentist must keep anxiety under control at all times. Communication is not limited to checking the list above, it must also be efficient. Its efficiency primarily involves active listening. This involves more than simply understanding the patient's language, it means paying full attention to the patient's message, without making judgments, without jumping to conclusions, and without interrupting it except to summarize or clarify certain aspects or if the conversation takes a direction other than that related to the treatment [32, 36]. The dentist must also be a fine psychologist, to obtain information from which to form an idea related to: the patient's personality, his psychological age, what is the final goal of the prosthetic treatment (what are his expectations), and of course what are the factors that trigger his anxiety related to prosthetic rehabilitation. Sometimes this is difficult to achieve because many patients do not know, in fact, what they are afraid of. In this case, the role of communication and active listening is to identify the stress factor before it occurs and, also through communication, resolve it.

Communication is not only verbal, but it also has a nonverbal and paraverbal component [31], which are perhaps more important than the verbal message. The transmission of positive body language, smiling, looking toward the patient during communication, body position slightly directed toward the patient, hand with palm up and open gestures during conversation, light touch on the shoulder, patient's position at the same level as the doctor reduce anxiety and enhance trust [35, 36]. Also, the tone of voice, paraverbal message, rhythm adapted to the patient's level of understanding, the pitch of sounds, and consistency of rhythm, enhance the verbal and nonverbal message [37, 38].

Communication also involves empathy conveyed to the patient, which will strengthen the relationship with the dentist, increase trust and decrease anxiety related to prosthetic treatment. It is recommended to involve the patient in decision-making at all stages of prosthetic treatment and to communicate with him/her on an ongoing basis. The information he/she possesses and the responsibility for decision-making will lead to a decrease in anxiety [35–38].

4.2 Dental practice management in prosthetic treatment

As we have already mentioned, anxiety in prosthetic treatment can begin even before presenting for treatment, during the search phase for the right practice. Therefore, the dentist must attach significant importance to the practice website and get involved in its creation, not just contract a specialized service in this regard [39].

It is recommended that the website present, in addition to photos of the practice, with the staff by specialization, a brief description of them (competencies, scientific titles) and a section with mini-articles related to the treatments being performed. These must be adapted to the patient's ability to understand, and be explanatory, not like a presentation at a scientific conference. For example - total prosthesis - what it is, the stages it involves, what the patient should expect after the work is done, what difficulties they will encounter (stability, nausea, speech), maintenance and hygiene rules, when they will need to return for scheduled or urgent check-ups (decubitus ulcers, candidiasis, allergic reactions). It is also good to combat common myths on the website, with explanations (for example, patients who avoid implant-supported prosthetic work because they have heard that it generates neoplasia) [40].

For patients with pain or anesthesia anxiety, it is recommended to specify on the website that there are methods of pain relief (anesthesia with atraumatic needles, inhalation sedation, etc.). It is also good to have a frequently asked questions section on the website and to clearly specify the method of payment for the prosthetic work (advance payment, full payment, possibility of financing, etc.) [39, 40].

Of course, all this information will also be communicated by the dentist, but the transparency and clarity of the information largely remove the patient's anxiety because he knows what to expect and can read and return to the information depending on the stage of treatment he is at.

The dental practice itself, the waiting room, and the related spaces must be welcoming, taking into account the color (white is avoided - it is a generator of hospital anxiety, but also strong red, black, color contrasts) [5, 39]. Cleanliness and order are also important in calming the patient. Means of distraction (television, magazines), waiting time as short as possible - managing appointments (anxiety increases immediately before treatment), and not having more patients in the waiting room (risk of anxiety contagion) are desirable in anxiety management [1, 5, 39, 40].

5. Anxiety treatment

5.1 Coping with dental anxiety and phobia: Psychological techniques

The treatment of anxiety in prosthetic treatment primarily involves *communication*, which we have also addressed in the prevention chapter. Effective communication 'iatrosedation' [6] alone or together with other treatment methods can resolve the problem of anxiety. The same principles are followed, with the clarification that verbal, nonverbal, and paraverbal language is important to convey the same message, empathetic and directed toward the patient's needs.

Melootherapy is important in reducing anxiety, according to a recent study. Music triggers the activity of the nucleus accumbens, part of the brain's mesolimbic system, which releases dopamine, which is involved in shaping expectations. At the same time, the auditory cortex, the amygdala involved in emotion processing, and the ventromedial prefrontal areas of the cerebral cortex involved in decision-making, perceptual analysis, and evaluation, are activated. Melootherapy is used both preventively and during dental treatment to reduce dental anxiety. It is used as ambient music in the waiting room and in the dental practice broadcast or on headphones only for the patient. It can be used throughout the treatment or only in the phases when the patient is anxious (anesthesia before tooth preparation, impression taking). There are

music playlists specially designed for reducing dental anxiety or classical music with a proven effect in decreasing anxiety [6, 35].

Breathing techniques are also used in anxiety management, diaphragmatic breathing by placing a hand on the abdomen, inspiration slowly and evenly, followed by a new slow and steady exhalation. Exhalation should last longer than inhalation [24, 41]. The method can be used at any time during treatment but has been proven to be especially effective in the gag or choking reflex during dental impressions [24].

Conrad progressive muscle relaxation is the most widely used relaxation method used in anxious patients. It consists of contracting certain muscle groups for 5–7 seconds, followed by 20 seconds of relaxation. It can be used by the trained patient at home before treatment or in the dental practice only for certain target muscle groups, for example, muscle relaxation for the purpose of recording occlusion in the completely edentulous patient [42]. It is good to combine it with breathing techniques.

Cognitive-behavioral therapy is based on the idea that a stimulus triggers a certain behavior through association [43]. For example, the patient associates the sound of the turbine, the needle with pain. A technique of gradual deconditioning and transformation of irrational ideas into rational thoughts is used to reduce anxiety. This technique requires the support of a psychologist or psychiatrist if the doctor does not have the necessary training [44].

Hypnosis is also included in the category of treatments that require the presence of a psychologist. It has been used since 1829 when Jean-Victor Ouddet was the first doctor to perform a tooth extraction under hypnosis [45, 46]. It is not widely used, but the method gives good results in reducing anxiety.

Virtual reality (VR) and augmented reality are tools used to facilitate the patient's understanding of the treatment, as well as to distract them from their anxiety. In prosthetics, the patient can view on the screen the final result of a prosthetic work, inserted into the oral cavity, from the first session [47, 48]. This will increase confidence in the dental treatment, motivate the patient to complete it, and implicitly reduce anxiety. VR glasses are also used to reduce anxiety, with the help of which the patient is 'placed' in a pleasant, safe environment (such as a forest or on the seashore) [48].

Last but not least, general conduct, reducing patient stress, and mindfulness techniques lead to decreased treatment anxiety.

5.2 Medication used in anxiety treatment

Currently, there are a multitude of medications that can help the anxious patient. Their effects are rapid, and they are often preferred to allocating a significant amount of time as is the case with psychological methods. However, we must know that medications resolve fear but do not resolve conflict [6]. However, there are many cases in which medication is needed to reduce anxiety and control the patient's pain.

5.2.1 Natural remedies

Increasingly, research is focusing on the use of natural remedies in the treatment of dental anxiety. Plant extracts are used in several forms: aromatherapy, capsules, jellies, patches, and topical applications in certain areas (wrist, behind the ear). Studies show that extracts from certain plants, in adequate concentrations, can decrease salivary cortisol levels, which indicates a decrease in anxiety [48–52].

The use of plant extracts, alone or in combination, is well known, such as jasmine [50], lavender, orange [51], *Piper methysticum*, *Matricaria recutita*, *Ginkgo biloba*,

Scutellaria lateriflora, *Silybum marianum*, *Passiflora incarnata*, *Withania somniferum*, *Galphimia glauca*, *Centella asiatica*, *Rhodiola rosea*, *Echinacea* spp., *Melissa officinalis*, and *Echium amoenum* [52, 53]. Studies mention at least 53 plants whose effects have been proven in reducing anxiety during dental treatment [53].

These preparations can be used before and during prosthetic treatment as a means of prevention or anxiety reduction. For example, the patient will more easily accept the impression that he fears if he first smells a preparation containing essential oils in predetermined doses. Also, the patient wearing removable dentures will adapt much more easily if he is given candies (not sticky) containing essential oils.

5.2.2 Medication used to reduce anxiety

There are several types of medication used depending on the patient and the severity of their anxiety. Prosthetic treatments can benefit from any of the drug administration options, they have the advantage that they act quickly, and it is not necessary for the doctor to develop his communication skills or to 'waste time' with the patient's psychology.

Both anxious patients and many doctors prefer them to save time. However, as I said before, they solve the effect and not the cause of anxiety. They are also not effective for pre-treatment and posttreatment anxiety, but only during its development. Of course, they also have risks and contraindications.

- The cardiovascular system, the patient's cognitive response level, and the airways are all unaffected by *mild sedation* with anxiolytic medication. The intensity of panic episodes can be lessened by taking benzodiazepines like Xanax, Ativan, or Klonopin, or antidepressants like Paxil, Zoloft, Lexapro, or Celexa [6, 54].
- While drowsiness is brought on by conscious or *moderate sedation*, the patient is nevertheless responsive to touch and vocal cues. Intervention is typically not necessary for the cardiovascular system or the airways. Gaseous inhalants enter the lungs and circulatory system through the inhalation route. Because N₂O has analgesic properties, inhalation may be used in place of local anesthetic for several dental procedures [54, 55].
- The cardiovascular system is unaffected by *deep sedation*, although the patient may respond slowly and may need respiratory support [56].
- The last step of sedation, *general anesthesia*, renders the patient comatose and incapable of reacting to stimuli. In these circumstances, cardiovascular function may be affected, and breathing support is necessary, that is, the patient needs to be intubated [55].

6. Conclusions

Anxiety, although known to be very common among patients, is often ignored or treated exclusively with medication by the dentist. Prosthetic treatment, whether it is partial or total edentulism, is long-term and includes factors that depend on the patient's psychology (personality, background, age, sex, self-esteem, etc.). The patient is anxious long before starting prosthetic treatment, during it, and after the treatment is completed.

If ignored or treated only with medication, anxiety will often compromise the outcome of prosthetic treatment. Prosthetic and orthodontic rehabilitation are the most time-consuming procedures in dentistry. However, in prosthetics, there are more potentially painful procedures, it involves different stages of execution, it is not a repetitive treatment, and it is less predictable. (In orthodontics, we usually have a clear objective, for example, aligning the teeth, in prosthetics the patient does not know how he will look and feel after extensive rehabilitation).

Even if drug treatment is faster, the recommendation is to insist on knowing the patient, investing time in communication, active listening, identifying the cause of anxiety, removing it mainly through psychological methods, and using medication only as a last resort or adjuvant.

Author details

Gabriela Ciavoi^{1*}, Alexandra Roxana Cristea^{1*} and Sergiu-Mihai Ciavoi²

1 Department of Dental Medicine, Faculty of Medicine and Pharmacy, University of Oradea, Oradea, Romania

2 William Carey University College of Osteopathic Medicine, Hattiesburg, MS, United States

*Address all correspondence to: gciavoi@uoradea.ro;
cristea.roxana.alexandra@didactic.uoradea.ro

IntechOpen

© 2025 The Author(s). Licensee IntechOpen. This chapter is distributed under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/4.0>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited. 

References

- [1] Alsakr A, Gufran K, Alqahtani AS, Alkharaan H, Abushanan A, Alnufaiy B, et al. Pre-treatment and post-treatment dental anxiety in patients visiting intern dental clinic. *Medicina* (Kaunas, Lithuania). 2023;**59**(7):1284. DOI: 10.3390/medicina59071284
- [2] Carlsson V, Hakeberg M, Wide BU. Associations between dental anxiety, sense of coherence, oral health-related quality of life and health behaviour—A national Swedish cross-sectional survey. *BMC Oral Health*. 2015;**15**:100. DOI: 10.1186/s12903-015-0088-5
- [3] Majanta SK, Aashwini S, Baidya S, Ashma R, Ghosh S, Prajapati D. Dental anxiety levels and implementing anxiety-reduction techniques in pre-and post-operative dental patients. *Journal of College of Medical Sciences-Nepal*. 2024;**20**(4):345-350. DOI: 10.3126/jcmsn.v20i4.68117
- [4] Bano S, Ahmad SA, Vyas K. Exploring dental anxiety among male and female across adolescents, young adults, and middle adults. *Journal of Dental Research and Review*. 2021;**8**(2):107-112. DOI: 10.4103/jdrr:jdrr_142_20
- [5] Muneer MU, Ismail F, Munir N, Shakoor A, Das G, Ahmed AR, et al. Dental anxiety and influencing factors in adults. In *Healthcare*. 2022;**10**(12):2352. DOI: 10.3390/healthcare10122352
- [6] Avramova NT. Dental fear, anxiety, and phobia-behavioral management and implications for dentists. *Journal of Mind and Medical Sciences*. 2023;**10**(1):42-50. DOI: 10.22543/2392-7674.1349
- [7] Garza M, David M, Salloum IM. The crossroads of addiction and anxiety. In: Rocco EA, Espinel Z, editors. *Anxiety Disorders, What Do I Do Now Psychiatry*. online ed. New York: Oxford Academic; 2024. DOI: 10.1093/med/9780197667859.003.0011
- [8] Firmawati F, Uyuun N, Rahayu S. Anxiety score in anxiety patients using slow deep breathing relaxation therapy. *Journal La Medihealthico*. 2024;**5**(5):1043-1050. DOI: 10.37899/journallamedihealthico.v5i5.1568
- [9] Slabšinskienė E, Radlinskaitė K, Kavaliauskienė A, Vasiliauskienė I, Zūbienė J, Saldūnaitė-Mikučionienė K, et al. Do subjects from different occupational groups experience dental fear and anxiety equally? *Medicina* (Kaunas, Lithuania). 2024;**60**(4):674. DOI: 10.3390/medicina60040674
- [10] Bernson JM, Elfström ML, Hakeberg M. Dental coping strategies, general anxiety, and depression among adult patients with dental anxiety but with different dental-attendance patterns. *European Journal of Oral Sciences*. 2013;**121**:270-276
- [11] Bernson JM, Elfstrom ML, Berggren U. Self-reported dental coping strategies among fearful adult patients: Preliminary enquiry explorations. *European Journal of Oral Sciences*. 2007;**115**:490.22
- [12] Bernson JM, Elfstrom ML, Hakeberg M. Adaptive coping strategies among adults with dental fear. Further development of a new version of the dental coping strategy questionnaire. *Acta Odontologica Scandinavica*. 2012;**70**:414-420
- [13] Katz CA. Stress factors operating in the dental office work environment. *Dental Clinics of North America*. 1986;**30**(4 Suppl):S29-S36

- [14] Mazey KA. Stress in the dental office. *Journal of the California Dental Association*. 1994;**22**(2):13-19
- [15] Niemczyk W, Balicz A, Lau K, Morawiec T, Kasperczyk J. Factors influencing peri-extraction anxiety: A cross-sectional study. *Dental Journal*. 2024;**12**:187. DOI: 10.3390/dj12060187
- [16] Aartman IH, de Jongh A, van der Meulen MJ. Psychological characteristics of patients applying for treatment in a dental fear clinic. *European Journal of Oral Sciences*. 1997;**105**(5P1):384-388
- [17] Muppa R, Bhupatiraju P, Duddu M, Penumatsa NV, Dandempally A, Panthula P. Comparison of anxiety levels associated with noise in the dental clinic among children of age group 6-15 years. *Noise and Health*. 2013;**15**(64):190-193
- [18] Carter AE, Carter G, Boschen M, Al Shwaimi E, George R. Pathways of fear and anxiety in dentistry: A review. *World Journal of Clinical Cases*. 2014;**2**:642-653. DOI: 10.12998/wjcc.v2.i11.642
- [19] Svensson L, Hakeberg M, Boman UW. Dental anxiety, concomitant factors and change in prevalence over 50 years. *Community Dental Health*. 2016;**33**:121-126
- [20] Yildirim-Bicer AZ, Akarslan ZZ. Influence of gag reflex on removable prosthetic restoration tolerance according to the patient section of the short form of the gagging problem assessment questionnaire. *Journal of Advanced Prosthodontics*. 2014;**6**(6):474-482. DOI: 10.4047/jap.2014.6.6.474
- [21] Mathew JA, Mathew AA, Deolia S, Mantri U, Kadu T, Reche A. Assessment of correlation of gagging and dental anxiety in male and female patients of Sawangi- A pilot study. *Medical Science*. 2020;**24**(103):1255-1260
- [22] Settineri S, Tati F, Fanara G. Gender differences in dental anxiety: Is the chair position important? *The Journal of Contemporary Dental Practice*. 2005;**6**:115-122
- [23] Ullah A, Khan AN, Khan NR, Mirza W, Masood L, Mahreen A. Impact of sociodemographic and dental clinic related factors causing dental anxiety in patients: Factors causing dental anxiety. *Pakistan Journal of Health Sciences*. 2024;**5**(08):22-26. DOI: 10.54393/pjhs.v5i08.1701
- [24] Appukuttan DP. Strategies to manage patients with dental anxiety and dental phobia: Literature review. *Clinical, Cosmetic and Investigational Dentistry*. 2016;**10**(8):35-50
- [25] Elfadil S, Johnston B, Normand C, Allen F, O'Connell B. An investigation of the characteristics of edentulous patients who choose or refuse implant treatment. *The International Journal of Prosthodontics*. 2021;**34**(2):147-153
- [26] Yoshida T, Masaki C, Komai H, Misumi S, Mukaibo T, Kondo Y, et al. Changes in oral health-related quality of life during implant treatment in partially edentulous patients: A prospective study. *Journal of Prosthodontic Research*. 2016;**60**(4):258-264
- [27] Wetselaar P, Koutris M, Visscher CM, Larsson P, John MT, Lobbezoo F. Psychometric properties of the Dutch version of the orofacial esthetic scale (OES-NL) in dental patients with and without self-reported tooth wear. *Journal of Oral Rehabilitation*. 2015;**42**(11):803-809
- [28] Baumgarten A, Bastos JL, Toassi RFC, Hilgert JB, Hugo FN, Celeste RK. Discrimination, gender and self-reported aesthetic problems among Brazilian adults. *Community*

Dentistry and Oral Epidemiology. 2018;**46**(1):24-29

[29] Xie X, Zhang Z, Zhou J, et al. Changes of dental anxiety, aesthetic perception and oral health-related quality of life related to influencing factors of patients' demographics after anterior implant treatment: A prospective study. *International Journal of Implant Dentistry*. 2023;**9**:22. DOI: 10.1186/s40729-023-00486-y

[30] Persic S, Celebic A. Influence of different prosthodontic rehabilitation options on oral health-related quality of life, orofacial esthetics and chewing function based on patient-reported outcomes. *Quality of Life Research*. 2015;**24**(4):919-926

[31] Ho CY, Chai H, Lo EC, Huang Z, Chu CH. Dentist-patient communication in quality dental care. *Frontiers in Oral Health*. 2024;**18**:1385-1394

[32] Khalifah AM, Celenza A. Teaching and assessment of dentist-patient communication skills: A systematic review to identify best-evidence methods. *Journal of Dental Education*. 2019;**83**(1):16-31. DOI: 10.21815/JDE.019.003

[33] Ho JCY, Chai HH, Lo ECM, Huang MZ, Chu CH. Strategies for effective dentist-patient communication: A literature review. *Patient Preference and Adherence*. 2024;**18**:1385-1394. DOI: 10.2147/PPA.S465221

[34] Patient Communications: A Guide for Dentists. Nova Scotia Dental Association; 2015. Available from: http://www.cdaadc.ca/_files/practice/practice_management/patient_communications/guides/dentalguide-ns.pdf [Accessed: January 06, 2025]

[35] Patient Communication Guide. College of Dental Surgeon of Alberta;

2012. Available from: https://www.cdsab.ca/wpcontent/uploads/2021/01/CDSA_PatientComGuide.pdf [Accessed: January 06, 2025]

[36] Dalonges DA, Fried JL. Creating immediacy using verbal and nonverbal methods. *Journal of Dental Hygiene*. 2016;**90**(4):221-225

[37] Levin RP. Body language speaks volumes. *Journal of the American Dental Association*. 2008;**139**(9):1262-1263. DOI: 10.14219/jada.archive.2008.0343

[38] Gazal G, Tola AW, Fareed WM, Alnazzawi AA, Zafar MS. A randomized control trial comparing the visual and verbal communication methods for reducing fear and anxiety during tooth extraction. *The Saudi Dental Journal*. 2016;**28**(2):80-85

[39] Iurcov R, Pop LM, Ciavoi G, Iorga M. Evaluating the practice of preventive behaviors and the fear of COVID-19 among dentists in Oradea metropolitan area after the first wave of pandemic; a cross-sectional study. *Healthcare*. 2021;**9**(4):443. DOI: 10.3390/healthcare9040443

[40] Moca AE, Țig IA, Ciavoi G, Iurcov R, Șipoș LR, Todor L. The impact of the COVID-19 pandemic on the dental emergency service from Oradea, Romania: A retrospective study. *Healthcare*. 2022;**10**:1786. DOI: 10.3390/healthcare10091786-

[41] Biggs QM, Kelly KS, Toney JD. The effects of deep diaphragmatic breathing and focused attention on dental anxiety in a private practice setting. *Journal of Dental Hygiene*. 2003;**77**(2):105-113

[42] Conrad A, Roth WT. Muscle relaxation therapy for anxiety disorders: It works but how? *Journal of Anxiety Disorders*. 2007;**21**(3):243-264

- [43] Wenzel A. Basic strategies of cognitive behavioral therapy. *The Psychiatric Clinics of North America*. 2017;**40**(4):597-609. DOI: 10.1016/j.psc.2017.07.00137
- [44] de Jongh A, Muris P, ter Horst G, van Zuuren F, Schoenmakers N, Makkes P. One-session cognitive treatment of dental phobia: Preparing dental phobics for treatment by restructuring negative cognitions. *Behaviour Research and Therapy*. 1995;**33**(8):947-954. DOI: 10.1016/0005-7967(95)00027-u
- [45] Allison N. Hypnosis in modern dentistry: Challenging misconceptions. *FDJ*. 2015;**6**:172-175. DOI: 10.1308/rcsfdj.2015.172
- [46] Lahmann C et al. Brief relaxation versus music distraction in the treatment of dental anxiety: A randomized controlled clinical trial. *Journal of the American Dental Association* (1939). 2008;**139**(3):317-324. DOI: 10.14219/jada.archive.2008.016133
- [47] Kong X, Song N, Chen L, Li Y. Non-pharmacological interventions for reducing dental anxiety in pediatric dentistry: A network meta-analysis. *BMC Oral Health*. 2024;**24**(1):1151. DOI: 10.1186/s12903-024-04919-x
- [48] Moussa R, Alghazaly A, Althagafi N, Eshky R, Borzangy S. Effectiveness of virtual reality and interactive simulators on dental education outcomes: systematic review. *European Journal of Dentistry*. 2022;**16**(1):14-31. DOI: 10.1055/s-0041-1731837. Epub 2021 Aug 24
- [49] Armfield JM, Heaton LJ. Management of fear and anxiety in the dental clinic: A review. *Australian Dental Journal*. 2013;**58**(4):390-407. DOI: 10.1111/adj.1211834
- [50] Jafarzadeh Samani M, Ziaei S, Monjezi N, Fazaeli R, Sedaghat N, Panahi H, et al. Anxiolytic effect of jasmine aromatherapy in pediatric dental procedures: A single-blinded randomized placebo-controlled trial. *Front-Dent*. 2024;**21**:39
- [51] Cai H, Xi P, Zhong L, Chen J, Liang X. Efficacy of aromatherapy on dental anxiety: A systematic review of randomised and quasi-randomised controlled trials. *Oral Diseases*. 2021;**27**(4):829-847
- [52] da Fonseca LR, Rodrigues RA, Ramos AS, da Cruz JD, Ferreira JLP, Silva JRA, et al. Herbal medicinal products from *Passiflora* for anxiety: An unexploited potential. *The Scientific World Journal*. 2020;**2020**:6598434. DOI: 10.1155/2020/6598434
- [53] Sarris J, McIntyre E, Camfield DA. Plant-based medicines for anxiety disorders, part 2: A review of clinical studies with supporting preclinical evidence. *CNS Drugs*. 2013;**27**(4):301-319. DOI: 10.1007/s40263-013-0059-9. Erratum in: *CNS Drugs*. 2013;**27**(8):675. Dosage error in article text
- [54] Rosu MF, Forna DA, Forna NC. Interrelations between anesthetic substances, general condition of the patient and implant rehabilitation procedure. *Revista de Chimie*. 2017;**68**(7):1674-1676
- [55] Adams V. Office dental rehabilitation under deep IV sedation. In: Jaffe RA, Schmiesing CA, Golianu B, editors. *Anesthesiologist's Manual of Surgical Procedures*. 5th ed. Philadelphia: Wolters Kluwer Health; 2014. p. 448
- [56] Kızılıcı E, Kızılay F, Mahyaddinova T, et al. Stress levels of a group of dentists while providing dental care under clinical, deep sedation, and general anesthesia. *Clinical Oral Investigations*. 2023;**27**:3601-3609. DOI: 10.1007/s00784-023-04973-9

*Edited by Lavinia Cosmina Ardelean
and Laura-Cristina Rusu*

There is a continuous and well-defined need for novel dental prosthetic solutions that not only support improved oral health but also encourage patient compliance. In this context, this book includes seven chapters that focus on key aspects of dentures. Complex issues such as tooth loss and its consequences, management of patients' anxiety, modern material choices, novel technologies, and approaches to restoration design are presented, aiming to address both functional and esthetic issues caused by edentulism.

Sergio Alexandre Gehrke, Dentistry Series Editor

Published in London, UK

© 2025 IntechOpen
© Gile68 / iStock

IntechOpen

ISSN 2631-6218

ISBN 978-1-83634-965-5

