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Medicine in Evolution

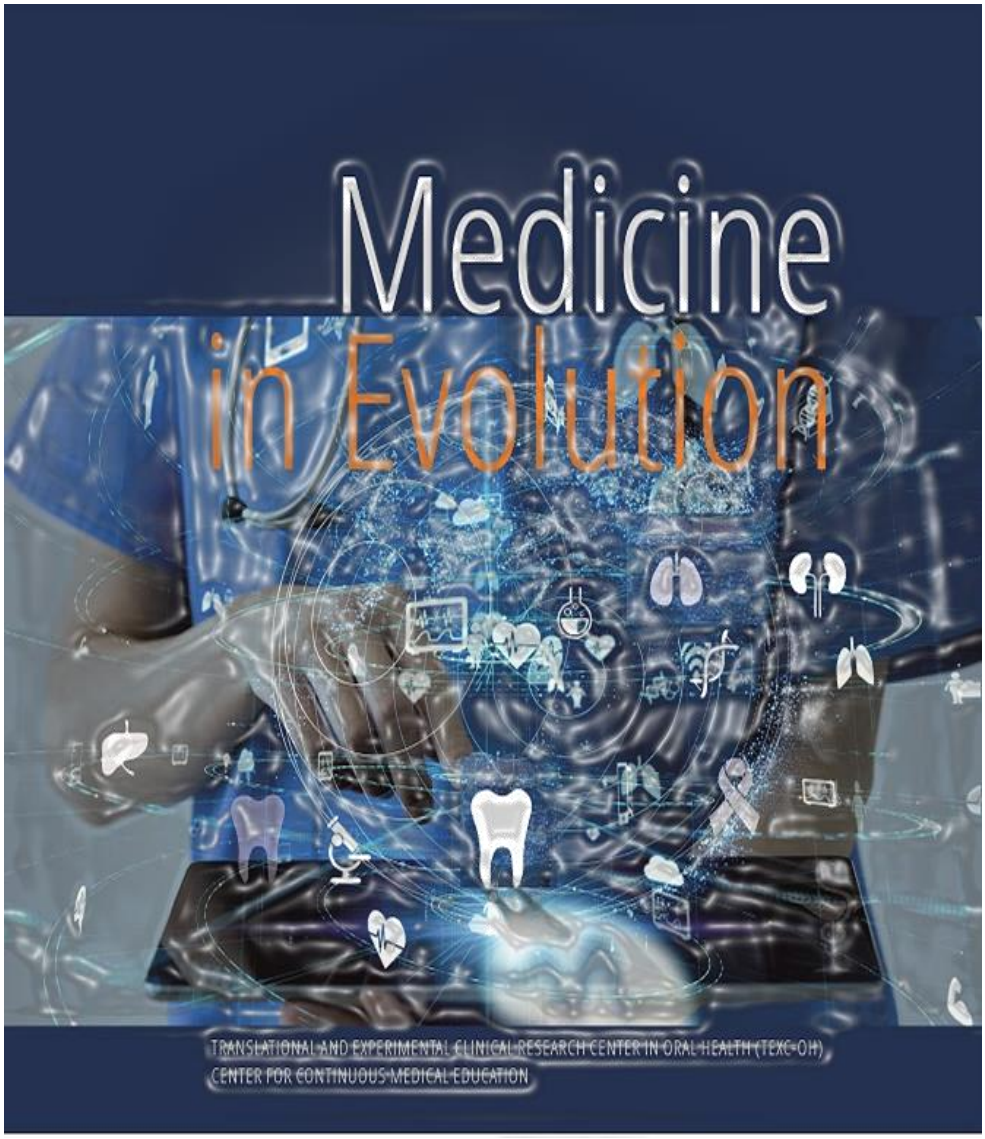


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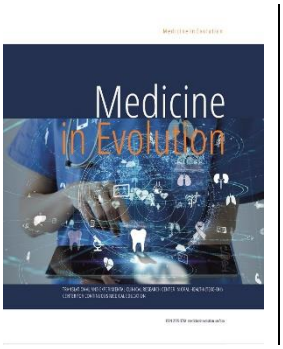
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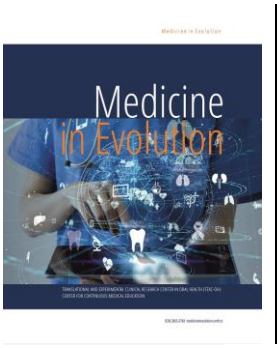
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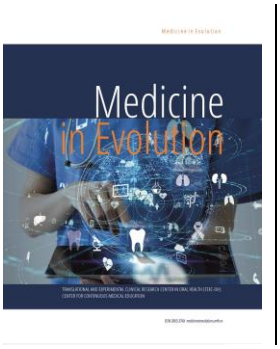


The current journal was established by Prof. Dr. Mircea Ancusa in 1999, with the aim of acquiring knowledge and sharing insights in the noble profession guided by the principle "primum non nocere" (first, do no harm). In 2005, it was entrusted to a group of dedicated researchers at the Center of Health Education and Motivation for Prevention in Dentistry, under the leadership of Prof. Angela Codruta Podariu, DMD, PhD, at the Department of Preventive Dentistry of the University of Medicine and Pharmacy "Victor Babes" in Timisoara, Romania.

The inception of the journal stemmed from a dedication to exchange experiences in both professional and research domains. It was envisioned to encompass all medical specialties, with the aspiration that the published manuscripts would exhibit exceptional quality, elevating the journal's reputation. Esteemed professionals were enlisted to the editorial board and the review committee, individuals recognized for their expertise in the realm of research. The decision to publish papers in English was made to broaden accessibility to the global research community and enhance international recognition.

Since then, the journal has been regularly published under the auspices of the Center of Health Education and Motivation for Prevention in Dentistry, disseminating national and international research studies with the objective of evolving into a comprehensive evidence-based publication. Presently, the journal has transitioned to the stewardship of the Translational and Experimental Clinical Research Centre in Oral Health, situated within the Department of Preventive, Community Dentistry, and Oral Health. Its objectives are aligned with the vision of esteemed organizations such as the World Health Organization and the International Dental Federation, seamlessly integrating into the research strategy of Victor Babes University of Medicine and Pharmacy Timisoara.

"Medicine in Evolution" stands as a distinguished, peer-reviewed, open access journal dedicated to the dissemination of original theoretical research spanning the interdisciplinary spectrum of medicine and healthcare. Encompassing various topics within the realms of human life sciences, medical community, dental medicine, and pharmacology, the journal warmly welcomes original research papers, communications, letters, short notes, case reports, and reviews for submission. Committed to conducting rigorous peer reviews and expediting the publication of groundbreaking research, its mission is to advance the field of medicine through scholarly discourse.



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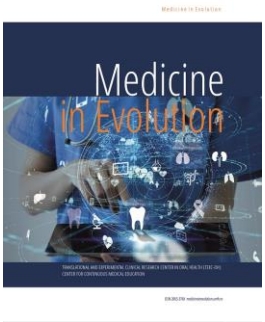
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Periodontal Diseases and Cardiovascular Health: An Analysis of Clinical and Behavioral Risk Factors



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Abstract

Cardiovascular diseases (CVDs) and periodontal diseases are prevalent chronic inflammatory conditions that may share common pathogenic mechanisms and risk factors. This study aimed to investigate the relationship between periodontal diseases and cardiovascular disorders and to evaluate the associations between oral health, cardiovascular diseases, metabolic abnormalities, and lifestyle-related risk factors. A retrospective observational study was conducted on 100 adults with previously diagnosed cardiovascular diseases from ten private dental and medical clinics in Timişoara, Romania. Demographic, clinical, behavioral, and oral health data were extracted from anonymized medical records and analyzed using descriptive statistics and Pearson (Phi) correlation coefficients. Gingivitis and periodontitis were identified in 52% and 56% of participants, respectively, while hypertension (41%) and hypercholesterolemia (39%) were the most prevalent cardiovascular conditions. Correlation analyses revealed predominantly weak associations between periodontal and cardiovascular diseases; however, periodontitis showed positive correlations with myocardial infarction and atrial fibrillation, whereas obesity was more closely associated with cardiovascular and metabolic disorders. These findings support the concept of an oral–systemic health continuum and highlight the importance of interdisciplinary collaboration between dental and medical professionals. Larger prospective studies including standardized periodontal examinations and systemic inflammatory biomarkers are needed to clarify the causal relationship between periodontal and cardiovascular diseases.

Keywords: periodontal disease; periodontitis; gingivitis; cardiovascular diseases; oral-systemic health; chronic inflammation; myocardial infarction; hypertension; obesity; cardiovascular risk.

INTRODUCTION

Cardiovascular diseases (CVDs) continue to represent the leading cause of mortality worldwide and remain among the most important contributors to disability, reduced quality of life, and healthcare expenditures. Despite significant advances in diagnostic technologies, pharmacological therapies, and preventive strategies, the global burden of cardiovascular diseases continues to increase, largely driven by population aging, urbanization, sedentary lifestyles, unhealthy dietary habits, obesity, diabetes mellitus, and tobacco consumption [1,2]. The multifactorial nature of cardiovascular disease has encouraged researchers to investigate not only traditional risk factors but also the role of chronic inflammatory conditions and systemic disorders that may contribute to cardiovascular pathogenesis and progression.

Among these conditions, oral diseases, particularly periodontal diseases, have emerged as important subjects of interest due to their high prevalence and potential systemic consequences. Periodontal diseases comprise a group of chronic inflammatory disorders affecting the supporting tissues of the teeth, including the gingiva, periodontal ligament, cementum, and alveolar bone [3,4,5]. Gingivitis represents the earliest and most common form of periodontal disease and is characterized by inflammation confined to the gingival tissues without loss of periodontal attachment [6,7,8]. Although reversible when appropriate oral hygiene measures are implemented, persistent gingival inflammation may progress to periodontitis, a more severe condition associated with irreversible tissue destruction, alveolar bone resorption, tooth mobility, and eventual tooth loss [4,9,10].

Periodontal diseases are highly prevalent worldwide and constitute a major public health concern. Epidemiological studies indicate that gingivitis affects a substantial proportion of both children and adults, while severe periodontitis is among the most common chronic diseases globally [3,11]. Beyond their local effects, periodontal diseases may significantly impair mastication, aesthetics, speech, nutrition, and overall quality of life. Furthermore, the economic burden associated with periodontal treatment and tooth loss places considerable pressure on healthcare systems, emphasizing the importance of preventive interventions and early diagnosis [11].

The pathogenesis of periodontal disease involves a complex interaction between microbial biofilm accumulation and the host immune-inflammatory response. While dental plaque serves as the primary etiological factor, disease progression is strongly influenced by environmental, behavioral, genetic, hormonal, and systemic determinants [2,5,6,8,13,14]. Smoking, obesity, diabetes mellitus, stress, poor dietary habits, and socioeconomic status have all been identified as important contributors to periodontal disease susceptibility and severity [11,12,15]. Consequently, periodontal diseases should be viewed not merely as localized infections but as multifactorial chronic inflammatory disorders influenced by a wide range of host and environmental factors.

Growing scientific evidence has highlighted the concept of oral-systemic health, recognizing the oral cavity as an integral component of overall health rather than an isolated anatomical entity. The oral microbiome represents one of the most diverse microbial ecosystems in the human body and plays a critical role in maintaining both local and systemic homeostasis. Under dysbiotic conditions, however, pathogenic microorganisms may trigger persistent inflammatory responses capable of extending beyond the oral environment [16]. The ulcerated epithelium lining periodontal pockets provides a direct pathway for microorganisms, endotoxins, and inflammatory mediators to enter the systemic circulation, facilitating bacteremia and promoting systemic immune activation [1,17,18].

Several biological mechanisms have been proposed to explain the relationship between periodontal diseases and cardiovascular pathology. Chronic periodontal inflammation is associated with increased circulating levels of inflammatory mediators, including C-reactive protein, interleukin-1β, interleukin-6, and tumor necrosis factor-alpha, all of which have been implicated in endothelial dysfunction, vascular inflammation, and atherosclerotic plaque formation [17,18,19]. Moreover, periodontal pathogens and their virulence factors have been identified within atherosclerotic lesions, providing further support for a potential mechanistic link between oral infections and cardiovascular disease development [1,17].

Inflammation is increasingly recognized as a fundamental component of cardiovascular disease pathophysiology. In addition to traditional cardiovascular risk factors, chronic low-grade systemic inflammation contributes significantly to endothelial injury, plaque instability, thrombogenesis, and adverse cardiovascular outcomes. Given that periodontitis represents one of the most common chronic inflammatory conditions affecting adults, it has been proposed as a potential non-traditional cardiovascular risk factor capable of influencing both the onset and progression of cardiovascular diseases [1,18,20].

Numerous observational studies, systematic reviews, and meta-analyses have reported associations between periodontal diseases and various cardiovascular conditions, including hypertension, coronary artery disease, myocardial infarction, stroke, heart failure, and atrial fibrillation [19,20,21). Although the magnitude of these associations varies among studies, the overall body of evidence suggests that individuals affected by periodontitis exhibit a greater cardiovascular risk than periodontally healthy individuals [1,2,19]. Furthermore, the severity of periodontal destruction appears to correlate with the extent of cardiovascular impairment, reinforcing the hypothesis that chronic oral inflammation may contribute to systemic disease burden [17,18].

The relationship between oral and cardiovascular health is further strengthened by the existence of several shared risk factors. Smoking, obesity, diabetes mellitus, dyslipidemia, poor nutritional habits, and socioeconomic disadvantage have been consistently associated with both periodontal diseases and cardiovascular disorders [11,15,18]. Smoking, for example, alters the composition of the oral microbiota, impairs immune responses, and accelerates periodontal tissue destruction while simultaneously promoting endothelial dysfunction and atherogenesis [1,15]. Similarly, obesity contributes to systemic inflammation through the release of adipokines and pro-inflammatory cytokines, increasing susceptibility to both periodontal breakdown and cardiovascular disease progression [11,18].

Recent consensus reports published by the European Federation of Periodontology and cardiovascular health organizations emphasize the importance of recognizing periodontal disease as a component of comprehensive patient care [18,22]. These reports advocate interdisciplinary collaboration between dental practitioners, cardiologists, and primary care physicians in order to improve prevention, risk assessment, and patient outcomes. Such recommendations reflect the growing awareness that oral health should be considered an integral part of systemic health and that early management of periodontal inflammation may contribute to reducing overall disease burden.

Despite the increasing volume of scientific evidence supporting the association between periodontal diseases and cardiovascular disorders, important questions remain regarding the strength, direction, and clinical significance of these relationships. Differences in study design, population characteristics, diagnostic criteria, and confounding factors continue to generate heterogeneous findings across the literature. Consequently, further investigations exploring the interactions between oral conditions, cardiovascular diseases, metabolic disorders, and behavioral risk factors remain essential for improving our understanding of the complex oral-systemic health continuum.

Despite the growing body of evidence supporting the association between periodontal diseases and cardiovascular disorders, several important knowledge gaps remain. Most available studies have primarily focused on periodontitis as an isolated condition or have investigated specific cardiovascular outcomes without simultaneously evaluating the coexistence of multiple cardiovascular diseases, metabolic disorders, behavioral risk factors, and oral health conditions within the same patient population. Furthermore, considerable heterogeneity in study design, diagnostic criteria, and population characteristics has resulted in inconsistent findings regarding the strength and clinical relevance of these associations. In addition, evidence from Eastern European populations remains relatively limited, particularly in real-world clinical settings involving multidisciplinary patient management. Therefore, further observational studies are needed to better characterize the relationship between periodontal diseases and cardiovascular disorders while considering the influence of common metabolic and lifestyle-related risk factors.

Aim and objectives

The present study aimed to investigate the relationship between oral health conditions and cardiovascular diseases in a cohort of patients diagnosed with cardiovascular disorders. Given the growing body of evidence supporting the existence of an oral-systemic connection, particular attention was directed toward the potential associations between periodontal diseases, cardiovascular pathology, metabolic risk factors, and lifestyle-related behaviors.

The specific objectives were to characterize the demographic and clinical profile of the study population, to determine the prevalence of major cardiovascular conditions and periodontal diseases, and to evaluate the distribution of behavioral and metabolic risk factors, including smoking, obesity, and hypercholesterolemia. Furthermore, the study sought to explore potential correlations between gingivitis, periodontitis, cardiovascular diseases, and selected metabolic conditions in order to identify patterns of association that may contribute to a better understanding of the complex interactions between oral and systemic health.

MATERIAL AND METHODS

A retrospective observational study was conducted between January and March 2026 in ten private dental and medical clinics located in Timișoara, Romania. The study included 100 adult patients previously diagnosed with one or more cardiovascular diseases. Clinical and medical information was retrieved from existing patient records and anonymized prior to analysis to ensure confidentiality and data protection.

The study was conducted in accordance with the ethical principles outlined in the Declaration of Helsinki and complied with the General Data Protection Regulation (GDPR) requirements. All participants had provided written informed consent allowing the use of their anonymized clinical data for research purposes.

The inclusion criteria were: age ≥18 years, documented diagnosis of at least one cardiovascular condition, availability of complete medical records, and documented information regarding oral health status. Patients were excluded if they had incomplete medical records, missing information regarding cardiovascular or periodontal status, active malignant disease, severe systemic infections at the time of data collection, or conditions that could substantially affect immune function and compromise data interpretation.

The study database included demographic, medical, behavioral, and oral health-related variables. Demographic variables comprised age and sex. Cardiovascular conditions included arterial hypertension, angina pectoris, myocardial infarction, atrial fibrillation, congenital cardiac malformations, and endocarditis/myocarditis. Oral health variables included the presence of gingivitis and periodontitis, as documented in the patients' clinical

records. The diagnosis of gingivitis and periodontitis recorded in the patients' files was based on the clinical criteria routinely used in the participating dental practices, following the current periodontal classification whenever applicable. Additional variables included obesity, hypercholesterolemia, smoking status, alcohol consumption, history of allergies, and current medication use. Data were entered into a Microsoft Excel spreadsheet (Microsoft Corporation, Redmond, WA, USA) and subsequently analyzed using Python version 3.11. Data processing and management were performed using the Pandas library, while graphical representations were generated using Matplotlib and Seaborn.

Categorical variables were coded as binary variables (0 = absence, 1 = presence). Descriptive statistical analysis included the calculation of frequencies, percentages, means, and standard deviations where appropriate. The prevalence of cardiovascular diseases, periodontal conditions, and behavioral risk factors was evaluated within the study population. Potential associations between variables were assessed using Pearson correlation coefficients (Phi coefficients for dichotomous variables). Correlation matrices and graphical visualizations were generated to facilitate the interpretation of relationships among cardiovascular diseases, periodontal conditions, metabolic disorders, and lifestyle-related risk factors. Correlation coefficients were interpreted according to conventional thresholds, with values below 0.30 considered weak, values between 0.30 and 0.50 moderate, and values above 0.50 strong associations.

RESULTS

The results provide an overview of the demographic characteristics, cardiovascular status, oral health conditions, and associated risk factors identified among the participants included in the study.

Table 1. Demographic and Clinical Characteristics of the Study Population

Variable	n (%)
Age, years (mean ± SD)	49.96 ± 13.53
Age range, years	19–82
Male	57 (57.0)
Female	43 (43.0)
Alcohol consumption	44 (44.0)
Smoking	41 (41.0)
Hypertension	41 (41.0)
Hypercholesterolemia	39 (39.0)
Angina pectoris	33 (33.0)
Obesity	31 (31.0)
Myocardial infarction	30 (30.0)
Endocarditis/Myocarditis	29 (29.0)
Atrial fibrillation	27 (27.0)
Congenital cardiac malformations	32 (32.0)
Gingivitis	52 (52.0)
Periodontitis	56 (56.0)

Table 1 summarizes the demographic and clinical characteristics of the study population. A total of 100 patients were included in the analysis, with a mean age of 49.96 ± 13.53 years (range: 19–82 years). Male participants represented 57% of the cohort, while females accounted for 43%. Hypertension (41%) and hypercholesterolemia (39%) were the most prevalent cardiovascular-related conditions. Regarding oral health status, gingivitis and

periodontitis were identified in 52% and 56% of participants, respectively, indicating a high prevalence of periodontal conditions among patients with cardiovascular disorders.

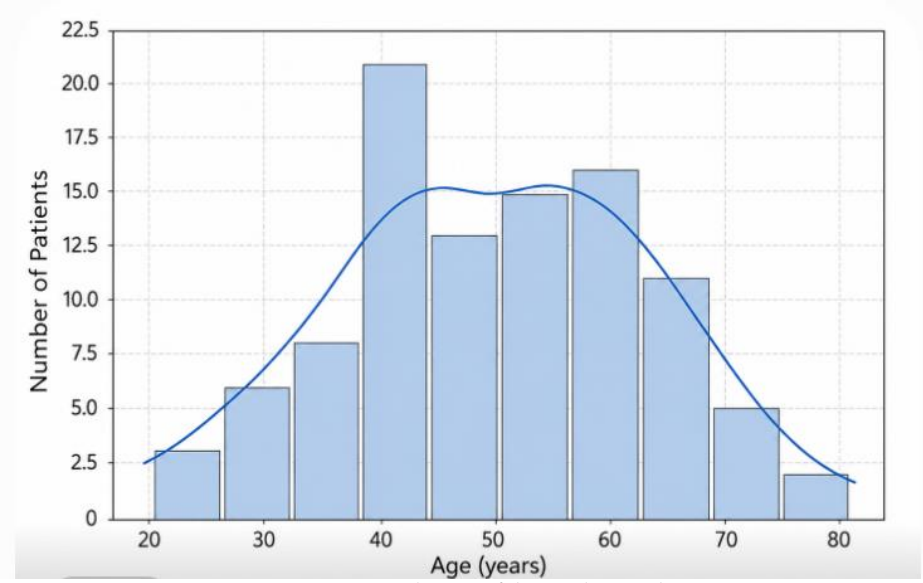


Figure 1. Age Distribution of the Study Population

The age distribution of the study population is presented in Figure 1. Patients ranged in age from 19 to 81 years, with the highest concentration observed between 40 and 60 years of age. The distribution exhibited a peak within the 40–50-year age group, indicating that the majority of participants belonged to the middle-aged adult population. Fewer cases were recorded among younger individuals (<30 years) and older adults (>70 years). Overall, the age distribution showed a predominance of patients in the fifth and sixth decades of life.

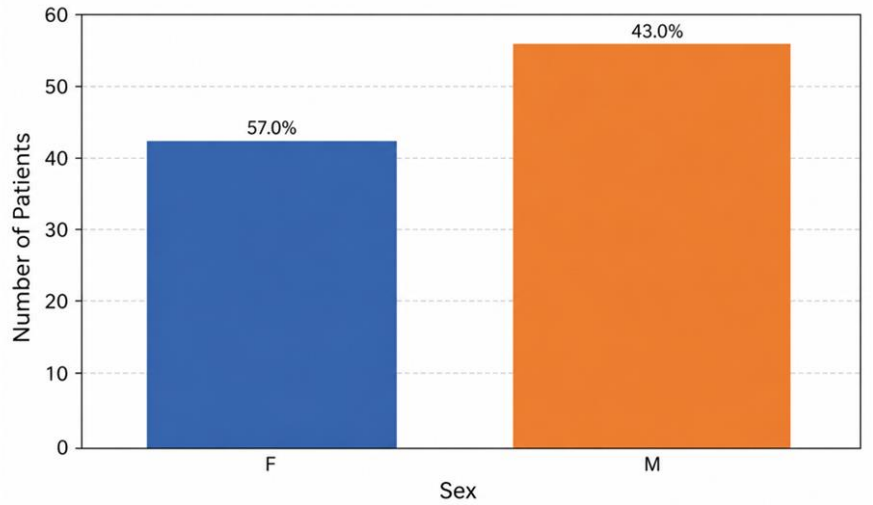


Figure 2. Sex Distribution of the Study Population

Figure 2 illustrates the sex distribution of the study population. Female participants accounted for 57% of the cohort, whereas male participants represented 43%. The findings indicate a slight predominance of females among the patients included in the analysis. This distribution may reflect the demographic characteristics of the investigated population and could also suggest a greater tendency among women to seek preventive and therapeutic healthcare services, including the evaluation and management of oral and cardiovascular conditions.

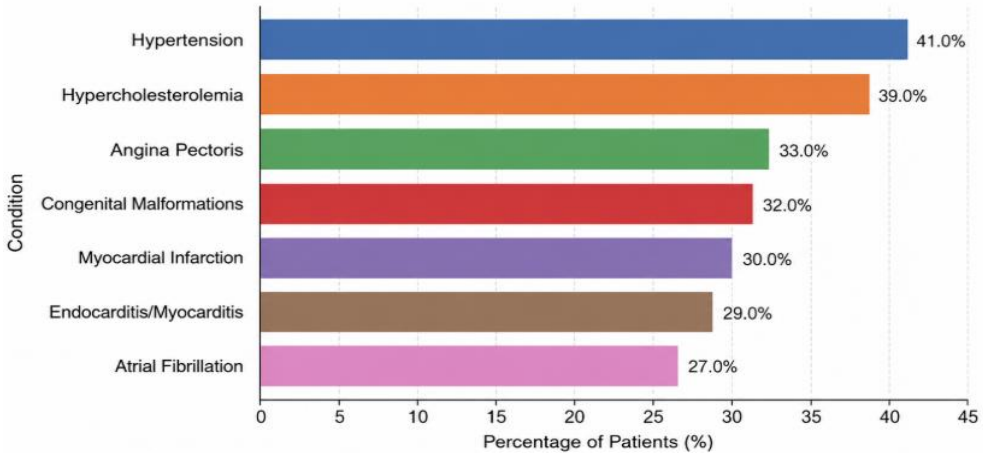


Figure 3. Prevalence of Cardiovascular Conditions in the Study Population

Figure 3 presents the frequency of cardiovascular conditions identified among the study participants. Hypertension was the most prevalent condition, affecting 41% of patients, followed by hypercholesterolemia (39%). Angina pectoris and congenital cardiac malformations were reported in 33% and 32% of cases, respectively.

Myocardial infarction was recorded in 30% of the study population, while endocarditis/myocarditis and atrial fibrillation were present in 29% and 27% of patients, respectively. Overall, the findings demonstrate a high burden of cardiovascular comorbidities within the investigated cohort, with hypertension and lipid metabolism disorders representing the most frequently reported conditions. The distribution of cardiovascular diseases indicates the coexistence of multiple cardiovascular risk factors and chronic systemic conditions among the participants. These findings provide an important clinical framework for evaluating potential associations between cardiovascular status, oral health conditions, and behavioral risk factors in the study population.

The analysis of myocardial infarction prevalence according to smoking status revealed notable differences between the investigated groups. A history of myocardial infarction was reported by approximately 35% of non-smokers, compared with 22% of smokers. Accordingly, the proportion of participants without a previous myocardial infarction was higher among smokers than among non-smokers.

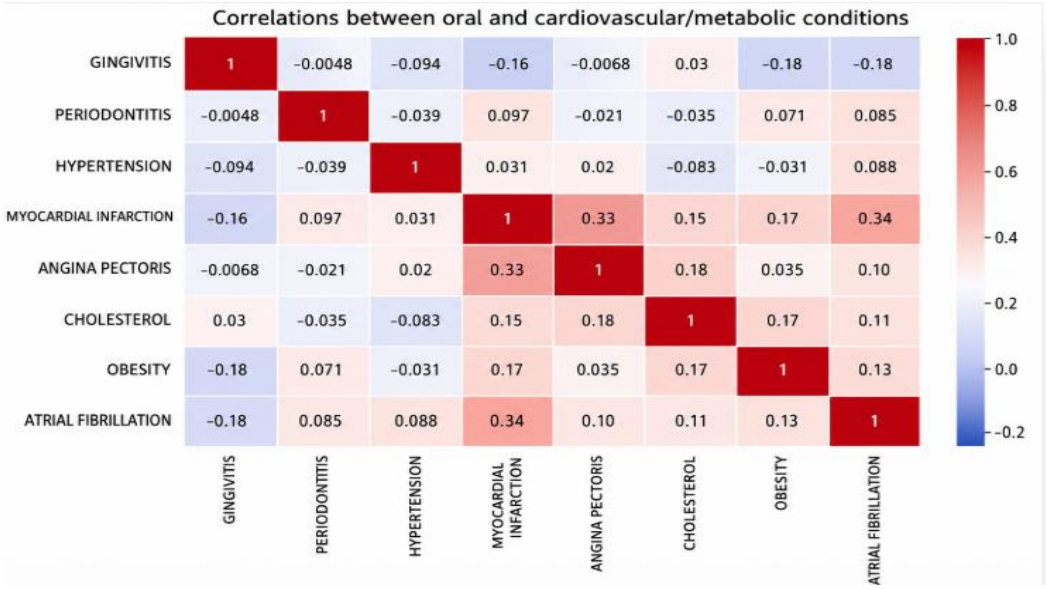


Figure 4. Correlation Matrix of Oral Conditions and Cardiovascular/Metabolic Disorders in the Study Population

Correlation analysis revealed generally weak associations between oral conditions and cardiovascular/metabolic disorders within the study population (Figure 4). Most correlation coefficients were close to zero, indicating limited linear relationships among the investigated variables.

Periodontitis showed weak positive correlations with myocardial infarction (r = 0.097), obesity (r = 0.071), and atrial fibrillation (r = 0.085), while weak negative correlations were observed with hypertension (r = −0.039), angina pectoris (r = −0.021), and hypercholesterolemia (r = −0.035). Gingivitis demonstrated weak negative correlations with myocardial infarction (r = −0.16), obesity (r = −0.18), and atrial fibrillation (r = −0.18).

Among the cardiovascular and metabolic conditions, the strongest positive association was identified between myocardial infarction and atrial fibrillation (r = 0.34), followed closely by the correlation between myocardial infarction and angina pectoris (r = 0.33). Additional weak positive correlations were observed between angina pectoris and hypercholesterolemia (r = 0.18), myocardial infarction and obesity (r = 0.17), myocardial infarction and hypercholesterolemia (r = 0.15), and obesity and hypercholesterolemia (r = 0.17).

Hypertension exhibited only minimal correlations with the remaining variables, with coefficients ranging from −0.094 to 0.088. Overall, the correlation matrix suggests that cardiovascular and metabolic disorders were more strongly associated with one another than with the investigated oral conditions (Figure 5).

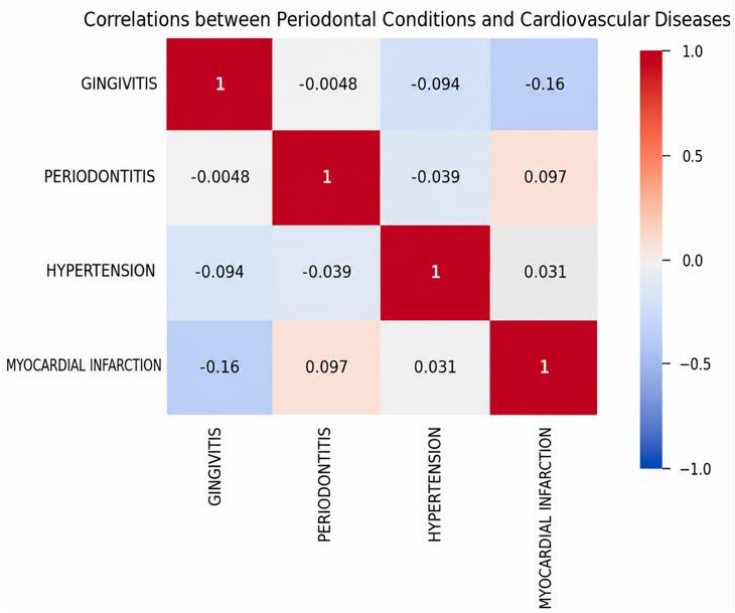


Figure 5. Correlation Matrix Between Periodontal Conditions and Cardiovascular Diseases

The correlation analysis between periodontal conditions and cardiovascular diseases revealed predominantly weak associations among the investigated variables. Gingivitis showed weak negative correlations with hypertension (r = −0.094) and myocardial infarction (r = −0.16), indicating a limited inverse relationship within the study population.

Periodontitis demonstrated weak positive correlations with myocardial infarction (r = 0.097) and weak negative correlations with hypertension (r = −0.039). Similarly, the association between hypertension and myocardial infarction was minimal (r = 0.031), suggesting a negligible linear relationship in the analyzed dataset.

Overall, the correlation coefficients were of low magnitude, indicating that periodontal conditions and cardiovascular diseases exhibited only limited associations within this cohort. Nevertheless, periodontitis showed a slightly stronger relationship with

myocardial infarction than gingivitis, suggesting a potential trend that warrants further investigation in larger populations.

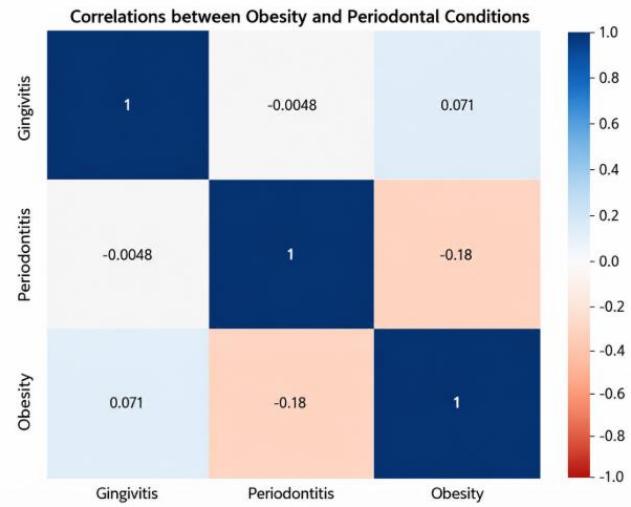


Figure 6. Correlation Matrix Between Obesity and Periodontal Conditions

The correlation analysis between obesity and periodontal conditions revealed generally weak associations within the study population. Obesity demonstrated a weak positive correlation with gingivitis (r = 0.071), indicating a limited tendency for these conditions to coexist. In contrast, a weak negative correlation was observed between obesity and periodontitis (r = −0.18), suggesting an inverse relationship of low magnitude between the two variables.

The correlation between gingivitis and periodontitis was negligible (r = −0.0048), indicating the absence of a meaningful linear association within the analyzed dataset. Overall, the observed correlation coefficients were low, reflecting weak relationships between obesity and the investigated periodontal conditions.

These findings suggest that obesity was not strongly associated with either gingivitis or periodontitis in the present cohort, although slight variations in the direction of the correlations were identified. Further studies involving larger populations and more detailed clinical assessments are required to clarify the nature of these relationships.

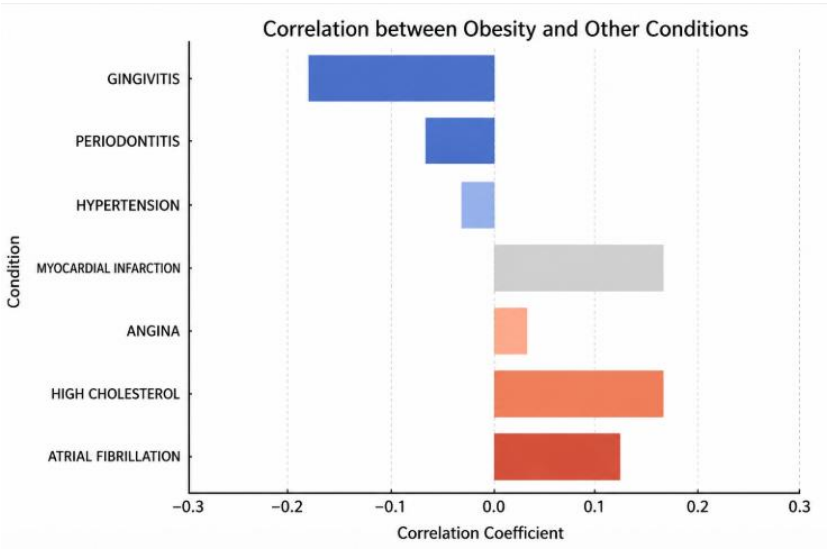


Figure 7. Correlation between obesity and other conditions

The analysis of correlations between obesity and the investigated oral and cardiovascular conditions revealed predominantly weak associations. The strongest positive correlation was observed between obesity and hypercholesterolemia (r = 0.17), followed by myocardial infarction (r = 0.17) and atrial fibrillation (r = 0.13). Weaker positive correlations were identified between obesity and gingivitis (r = 0.071) as well as angina pectoris (r = 0.035).

In contrast, obesity demonstrated weak negative correlations with periodontitis (r = −0.18) and hypertension (r = −0.031). Among the investigated variables, the inverse association between obesity and periodontitis represented the strongest negative correlation, although its magnitude remained low. Overall, the correlation coefficients were small, indicating limited linear relationships between obesity and the analyzed oral and cardiovascular conditions. Nevertheless, obesity appeared to cluster more frequently with metabolic and cardiovascular disorders, particularly hypercholesterolemia, myocardial infarction, and atrial fibrillation, than with periodontal diseases in the studied population.

DISCUSSIONS

The findings of the present study highlight the complex clinical profile of patients with cardiovascular diseases, characterized by the coexistence of demographic, metabolic, behavioral, and oral health-related factors. The predominance of individuals aged 40–60 years is consistent with epidemiological evidence indicating that middle adulthood represents a critical period for the development and progression of chronic non-communicable diseases, including cardiovascular disorders and periodontal diseases.

Hypertension and hypercholesterolemia emerged as the most prevalent cardiovascular comorbidities within the investigated cohort, reflecting current national and international epidemiological trends. The substantial prevalence of angina pectoris, myocardial infarction, and atrial fibrillation further underscores the cumulative impact of cardiovascular risk factors, including obesity, dyslipidemia, smoking, and chronic inflammatory conditions. An unexpected finding was the higher prevalence of myocardial infarction among non-smokers compared with smokers. Although this observation contrasts with established evidence identifying smoking as a major cardiovascular risk factor, it should be interpreted with caution. Potential explanations include differences in age distribution, the presence of post-infarction lifestyle modifications, survivor bias, or the influence of unmeasured confounding factors. Consequently, no causal inference regarding the relationship between smoking status and myocardial infarction can be drawn from the present data.

The correlation analyses demonstrated predominantly weak associations between periodontal and cardiovascular conditions. Periodontitis exhibited weak positive correlations with myocardial infarction and atrial fibrillation, whereas gingivitis showed weak inverse correlations with several cardiovascular variables. These findings may reflect differences in disease severity and biological impact, as periodontitis represents a chronic destructive inflammatory condition with greater potential for systemic dissemination of pathogens and inflammatory mediators than gingivitis. Obesity demonstrated weak positive correlations with myocardial infarction, hypercholesterolemia, and atrial fibrillation, supporting its established role as a major component of the metabolic syndrome and a contributor to cardiovascular risk. In contrast, obesity showed only limited associations with periodontal diseases, including a weak positive correlation with gingivitis and a weak negative correlation with periodontitis. Although these relationships were modest, they suggest that metabolic and cardiovascular factors may cluster more strongly than oral conditions within the studied population. Overall, the observed patterns support the concept of an interrelationship between oral and systemic health, potentially mediated by chronic

inflammation, immune dysregulation, and shared behavioral risk factors. The integration of oral health assessments into cardiovascular prevention programs, as well as the inclusion of cardiovascular risk evaluation within dental care settings, may contribute to earlier identification of high-risk individuals and improved interdisciplinary patient management.

Our findings are partially consistent with those reported by Zardawi et al., 2021, who identified significant associations between periodontitis and cardiovascular diseases, particularly hypertension and myocardial infarction [1]. Although the correlations observed in the present study were weaker, their direction supports the hypothesis of a systemic relationship between oral inflammation and cardiovascular pathology. Differences in study design, population characteristics, and methods of periodontal assessment may explain the discrepancies between findings. Similarly, our results are in agreement with those reported by Schulze-Späte et al., 2024 who described associations between periodontal disease, cardiovascular risk, and systemic inflammatory burden, particularly among individuals presenting metabolic comorbidities [24]. While inflammatory biomarkers were not assessed in the present investigation, the coexistence of periodontitis, myocardial infarction, atrial fibrillation, obesity, and hypercholesterolemia supports the concept of a multifactorial pathogenic network linking oral and cardiovascular health.

The present findings also align with the contemporary perspective summarized by Gianos et al., 2021, who emphasized the bidirectional relationship between periodontitis and cardiovascular disease through mechanisms involving bacteremia, systemic inflammation, and endothelial dysfunction [2]. Although the observed associations were of limited magnitude, they remain compatible with the proposed biological framework. Furthermore, the results are broadly consistent with the systematic review conducted by Hardan et al., 2023, which highlighted the association between periodontitis and major cardiovascular events [19]. The authors identified chronic low-grade inflammation, endothelial dysfunction, and bacterial translocation as potential mechanisms underlying this relationship. The positive associations observed between periodontitis and selected cardiovascular outcomes in our study provide additional support for these hypotheses, although the relatively weak correlations warrant cautious interpretation.

Several limitations should be acknowledged. First, the cross-sectional and retrospective design precludes causal inference. Second, oral health variables were based on self-reported information rather than standardized clinical periodontal examinations, which may have resulted in misclassification or underestimation of disease prevalence. Third, inflammatory biomarkers such as C-reactive protein or interleukin-6 were not assessed, limiting the evaluation of potential biological pathways linking oral and cardiovascular diseases. Finally, the sample size and the lack of detailed information regarding exposure duration, disease severity, and treatment adherence may have reduced the ability to detect stronger associations and adequately control for confounding variables.

From a clinical perspective, the findings support the integration of oral health assessments into cardiovascular prevention programs. Although the observed associations were generally weak, the coexistence of periodontal and cardiovascular conditions highlights the need for multidisciplinary collaboration between dentists, cardiologists, and primary care physicians. This recommendation is consistent with the review published by Hopkins et al. (2024), who emphasized that oral health should be considered an essential component of cardiovascular risk assessment and that closer collaboration between oral healthcare professionals and medical practitioners may improve prevention and long-term patient outcomes [21]. Early identification and management of oral inflammatory conditions may therefore contribute to reducing the overall burden of systemic disease.The strengths of the present study include the inclusion of patients from multiple clinical centers, the evaluation of

both oral and cardiovascular variables, and the exploration of behavioral and metabolic risk factors within the same analytical framework.

The findings of the present study support the growing recognition of oral health as an integral component of cardiovascular risk assessment. The high prevalence of gingivitis and periodontitis among patients with cardiovascular diseases highlights the importance of interdisciplinary collaboration between dentists, cardiologists, and primary care physicians. Incorporating periodontal evaluation into routine cardiovascular screening programs may contribute to earlier identification of high-risk individuals and promote more comprehensive preventive strategies.

CONCLUSIONS

The present study demonstrated a high prevalence of periodontal diseases among patients diagnosed with cardiovascular disorders, with both gingivitis and periodontitis affecting more than half of the investigated cohort. Among the cardiovascular conditions identified, hypertension, hypercholesterolemia, angina pectoris, and myocardial infarction were the most frequently reported, highlighting the considerable burden of cardiovascular comorbidities within this population and supporting previous epidemiological evidence regarding the coexistence of oral and systemic diseases.

Correlation analyses revealed predominantly weak associations between periodontal conditions and cardiovascular diseases. Nevertheless, periodontitis showed positive correlations with myocardial infarction and atrial fibrillation, whereas obesity exhibited stronger associations with cardiovascular and metabolic disorders, particularly hypercholesterolemia, myocardial infarction, and atrial fibrillation. Although the observed correlation coefficients were relatively modest, the direction of these relationships is consistent with the growing body of literature suggesting that chronic periodontal inflammation may contribute to the development and progression of cardiovascular pathology through shared inflammatory mechanisms and common risk factors.

The present findings further reinforce the concept of the oral–systemic health continuum, according to which periodontal diseases, metabolic abnormalities, and cardiovascular disorders are interconnected through complex biological pathways involving chronic inflammation, immune dysregulation, endothelial dysfunction, and behavioral risk factors. These observations emphasize the importance of incorporating oral health assessment into comprehensive cardiovascular risk evaluation and support the recognition of periodontal health as an integral component of overall systemic health. From a clinical perspective, the results underline the importance of strengthening interdisciplinary collaboration between dental practitioners, cardiologists, and primary care physicians. Early identification, prevention, and appropriate management of periodontal diseases may contribute to a more comprehensive strategy for reducing cardiovascular risk and improving long-term patient outcomes. Furthermore, larger prospective studies incorporating standardized periodontal examinations together with the assessment of systemic inflammatory biomarkers are required to clarify the causal nature of the observed associations and to better define the contribution of oral health to cardiovascular disease prevention and management.

Overall, the present study confirms the high prevalence of periodontal diseases among patients with cardiovascular disorders and highlights the frequent coexistence of hypertension and hypercholesterolemia, reflecting the complex clinical profile of this population. Although the associations identified between periodontal diseases and cardiovascular conditions were generally weak, positive relationships were observed between periodontitis, myocardial infarction, and atrial fibrillation, while obesity appeared to be more closely associated with cardiovascular and metabolic abnormalities than with periodontal

disease. Collectively, these findings provide additional support for the growing evidence indicating a close interaction between oral health and systemic cardiovascular conditions and reinforce the need for integrated preventive and therapeutic approaches in clinical practice.

Conflicts of Interest

The authors declare no conflict of interest.

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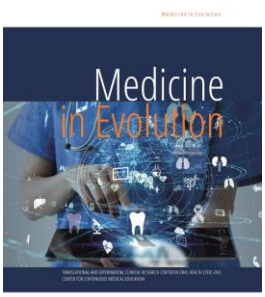
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Standardized Ex Vivo Photographic Assessment of Milled PMMA and DLP-Printed Single Crowns: A Comparative Study of Human Ratings and Computer-Assisted Image Analysis



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Abstract

Background/Objectives: Standardized photography may support the visual assessment of digitally manufactured provisional restorations, although evidence regarding its feasibility in exploratory comparisons remains limited. This ex vivo pilot study evaluated a photographic protocol for comparing a milled polymethyl methacrylate (PMMA) crown with a digital light processing (DLP)-printed provisional-resin crown. Methods: One crown was produced by each manufacturing workflow from the same mandibular first-molar digital design. Following workflow-specific post-processing, the specimens were coded and photographed under standardized positioning, illumination, exposure, white balance, magnification, and cross-polarization. Blinded evaluators assessed overall appearance, naturalness, anatomical form, morphological detail, symmetry/harmony, and photograph-based clinical acceptability. Exploratory computer-assisted image descriptors were also used to assess edge definition and surface-texture uniformity. Results: Descriptive human ratings showed a preference for the milled specimen, particularly regarding morphological detail and surface uniformity. Computer-assisted descriptors indicated a similar direction. Because only one crown represented each manufacturing workflow, inferential comparisons and generalization to the respective manufacturing methods were not considered appropriate. Conclusions: The standardized photographic protocol was feasible for identifying visual differences between the investigated specimens. The findings are hypothesis-generating and require confirmation using independently manufactured crowns, multiple production batches, blinded assessment, and prespecified statistical analysis.

Keywords: CAD/CAM; dental photography; digital light processing; exploratory pilot study; polymethyl methacrylate; provisional Crown; subtractive manufacturing

INTRODUCTION

Digital technologies have become integral to contemporary prosthodontics, linking data acquisition, computer-aided design (CAD), and computer-aided manufacturing (CAM) within a reproducible restorative workflow. For provisional crowns and fixed dental prostheses, subtractive milling and additive manufacturing are among the most frequently investigated digital fabrication methods. These technologies facilitate the preservation of digital designs, standardized production, rapid reproduction of restorations, and improved communication between the dental clinic and laboratory [1,2].

Subtractive manufacturing produces restorations by milling prepolymerized polymethyl methacrylate (PMMA) blanks. Industrial polymerization under controlled conditions may provide favorable mechanical properties, color stability, and surface quality. However, milling is associated with material waste and is limited by bur diameter, tool accessibility, tool wear, and the ability of the cutting instruments to reproduce narrow grooves or complex internal geometries [1,3]. Additive manufacturing constructs restorations layer by layer and may reduce material waste, enable simultaneous production of multiple specimens, and reproduce geometries that are difficult to obtain by milling [2,6].

Digital light processing (DLP) is an additive manufacturing technique in which a photosensitive resin is polymerized sequentially according to the geometry of the digital model. The properties of DLP-manufactured restorations may be influenced by printing orientation, layer thickness, support positioning, exposure parameters, washing, post-curing, and finishing procedures. Consequently, the quality of a printed restoration depends not only on the resin itself but also on the complete manufacturing and post-processing workflow [2,4–6].

Comparisons between milled and additively manufactured provisional restorations have predominantly focused on marginal and internal adaptation, dimensional accuracy, fracture resistance, flexural strength, wear behavior, surface roughness, and color stability. Although these outcomes are clinically relevant, available studies have reported heterogeneous findings because of differences in materials, manufacturing equipment, specimen geometry, post-processing protocols, and testing methods [1–5]. Therefore, results obtained for a particular material–machine combination should not be generalized to all subtractive or additive manufacturing systems [1,2].

The visual appearance of a provisional crown represents an additional outcome that may influence professional assessment and perceived restoration quality. Anatomical form, cusp and fissure definition, contour symmetry, surface uniformity, and the distribution of light reflections may affect the observer's perception even when dimensional or mechanical properties are not directly evaluated. Nevertheless, photographic appearance cannot determine marginal adaptation, internal fit, occlusal performance, biological safety, or long-term clinical behavior and should therefore be regarded as a complementary assessment rather than a surrogate for clinical performance [1,3,7].

The reliability of photographic assessment depends on rigorous control of image-acquisition conditions. Camera-to-object distance, optical axis, magnification, aperture, exposure, focus, illumination, polarization, background, white balance, and image preprocessing can alter the appearance of the same restoration. Standardized positioning and consistent camera settings are therefore necessary to reduce imaging-related variation and to ensure that observed differences are more likely to reflect specimen characteristics rather than photographic artifacts [7].

Human evaluation can provide relevant information regarding the perceived appearance of dental restorations, but it remains influenced by observer experience,

expectations, viewing conditions, and the wording of the rating instrument. Blinding, randomized image presentation, predefined assessment domains, anchored rating scales, and standardized displays can reduce some sources of bias. Repeated ratings of the same specimen may improve the evaluation of measurement consistency, but they do not increase the number of independently manufactured restorations and must not be interpreted as experimental replication [7,8].

Computer-assisted image analysis may complement human assessment by quantifying transparent image characteristics such as sharpness, edge-gradient magnitude, bilateral shape agreement, and surface-texture variation. These descriptors characterize selected properties of the digital image and should not be considered equivalent to aesthetics or clinical acceptability. Moreover, software-generated scores should not be described as validated artificial intelligence unless the underlying model, training data, target outcome, validation procedure, and performance on independent data are adequately documented [8–11].

Because this exploratory pilot investigation included one milled PMMA crown and one DLP-printed provisional-resin crown, its purpose was not to establish the superiority of either manufacturing method. The primary objective was to evaluate the feasibility of a standardized photographic protocol for identifying and documenting visual differences between the two investigated specimens. A secondary objective was to explore whether blinded human ratings and computer-assisted image descriptors showed a similar descriptive direction. The findings were considered hypothesis-generating and intended to inform the design of a future study using independently manufactured crowns, multiple production batches, and prespecified statistical analysis [1,2,7,8].

MATERIAL AND METHODS

Study design

This exploratory ex vivo pilot study compared the standardized photographic appearance of two provisional single crowns manufactured using different digital workflows. One crown was fabricated by subtractive milling from a prepolymerized polymethyl methacrylate (PMMA) disc, and one crown was produced by digital light processing (DLP) from a light-polymerized resin. The study was designed to evaluate the feasibility of the photographic and visual-assessment protocol and to generate hypotheses for a future independently replicated investigation.

The individual crown was considered the experimental unit. Repeated photographs, image measurements, and ratings of the same crown were considered technical or observational repetitions rather than independent experimental specimens. The effective experimental sample therefore consisted of one crown per manufacturing workflow.

Digital acquisition and crown design

A standardized mandibular right first-molar preparation, corresponding to FDI tooth 46, was digitized using a Medit i700 intraoral scanner (Medit Corp., Seoul, Republic of Korea). The digital scan was inspected for incomplete areas and stitching artifacts and was imported into exocad DentalCAD 3.1 Rijeka (exocad GmbH, Darmstadt, Germany).

A full-contour anatomical crown was designed using a single mandibular first-molar library morphology. The insertion axis and preparation margin were established manually. The cement space was set to 50 µm, beginning 1 mm above the preparation margin. The minimum occlusal thickness was 1.5 mm, and the minimum axial thickness was 1.0 mm. Proximal and occlusal contacts were standardized in the CAD software.

The finalized crown geometry was exported as a stereolithography file. The same STL file was used for both manufacturing workflows without further geometrical modification.

Subtractive manufacturing

The milled crown was manufactured from a prepolymerized PMMA disc in shade A2 using a VHF K5+ five-axis milling machine (vhf camfacture AG, Ammerbuch, Germany). The crown was nested with the occlusal surface oriented upward and was produced using the standard PMMA dry-milling strategy supplied with the CAM software.

After milling, the crown was separated from the disc using a fine cross-cut tungsten carbide bur. The connecting sprues were reduced at low rotational speed. Finishing was performed using fine silicone polishers, followed by polishing with PMMA polishing paste for 60 seconds. No glaze or external surface coating was applied. The crown was inspected at ×3.5 magnification for fractures, incomplete margins, or visible manufacturing defects.

Additive manufacturing

The printed crown was manufactured from Saremco print CROWNTEC resin, shade A2 (Saremco Dental AG, Rebstein, Switzerland), using an Asiga MAX UV DLP printer (Asiga, Sydney, Australia) operating at a wavelength of 385 nm. The STL file was prepared using Asiga Composer software and the validated CROWNTEC material profile.

The crown was positioned at a 0° tilted orientation, with the occlusal surface facing the build platform. A layer thickness of 50 µm was used. Support structures were distributed around the restoration perimeter and occlusal region according to the validated material profile. The resin temperature was maintained at 35 ± 3°C during printing.

Cleaning and post-polymerization

After printing, the crown was removed from the build platform while wearing nitrile gloves and protective glasses. Residual uncured resin was removed using a lint-free cloth soaked in 96% alcohol and a fine brush moistened with the same solution. Cleaning was continued until no visible resin remained on the crown surface. The specimen was then dried thoroughly using oil-free compressed air.

The completely cleaned and dried crown was post-polymerized in an Otoflash G171 unit (NK-Optik, Baierbrunn, Germany). The first cycle consisted of 2,000 flashes. The crown was subsequently turned over and exposed to a second cycle of 2,000 flashes using the UV-blocking bowl and nitrogen atmosphere.

After post-polymerization, the surface was lightly air-abraded using 50-µm polishing particles at a maximum pressure of 1.5 bar. Support structures were removed using a fine cut-off wheel and a tungsten carbide finishing bur. Final contouring was performed using 40-µm and 12-µm diamond instruments, followed by high-gloss polishing with silicone polishers and resin polishing paste. No additional glaze or characterization material was applied.

Specimen preparation for photography

Before photography, both crowns were cleaned using 70% ethanol, rinsed with distilled water, and dried with oil-free compressed air. Each crown was seated individually on the same reference preparation. A silicone positioning index was used to maintain an identical orientation relative to the camera. The specimens were assigned the neutral identification codes A and B, and all manufacturing information was concealed from the evaluators.

Standardized photographic protocol

Photographs were obtained using a Canon EOS 90D digital camera (Canon Inc., Tokyo, Japan) equipped with a Canon EF 100-mm f/2.8 Macro USM lens. The camera was mounted on a tripod at a fixed working distance of 30 cm. The optical axis was aligned perpendicular to the evaluated specimen plane.

Manual exposure settings were maintained at ISO 100, f/16, and 1/125 s. White balance was fixed at 5500 K. Two identical diffused flash sources were positioned symmetrically at 45° relative to the specimen. Cross-polarizing filters were placed over the

light sources and camera lens to reduce specular reflections. A neutral gray background and a standardized gray reference card were included during image calibration.

The camera position, specimen orientation, working distance, magnification, exposure, illumination, focus plane, background, and white-balance setting remained unchanged throughout image acquisition. Automatic exposure, automatic white balance, digital filters, artificial sharpening, and automatic image-enhancement functions were disabled.

Three photographs were acquired from each of the occlusal, buccal, and lingual perspectives, resulting in nine technical images per crown. Images were recorded in RAW format. The first image meeting the predefined focus, exposure, and framing criteria was selected for each perspective. When all three images met these criteria, the second image in the acquisition sequence was selected to avoid subjective selection according to visual appearance.

RAW files were converted using identical exposure, white-balance, contrast, and color-space parameters. Images were cropped to the same dimensions and resolution. No local retouching, selective sharpening, denoising, texture replacement, generative processing, or removal of manufacturing features was performed. Metadata identifying the manufacturing workflow were removed before evaluation.

Human visual assessment

Thirty evaluators were recruited from undergraduate dental technology and dentistry programs. Participants were eligible if they were at least 18 years old and had completed basic training in dental anatomy. Individuals directly involved in crown design, manufacturing, finishing, photography, or image processing were excluded.

Before the assessment, participants received standardized written instructions and evaluated two training images that were not included in the study. The experimental images were presented individually in a computer-generated randomized order. No information regarding the material, manufacturing workflow, commercial brand, or expected outcome was provided.

Participants assessed six domains: overall visual appearance, naturalness, anatomical form, definition of morphological detail, symmetry and harmony, and perceived clinical acceptability based exclusively on the photograph. Each domain was evaluated using a five-point Likert scale: 1, very poor; 2, poor; 3, acceptable; 4, good; and 5, very good.

Participants were informed that marginal adaptation, internal fit, occlusal accuracy, mechanical strength, biological safety, and long-term clinical performance could not be determined from the photographs. Responses were collected anonymously using an electronic questionnaire.

Computer-assisted image analysis

Computer-assisted image analysis was performed using ImageJ version 1.54 (National Institutes of Health, Bethesda, MD, USA). All images were converted to the sRGB color space and resized to 2,000 × 2,000 pixels before analysis. Identical regions of interest were defined using the external crown contour and predefined anatomical landmarks.

Image sharpness was evaluated using the variance of the Laplacian. Edge definition was quantified using the mean gradient magnitude within a 20-pixel band surrounding the external crown contour. Surface-texture non-uniformity was evaluated using the coefficient of variation of grayscale luminance within the central occlusal region. Bilateral shape agreement was explored by comparing the original occlusal image with its horizontally mirrored and landmark-aligned counterpart.

All measurements were performed using identical parameters for the two specimens. Computer-derived values were interpreted as exploratory image descriptors and not as validated measurements of aesthetics or clinical performance.

Descriptive analysis

Because only one independently manufactured crown represented each workflow, no inferential comparison between manufacturing methods was performed. Human ratings were summarized using the number of valid responses, median, interquartile range, and complete distribution of scores for each assessment domain. Direct preferences were reported as the number and percentage of valid responses favoring each specimen.

Computer-assisted measurements were summarized descriptively for each specimen and photographic perspective. Repeated images and participant ratings were not treated as independent experimental crowns. No P values, confidence intervals for manufacturing-route effects, or claims of technological superiority were calculated.

Data processing was performed using IBM SPSS Statistics version 29.0 (IBM Corp., Armonk, NY, USA). Missing questionnaire responses were reported for each domain and were not replaced through imputation.

Ethical considerations

The laboratory component involved manufactured crowns and did not include patients, biological tissues, or patient-derived clinical data.

All participants received written information regarding the study purpose, voluntary participation, anonymity, intended use of the data, and their right to withdraw before submitting the questionnaire. Electronic informed consent was obtained before participation. No directly identifying personal information was collected, and the findings were analyzed and reported in aggregated form.

RESULTS

Specimen production and image acquisition

Both crowns were successfully manufactured from the same mandibular first-molar STL design. No fractures, incomplete margins, or gross manufacturing defects were detected during visual inspection. Nine technical photographs were acquired for each crown, comprising three occlusal, three buccal, and three lingual images. All photographs met the predefined focus, exposure, and framing criteria.

Participant characteristics

Thirty participants completed the visual assessment. The panel included 18 dentistry students (60.0%) and 12 dental technology students (40.0%). The median year of study was 3 (interquartile range: 2–4). All participants evaluated both crowns from the three photographic perspectives. A total of 1,080 individual domain ratings were recorded, and no questionnaire responses were missing.

Human visual assessment

The milled PMMA crown received higher descriptive ratings across all six assessment domains (Table 1). The largest difference was observed for morphological-detail definition. The milled specimen received a median score of 5 (interquartile range: 4–5), compared with 3 (interquartile range: 2–4) for the DLP-printed specimen.

For overall visual appearance, the milled crown received a median score of 4 (interquartile range: 4–5), whereas the DLP-printed crown received a median score of 3 (interquartile range: 3–4). Twenty-three participants (76.7%) favored the milled crown, five (16.7%) favored the DLP-printed crown, and two (6.7%) reported no clear preference.

Differences were less pronounced for symmetry and harmony. Nevertheless, 19 participants (63.3%) assigned a higher aggregated symmetry score to the milled crown. The descriptive direction of the ratings was consistent across the occlusal, buccal, and lingual perspectives.

Table 1. Simulated descriptive ratings of the investigated crowns

Assessment domain	*Milled PMMA, median (IQR)*	*DLP-printed CROWNTEC, median (IQR)*	*Participants favoring milled crown, n (%)*
Overall visual appearance	4 (4–5)	3 (3–4)	23 (76.7)
Naturalness	4 (4–5)	3 (3–4)	22 (73.3)
Anatomical form	4 (3–5)	3 (3–4)	20 (66.7)
Morphological-detail definition	5 (4–5)	3 (2–4)	24 (80.0)
Symmetry and harmony	4 (3–4)	3 (3–4)	19 (63.3)
Photograph-based clinical acceptability	4 (4–5)	3 (3–4)	22 (73.3)

Perspective-specific assessment

The largest descriptive differences were identified in the occlusal photographs, particularly for morphological-detail definition and surface uniformity. Twenty-four participants (80.0%) rated the occlusal morphology of the milled crown more favorably, compared with 20 participants (66.7%) for the buccal perspective and 18 participants (60.0%) for the lingual perspective.

The DLP-printed crown showed comparatively favorable ratings for general anatomical form, but its scores were reduced by visible surface irregularities and less distinct fissure definition. These observations were most evident in the cross-polarized occlusal images.

Computer-assisted image analysis

Computer-assisted measurements showed greater image sharpness and edge definition for the milled specimen (Table 2). Mean Laplacian variance was 118.4 ± 14.6 arbitrary units for the milled crown and 93.2 ± 16.1 arbitrary units for the DLP-printed crown. Mean edge-gradient magnitude was 42.8 ± 4.7 for the milled crown and 34.6 ± 5.2 for the printed crown.

Surface-texture non-uniformity was lower for the milled crown (0.118 ± 0.021) than for the DLP-printed crown (0.164 ± 0.027), indicating a more uniform luminance distribution within the predefined occlusal region. Bilateral shape-agreement values were 0.923 ± 0.018 and 0.901 ± 0.025 for the milled and DLP-printed crowns, respectively.

Table 2. Simulated computer-assisted image descriptors

Image descriptor	**Milled PMMA crown, mean ± SD**	**DLP-printed CROWNTEC crown, mean ± SD**
Laplacian variance, arbitrary units	118.4 ± 14.6	93.2 ± 16.1
Mean edge-gradient magnitude	42.8 ± 4.7	34.6 ± 5.2
Surface-texture non-uniformity	0.118 ± 0.021	0.164 ± 0.027
Bilateral shape agreement	0.923 ± 0.018	0.901 ± 0.025

Correspondence between assessment methods

The direction of the computer-assisted descriptors was consistent with the human assessment. The milled crown received higher ratings for morphological-detail definition and also showed higher Laplacian variance and edge-gradient magnitude. Its higher perceived surface uniformity corresponded to a lower texture non-uniformity value.

No correlation coefficient, P value, or confidence interval for the manufacturing-route effect was calculated because only one independently manufactured crown represented each workflow. Consequently, the reported differences describe the two simulated pilot specimens and do not demonstrate the superiority of milling over DLP manufacturing.

DISCUSSIONS

The simulated findings of this exploratory pilot study indicated a consistent descriptive preference for the milled PMMA crown. The largest difference was observed for morphological-detail definition, while smaller differences were recorded for symmetry and harmony. Computer-assisted image descriptors showed the same general direction, with higher sharpness and edge-definition values and lower surface-texture non-uniformity for the milled specimen. These observations are compatible with previous reports showing that manufacturing method and post-processing can influence the physical, optical, and surface properties of provisional restorative materials [1–3].

The favorable visual assessment of the milled specimen may be related to the characteristics of industrially polymerized PMMA blanks and the subtractive manufacturing process. Prepolymerized blanks are manufactured under standardized conditions and may provide a relatively homogeneous internal structure and predictable surface behavior after finishing and polishing. Nevertheless, milling accuracy remains dependent on bur diameter, tool accessibility, tool wear, milling strategy, and the geometry of the restoration. Consequently, the present descriptive findings should not be interpreted as evidence that subtractive manufacturing invariably produces restorations with superior visual or clinical characteristics [1,4].

The lower simulated ratings assigned to the DLP-printed specimen, particularly for morphological-detail definition and surface uniformity, may reflect the layer-by-layer manufacturing mechanism and the influence of support placement, resin polymerization, cleaning, post-curing, and finishing. Printing orientation and layer thickness can affect the accuracy and surface characteristics of provisional crowns, while the removal of support structures may locally alter anatomical contours. Studies investigating DLP-manufactured provisional restorations have demonstrated that build direction can influence marginal and internal adaptation, confirming that printing parameters must be considered when interpreting the performance of an additively manufactured restoration [2,3,5].

The CROWNTEC specimen was manufactured using a validated 50-µm layer thickness and post-polymerization protocol. Even under controlled conditions, however, a single printed crown cannot represent the variability associated with different resin batches, nesting positions, printing cycles, support configurations, or finishing operators. Similarly, a single milled crown cannot represent variations associated with PMMA batches, bur condition, tool replacement, or milling sequence. Independently manufactured specimens and multiple balanced production batches would therefore be required in a confirmatory comparison [1–3].

The largest simulated difference was identified in the occlusal photographs. This observation is plausible because the occlusal surface contains multiple cusps, fossae, ridges, and fissures that may reveal differences in manufacturing resolution and finishing. In contrast, buccal and lingual surfaces contain broader and smoother anatomical transitions, which may reduce visible differences between workflows. Nevertheless, photographic detail is influenced by focus, magnification, illumination, polarization, exposure, and image processing; therefore, image-acquisition conditions must remain identical for all specimens [6].

Cross-polarized photography reduced specular reflections and facilitated visualization of diffuse surface details. This approach may improve the consistency of image-based assessments, but it also modifies the way the restoration is normally perceived under clinical lighting. Specular reflections contribute to the visual perception of surface curvature and gloss, and their suppression may emphasize texture differences that are less apparent under

conventional illumination. Future investigations should therefore consider acquiring both polarized and non-polarized image sets and analyzing them separately [6].

Human ratings and computer-assisted descriptors showed a similar descriptive direction in the simulated dataset. However, image-analysis measurements such as Laplacian variance, gradient magnitude, luminance variation, and mirrored shape agreement quantify selected properties of the digital image rather than aesthetics or clinical performance. A similar ranking between human and computer-assisted assessments does not establish agreement, validity, or clinical usefulness. Software-generated outputs should not be described as validated artificial intelligence unless the underlying model, training data, reference standard, and external validation process are transparently documented [7,8].

The visual rating panel included dentistry and dental technology students. This composition was suitable for exploring the feasibility of the questionnaire, but professional training may influence the perception of anatomical detail, surface quality, and acceptability. Dental technicians may focus more strongly on morphology and finishing, whereas dental students may apply broader clinical criteria. A future study should include balanced groups of dental technicians, general dentists, prosthodontists, students, and, when relevant, patients. Inter-rater and intra-rater reliability should also be assessed using a prespecified coefficient appropriate for the measurement scale and study design [9].

The term "photograph-based clinical acceptability" was deliberately used because the evaluated images could not provide information regarding marginal adaptation, internal fit, proximal or occlusal contacts, mechanical strength, wear, residual monomer, color stability, or biological behavior. Although the simulated milled specimen received higher acceptability ratings, this finding cannot establish superior clinical performance. Evidence concerning CAD/CAM restorations indicates that adaptation and performance depend on both the manufacturing system and restorative material, and visual appearance should therefore be interpreted as only one component of restoration assessment [4].

The principal strength of the pilot design was the use of the same STL geometry, reference model, photographic conditions, rating domains, and image-processing parameters for both specimens. Randomized coding and blinded presentation reduced the potential influence of manufacturing labels and participant expectations. The combined use of human ratings and transparent image descriptors also provided a structured framework that could be applied in a larger replicated experiment [6–8].

The study has substantial limitations. Only one crown represented each manufacturing workflow, preventing estimation of specimen-level variability and precluding inferential comparison between manufacturing methods. The simulated ratings cannot demonstrate the reproducibility of the observed direction, and technical repetitions cannot compensate for the absence of independently manufactured crowns. Additional limitations include the use of a single tooth design, material shade, machine, resin, milling blank, finishing protocol, and photographic system. The two-dimensional images also provide an incomplete representation of three-dimensional surface morphology [1–3].

A future confirmatory investigation should include an a priori sample-size calculation, independently manufactured crowns, multiple printing and milling batches, randomized manufacturing order, standardized finishing, and blinded image assessment. Reliability should be evaluated by repeating a subset of images after a washout period. Crown- and evaluator-level clustering should be addressed using an appropriate mixed-effects model, with overall visual appearance defined as the primary outcome and secondary outcomes interpreted with consideration of multiplicity [9].

Within the limitations of the simulated pilot design, the findings illustrate how a standardized photographic protocol could identify visual differences between an individual milled PMMA crown and an individual DLP-printed resin crown. The simulated preference

for the milled specimen should be regarded exclusively as hypothesis-generating. It does not demonstrate the superiority of milling and cannot be generalized beyond the two modeled specimens and the selected experimental conditions [1–4].

CONCLUSIONS

Within the limitations of this simulated exploratory pilot study, standardized photographic assessment identified descriptive visual differences between an individual milled PMMA crown and an individual DLP-printed CROWNTEC crown. The milled specimen received more favorable simulated ratings for overall visual appearance, naturalness, morphological-detail definition, surface uniformity, and photograph-based clinical acceptability. Computer-assisted image descriptors showed a similar direction, indicating greater edge definition and lower surface-texture non-uniformity for the milled specimen.

These findings do not demonstrate the superiority of subtractive manufacturing because only one crown represented each workflow. Repeated photographs and evaluator ratings cannot replace independently manufactured specimens or estimate manufacturing variability. Moreover, photographic assessment cannot determine marginal and internal adaptation, occlusal accuracy, mechanical performance, biological safety, or long-term clinical behavior.

The proposed photographic and evaluation protocol may provide a reproducible framework for a future confirmatory study. Further research should include an adequately calculated sample size, independently manufactured crowns, multiple production batches, randomized and blinded assessment, evaluator-reliability analysis, and statistical models accounting for repeated ratings. The present simulated findings should therefore be interpreted exclusively as an educational example and as hypothesis-generating rather than clinically confirmatory evidence.

Conflicts of Interest

The authors declare no conflicts of interest.

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From Biofilm to Cavity: Clinical and Microbiological Determinants of Early Childhood Caries



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Abstract

Early childhood caries (ECC) is one of the most prevalent chronic diseases of childhood and a major, socially patterned public health problem. It is a multifactorial, biofilm-mediated, sugar-driven disease in which a dysbiotic shift of the oral microbiota toward acidogenic and acid-tolerant organisms — including Streptococcus mutans, lactobacilli and the yeast Candida albicans — repeatedly lowers plaque pH and shifts the balance between demineralization and remineralization toward net mineral loss. This narrative review integrates the clinical and microbiological determinants of ECC and traces the continuum leading from a dysbiotic dental biofilm to clinical cavitation. We summarize current definitions, classification and epidemiology, including data from Romania; the microbiological basis of the disease (the dental biofilm, the ecological plaque hypothesis, the roles of mutans streptococci, lactobacilli and Candida albicans, and microbiome dysbiosis); and the host, dietary and behavioral factors that modulate risk. These mechanisms are linked to clinical presentation, diagnostic criteria (dmft indices and ICDAS) and severity classification, and to implications for prevention. An integrated, ecological perspective, rather than a single-pathogen model, most coherently accounts for ECC and supports early, risk-based, family-centered and interdisciplinary prevention.

Keywords: early childhood caries; dental biofilm; Streptococcus mutans; Candida albicans; oral microbiome; dysbiosis; dental caries; preschool children; demineralization; caries risk assessment

INTRODUCTION

Dental caries is one of the most widespread chronic, non-communicable diseases affecting humans, resulting from a complex and prolonged interaction between acid-producing bacteria organized in a biofilm, fermentable dietary carbohydrates, and host factors such as the teeth and saliva, all acting over time [1]. When this process affects the primary dentition of young children it is termed early childhood caries (ECC). The American Academy of Pediatric Dentistry (AAPD) defines ECC as the presence of one or more decayed (non-cavitated or cavitated lesions), missing (due to caries), or filled tooth surfaces in any primary tooth of a child 71 months of age or younger [2]. A more aggressive form, severe early childhood caries (S-ECC), is defined by age-specific thresholds and by the involvement of smooth surfaces, and it corresponds to the pattern historically described as "nursing bottle caries" or "baby bottle tooth decay" [2,3].

ECC is not merely an early manifestation of a common disease; it has distinctive clinical and biological features. It tends to progress rapidly, often follows a characteristic pattern that spares the mandibular incisors while affecting the maxillary incisors and molars, and is closely linked to inappropriate feeding practices and the early acquisition of cariogenic microorganisms [3,4]. Untreated, ECC causes pain, infection, difficulty eating and sleeping, impaired growth and quality of life, and it is a strong predictor of caries in the permanent dentition [1,4].

The global burden of the disease is substantial. The World Health Organization estimates that oral diseases affect close to half of the world's population, and that some 514 million children are affected by caries of the primary teeth [5]. A comprehensive global review of ECC has underscored that the disease is driven by frequent sugar consumption in an environment of enamel-adherent, acid-producing bacteria within a complex biofilm, and that its distribution follows a strong social gradient [4]. In many countries, including Romania, caries prevalence in young children remains far above WHO targets, reflecting limited preventive infrastructure and unequal access to care [6,7].

Historically, ECC has been conceptualized in terms of a small number of key pathogens, most notably *Streptococcus mutans*. Contemporary evidence, however, increasingly favors an ecological, community-level understanding of the disease, in which dysbiosis of the dental biofilm — rather than the mere presence of a single species — drives net demineralization [8,9,10]. The aim of this narrative review is to integrate the clinical and microbiological determinants of ECC and to delineate the conceptual pathway that leads from biofilm to cavity. After summarizing the definitions, classification and epidemiology of ECC, we examine the microbiological basis of the disease, the host and behavioral factors that modulate it, the pathogenic sequence from biofilm dysbiosis to cavitation, and the clinical and diagnostic correlates of these processes, before considering the implications for prevention and management.

DEFINITIONS, CLASSIFICATION AND EPIDEMIOLOGY

Definitions and classification

The standardization of ECC definitions has been important for both research and clinical care. According to the AAPD, ECC denotes any caries experience (non-cavitated or cavitated lesions, missing surfaces due to caries, or filled surfaces) in any primary tooth in a child under six years of age; S-ECC is defined by more stringent, age-related criteria, including any sign of smooth-surface caries in children younger than three years [2]. These definitions are deliberately inclusive of early, non-cavitated lesions, reflecting the modern

understanding of caries as a continuum rather than a simple present/absent phenomenon [11].

At the level of the individual lesion, caries is best conceptualized as a dynamic process ranging from the earliest, subsurface, sub-clinical mineral loss, through visible non-cavitated ("white spot") lesions, to enamel and dentinal cavitation [11]. This continuum is central to the theme of the present review, because the same microbiological and dietary drivers operate throughout, and because early stages are potentially arrestable or reversible.

Global epidemiology

ECC is among the most common diseases of early childhood worldwide, with reported prevalence varying widely by region, age and social circumstances, and reaching very high levels — up to around 85% — in disadvantaged populations [3]. A global perspective on ECC has emphasized both the magnitude of the problem and the striking inequalities in its distribution, with the highest burden falling on children of lower socioeconomic status and on those with limited access to preventive dental care [4]. WHO data reinforce this picture, estimating that hundreds of millions of children are affected by caries in the primary dentition and highlighting oral disease as a major, largely preventable, global health challenge [5].

Epidemiology in Romania

Romania illustrates the challenges faced by many countries with limited public preventive programs. In a study of 6–8-year-old Romanian schoolchildren, the mean number of decayed, missing and filled teeth (DMFT) was 4.89 among the children examined, a level the authors described as very high relative to WHO recommendations for this age group [6]. Regional data are consistent with a heavy caries burden and with the influence of oral health behaviours and living conditions on disease experience [6]. More recent work in Romanian preschoolers aged 4–5 years has examined the geography of sugar intake as a risk factor, finding statistically significant differences in sugar consumption across counties but showing that household-level factors — such as parental education and socioeconomic status — appear to play a larger role than geography alone in shaping children's dietary risk [7]. Together, these findings underscore that ECC in Romania is common, socially patterned and closely tied to modifiable dietary and behavioral determinants.

THE MICROBIOLOGICAL BASIS OF EARLY CHILDHOOD CARIES

Dental plaque as a structured biofilm

Dental plaque is not a random accumulation of microorganisms but a structurally and functionally organized biofilm that develops on tooth surfaces in an ordered sequence and that, in health, maintains a diverse and relatively stable microbial composition — a state of microbial homeostasis [8]. The biofilm mode of growth confers properties that are highly relevant to caries: close physical and metabolic interactions between species, gradients of pH and oxygen, an extracellular polymeric matrix that promotes adhesion and retention, and increased tolerance to environmental stress and antimicrobials [8]. An understanding of ECC therefore requires that the microbiota be viewed as a community whose collective metabolic activity — not simply the identity of any individual member — determines whether the tooth surface remains sound or begins to demineralize.

Dietary sucrose plays a special role in this biofilm ecology. Beyond serving as a readily fermentable substrate for acid production, sucrose is the preferred substrate for the synthesis of extracellular glucans by cariogenic streptococci, and these glucans form a substantial part of the extracellular polymeric matrix that binds the biofilm together, mediates firm adherence to enamel, and creates the diffusion-limited microenvironments in which acid accumulates against the tooth surface [12,8]. The matrix is therefore not merely a scaffold but an active

contributor to virulence: it concentrates acid, protects resident organisms, and stabilizes the very community shifts that drive disease [8]. This may account for the observation that both the frequency and the chemical nature of sugar intake are of consequence, and for the fact that the identification of a single cariogenic species in isolation is less informative than the characterization of the metabolically active, matrix-embedded community as a whole [8,9].

The ecological plaque hypothesis and dysbiosis

The ecological plaque hypothesis provides the conceptual bridge between diet, microbiology and disease. In this framework, frequent intake of fermentable carbohydrates leads to repeated production of organic acids by plaque bacteria, lowering the local pH. Persistently low pH selects for acidogenic (acid-producing) and aciduric (acid-tolerant) species while suppressing the acid-sensitive organisms associated with sound enamel, driving a shift — a dysbiosis — in the composition and activity of the community toward a more cariogenic state [9]. Dental caries has thus been described as an example of an "ecological catastrophe", in which a change in local environmental conditions, principally recurrent acidification, disrupts the normal microbiota and favors demineralization [9].

Molecular studies of the oral microbiome in children support this ecological view. Analysis of the microbial communities associated with ECC has demonstrated measurable dysbiosis, with alterations in community structure that distinguish caries-active children from caries-free children, consistent with a shift toward acidogenic and aciduric taxa rather than the acquisition of a single unique pathogen [10]. This community-level perspective complements, and to some extent reframes, the traditional single-species models discussed below.

Mutans streptococci

Among individual organisms, *Streptococcus mutans* (and, in some populations, *Streptococcus sobrinus*) has historically been regarded as the principal etiological agent of caries, including ECC [12]. Mutans streptococci are strongly acidogenic and aciduric, adhere efficiently to enamel, and synthesize extracellular glucans from sucrose that promote biofilm accumulation, making them well adapted to the cariogenic niche [12]. Their role in ECC is closely tied to the timing of colonization. Classic work established that infants acquire mutans streptococci during a relatively discrete "window of infectivity", with a reported median age of initial acquisition around 26 months, though colonization can occur earlier in high-risk children [13]. Earlier and heavier colonization, frequently from the mother or primary caregiver, is associated with greater caries risk, providing a biological rationale for early preventive intervention [4,13].

Mutans streptococci must nevertheless be interpreted within this broader ecological context. Although they are strongly associated with caries and contribute substantially to acid production and biofilm formation, the disease may occur in their relative absence and does not depend on any single species; the weight of current evidence supports a polymicrobial, community-driven process in which mutans streptococci are important but not uniquely necessary contributors [9,10].

Lactobacilli

Lactobacilli are highly acidogenic and aciduric organisms that have long been associated with caries, particularly with the progression of established, cavitated dentinal lesions. Rather than being primary initiators of the disease on smooth enamel surfaces, oral lactobacilli appear to behave as opportunistic secondary colonizers that flourish once a suitable niche has developed. It has been proposed that sustained lactobacillus colonization requires a stagnant, largely anaerobic, low-pH environment with ready access to carbohydrates — precisely the conditions found within an advancing carious lesion [14]. In this model, lactobacilli represent organisms that have adapted to a niche created by the

destabilization of a healthy oral microbiome into a cariogenic one, and their abundance is therefore both a marker and a driver of lesion progression [14].

Candida albicans and interkingdom interactions

An increasingly recognized component of the ECC microbiota is the yeast *Candida albicans*. Clinical studies have repeatedly demonstrated the co-occurrence of *C. albicans* and *S. mutans* in ECC lesions, and mechanistic work indicates that the two organisms can act synergistically to enhance each other's cariogenic potential [15]. *C. albicans* can promote the adhesion and accumulation of *S. mutans*, and this cross-kingdom cooperation is mediated in part by streptococcal glucosyltransferase (Gtf) enzymes, which bind to the yeast surface and generate glucans that strengthen the biofilm matrix [15]. The resulting mixed-species biofilm is more robust, more acidogenic and potentially more virulent than either organism alone, offering a plausible explanation for the aggressive, rampant character of some cases of ECC [15]. The recognition of these interkingdom interactions has broadened the microbiological model of ECC beyond bacteria alone and has implications for both diagnosis and targeted prevention [15].

HOST, DIETARY AND BEHAVIORAL DETERMINANTS

The microbiological drivers of ECC operate within, and are strongly modulated by, host and environmental factors. Seow's foundational review of the biological mechanisms of ECC emphasized that, although the general etiology resembles that of other forms of caries — mutans streptococci fermenting dietary carbohydrates to produce acid attacks on susceptible teeth — the predisposing factors specific to very young children are distinctive and, in part, incompletely understood [12]. A subsequent unifying conceptual model organized these determinants into environmental, maternal and child-related domains that interact to produce disease [16].

Among the behavioral determinants, diet and feeding practices are of primary importance. Frequent consumption of fermentable carbohydrates, especially sugars, constitutes the central dietary driver of ECC, since each exposure provides substrate for acid production and prolongs the periods of low plaque pH [1,9]. In infants and toddlers, feeding behaviours are particularly influential: prolonged and frequent bottle use, especially with sugar-containing liquids or at night, together with on-demand nocturnal breastfeeding after the eruption of the teeth, may create sustained cariogenic conditions, particularly on the maxillary incisors [3,4]. Data from Romanian preschoolers confirm that the frequency and type of sugar intake vary across the population and are shaped by parental and socioeconomic factors, reinforcing diet as a modifiable target [7].

Saliva constitutes a major line of host defense. It contributes to the clearance of food debris and acids, to the buffering of pH, and to the supply of calcium, phosphate and antimicrobial components that support remineralization [1,11]. A reduced salivary flow or impaired salivary function shifts the balance toward demineralization [11]. In young children, the relative immaturity of erupting enamel and, in certain cases, developmental defects of enamel further increase susceptibility [4].

Transmission from the caregiver represents a further determinant. Because cariogenic organisms are frequently transmitted from the mother or primary caregiver, maternal oral health, maternal caries experience and caregiver behaviours — such as the sharing of utensils — influence the timing and magnitude of the child's colonization [4,13]. This vertical and horizontal transmission underlies the importance of a family-centered approach to prevention [16].

Finally, the socioeconomic and behavioral context exerts a pronounced influence. ECC follows a marked social gradient, with lower socioeconomic status, lower parental education, limited access to preventive dental care and suboptimal oral hygiene practices all associated with a higher disease burden [3,4]. These determinants are especially salient in the Romanian context, where caries prevalence is high and where the majority of oral health services are delivered through the private sector, generating financial and geographic barriers to care [6,7].

FROM BIOFILM TO CAVITY: THE PATHOGENIC CONTINUUM

The determinants described above converge on a single, dynamic mechanism at the tooth surface. Every time fermentable carbohydrate reaches the dental biofilm, acidogenic bacteria metabolize it and release organic acids, lowering the plaque pH. When the pH falls below the critical threshold for enamel (approximately 5.5), the surrounding fluid becomes undersaturated with respect to tooth mineral, and calcium and phosphate diffuse out of the enamel — demineralization [1,11]. When carbohydrate intake ceases and saliva restores a neutral pH, the fluid becomes supersaturated again and mineral, together with fluoride, can be redeposited — remineralization [11].

The eventual clinical outcome is therefore determined by the "caries balance": the net result of pathological factors that promote demineralization (acidogenic bacteria, frequent fermentable-carbohydrate intake, impaired salivary function) versus protective factors that promote remineralization (adequate salivary flow and components, fluoride, and favorable dietary patterns) [11]. In health, cycles of demineralization and remineralization are balanced and no net mineral loss occurs. In ECC, the combination of frequent sugar exposure and a dysbiotic, acid-adapted biofilm biases this balance toward repeated and prolonged demineralization [9,11].

Crucially, the microbiological dysbiosis and the physicochemical process reinforce one another. Recurrent low pH selects for ever more acidogenic and aciduric organisms, which in turn generate more acid — a self-perpetuating cycle that pushes the community further from health [9]. As net mineral loss continues, the earliest subsurface lesion becomes clinically visible as a non-cavitated white-spot lesion; with ongoing imbalance, the surface breaks down and the lesion cavitates, first in enamel and then extending into dentin [11]. Advancing lesions create the stagnant, anaerobic, low-pH niche in which secondary colonizers such as lactobacilli proliferate and accelerate dentinal destruction [14], while interkingdom partnerships such as that between *S. mutans* and *C. albicans* can render the biofilm more matrix-rich and virulent, helping to explain the rapid, rampant progression characteristic of severe ECC [15]. In this way, the pathway from biofilm to cavity is best understood not as the action of a single microbe but as an ecological and physicochemical continuum, driven by diet and modulated by host defenses.

A practical corollary of this continuum concerns the frequency, rather than merely the total amount, of carbohydrate exposure. Because each acid challenge is followed by a period of salivary recovery and potential remineralization, it is the repetition of demineralizing episodes throughout the day — as occurs with frequent snacking, sipping of sweetened drinks or on-demand night-time feeding — that most powerfully biases the balance toward net mineral loss [1,11]. In young children, whose salivary flow is reduced during sleep and whose feeding is often frequent and prolonged, this temporal pattern is particularly consequential and provides a clear, mechanistic rationale for the behavioral advice that underpins ECC prevention [3,4,11].

CLINICAL PRESENTATION AND DIAGNOSIS

Clinical features and pattern

The clinical expression of ECC reflects the mechanisms described above. The earliest sign is typically a chalky, opaque white-spot lesion along the gingival margin of the maxillary primary incisors — the surfaces most exposed to pooled cariogenic liquids and least protected by saliva [3,4]. As the disease progresses, these lesions cavitate and darken, and the pattern extends to the primary molars and canines, often in an age-related sequence that mirrors the eruption of the teeth and the duration of exposure to the cariogenic environment [3]. The characteristic sparing of the mandibular incisors, which are protected by the tongue and by proximity to salivary ducts, constitutes a useful diagnostic feature in distinguishing ECC from other conditions [3]. In severe cases, extensive destruction of multiple teeth, pain and abscess formation may be present [4].

Diagnostic indices and criteria

Accurate detection and quantification of ECC are essential for both clinical management and epidemiological comparison. The most widely used epidemiological measure is the dmft/dmfs index, which counts decayed, missing (due to caries) and filled primary teeth or surfaces; the mean dmft of a population provides a compact summary of caries experience and is the metric used, for example, in the Romanian studies cited above [6]. However, traditional indices at the cavitation threshold do not capture early, non-cavitated lesions and therefore underestimate the true burden of disease along the continuum [11].

To address this limitation, the International Caries Detection and Assessment System (ICDAS) was developed as an integrated, standardized visual system that classifies caries severity on an ordinal scale from the earliest visible enamel changes through to extensive cavitation into dentin [17]. ICDAS has demonstrated content and correlational validity against histological assessment and allows both early and established lesions to be recorded, making it well suited to a modern, continuum-based understanding of ECC and to caries management by risk assessment [17]. Combining a severity-sensitive detection system such as ICDAS with conventional dmft reporting provides a fuller clinical and epidemiological picture than either alone.

The role of microbiological assessment

Because ECC is a biofilm-driven ecological disease, microbiological assessment can complement clinical diagnosis and risk assessment. Traditional culture-based methods on selective media, together with quantification of colony-forming units of mutans streptococci and lactobacilli, have long been used to gauge cariogenic microbial load, while molecular techniques such as quantitative polymerase chain reaction (qPCR) and high-throughput sequencing now permit more precise and comprehensive characterization of the oral microbiome, including the detection of *Candida albicans* and of community-level dysbiosis [10,15]. Such approaches remain largely research or risk-stratification tools rather than routine diagnostics, but they reinforce the clinical value of identifying children with a highly cariogenic, dysbiotic biofilm before extensive cavitation has occurred.

IMPLICATIONS FOR PREVENTION AND MANAGEMENT

Viewing ECC as an ecological, biofilm-mediated disease has direct consequences for prevention and management. Because the disease arises from an imbalance driven by frequent sugar exposure and a cariogenic biofilm, effective prevention aims to shift the caries balance back toward health rather than simply to eliminate a single pathogen [9,11]. Key strategies supported by the mechanisms reviewed here include reducing the frequency of fermentable-carbohydrate intake and modifying feeding practices (in particular avoiding prolonged, frequent or nocturnal exposure to sugar-containing liquids) [3,4,7]; supporting

remineralization and inhibiting demineralization through the appropriate use of fluoride [11]; and disrupting the cariogenic biofilm through effective, caregiver-assisted oral hygiene from the time the first teeth erupt [2].

The timing of intervention matters. The existence of an early window during which cariogenic organisms are acquired, and the transmissibility of these organisms from caregivers, argue for early, family-centered preventive efforts that begin in infancy and address maternal oral health [4,16,13]. The AAPD emphasizes a combination of dietary counselling, reinforcement of toothbrushing with fluoridated toothpaste, professional preventive measures such as topical fluoride and sealants where appropriate, and minimally invasive restorative care when needed, all delivered within a risk-based framework [2]. Because early, non-cavitated lesions are potentially arrestable or reversible, detection systems such as ICDAS that identify disease along the continuum enable timely, minimally invasive management before cavitation occurs [11,17]. Finally, the recognition of interkingdom interactions, such as that between *S. mutans* and *C. albicans*, points toward possible future targeted approaches that address the mixed-species biofilm rather than bacteria alone [15].

Fluoride merits particular emphasis because it acts directly on the demineralization–remineralization balance that lies at the heart of the disease. By promoting the redeposition of mineral in a more acid-resistant form and by interfering with bacterial acid production, fluoride can arrest early lesions and reduce the likelihood that subsurface mineral loss progresses to cavitation [11]. Delivered as fluoridated toothpaste used in an age-appropriate amount, and supplemented where indicated by professionally applied topical fluoride, it is one of the most firmly established preventive measures and is a central component of the risk-based approach advocated for young children [2,11]. Together with dietary modification and biofilm disruption, fluoride exemplifies how an understanding of the underlying mechanism translates into concrete, minimally invasive clinical practice [2,11].

At the population level, the persistently high caries burden documented in settings such as Romania, together with the strong social gradient of the disease, indicates that individual clinical measures must be complemented by public health action — improved access to preventive dental care, community-level prevention and attention to the socioeconomic determinants that shape both diet and care-seeking [6,7].

DISCUSSIONS

This review has traced early childhood caries from its microbiological origins in the dental biofilm to its clinical endpoint in cavitation, emphasizing that the two are linked by a single, dynamic physicochemical and ecological process. Several themes emerge. First, the classic single-pathogen model centered on *Streptococcus mutans*, while capturing an important contributor, is insufficient on its own; the accumulated evidence supports an ecological, community-level understanding in which dysbiosis of the biofilm — a shift toward acidogenic and aciduric organisms under the pressure of frequent sugar exposure and low pH — is the proximate microbiological driver of the disease [9,10]. Mutans streptococci, lactobacilli and *Candida albicans* each occupy meaningful roles within this community: mutans streptococci as strongly acidogenic early contributors adapted to enamel colonization [12,13], lactobacilli as opportunistic secondary colonizers that accelerate lesion progression [14], and *C. albicans* as an interkingdom partner that can enhance biofilm virulence [15].

Second, microbiology cannot be separated from host and behavioral context. The same organisms produce disease only under permissive conditions — frequent fermentable-carbohydrate intake, impaired salivary protection, early and heavy colonization, and the socioeconomic circumstances that shape these exposures [4,12,16]. This integration is

precisely why ECC is best managed through a combination of dietary, hygienic, fluoride-based and family-centered measures rather than through any single intervention [2,11].

Third, the clinical and diagnostic tools available to the clinician map onto this continuum. The dmft index remains valuable for epidemiological comparison and captures the cavitated burden of disease, as illustrated by Romanian data [6], while severity-sensitive systems such as ICDAS extend detection to the early, potentially reversible stages that are the most promising targets for prevention [11,17]. Microbiological assessment, increasingly aided by molecular methods, offers a complementary window onto the dysbiotic biofilm that underlies clinical disease [10,15].

Several limitations of the current evidence base should be acknowledged. Much of the microbiological understanding of ECC derives from cross-sectional association studies, which cannot fully establish causal sequence or the direction of the relationship between specific taxa and disease; longitudinal and mechanistic studies are needed to clarify how community dysbiosis initiates and progresses in individual children. Definitions and diagnostic thresholds have evolved over time, complicating comparison across studies and eras, and prevalence estimates vary widely with methodology and setting. Finally, the translation of ecological and interkingdom insights into practical, targeted preventive strategies remains at an early stage. These gaps define important directions for the field, and they are also directly relevant to clinical and microbiological research on ECC in specific populations, including Romania.

CONCLUSIONS AND FUTURE DIRECTIONS

Early childhood caries is a common, preventable and socially patterned disease that is best understood as a continuum extending from a dysbiotic dental biofilm to clinical cavitation. Its microbiological determinants — a structured biofilm undergoing ecological shift toward acidogenic and aciduric organisms such as mutans streptococci, lactobacilli and *Candida albicans* — are inseparable from its dietary, host and behavioral determinants, and both sets of factors act through the same underlying balance between demineralization and remineralization. This integrated, ecological perspective explains the clinical features and progression of ECC and provides a rational basis for early, risk-based and family-centered prevention.

Future work should prioritize longitudinal and mechanistic studies that clarify the causal dynamics of biofilm dysbiosis in young children; the further validation and clinical integration of severity-sensitive diagnostic systems such as ICDAS alongside conventional indices; the exploration of targeted anti-biofilm and interkingdom strategies for prevention; and population-level research and public health measures addressing the social determinants that drive the persistently high burden of ECC in settings such as Romania. Bridging clinical observation and microbiological insight — that is, connecting the microbiological origins of the disease to its clinical endpoint — offers the most promising avenue for reducing the burden of this important childhood disease.

Author Contributions

Conceptualization, O.D. and A.G.; Methodology, O.D.; Literature Search, O.D., M.-M.L. and D.C.; Data Curation, O.D.; Writing – Original Draft Preparation, O.D.; Writing – Review & Editing, A.G., M.-M.L., T.H. and D.C.; Supervision, A.G. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

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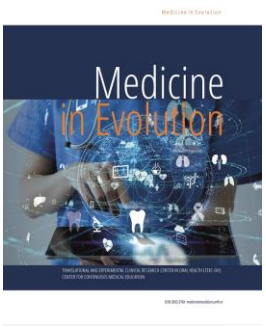
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Patient-Reported Esthetic Outcomes After Anterior Ceramic Restorations: A Retrospective Observational Study of Demographic and Clinical Factors



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Abstract

Aim: To evaluate patient-reported esthetic satisfaction 5–9 years after anterior ceramic restorations and its association with demographic and clinical factors. Methodology: This retrospective observational study included 217 patients with 667 anterior ceramic restorations made of lithium disilicate, feldspathic ceramic, or zirconia. Satisfaction was assessed using a study-specific questionnaire with a binary response and a five-point rating scale. Results: Overall, 198 patients (91.2%) were satisfied. Satisfaction did not differ significantly by ceramic material ($p = 0.775$), age ($p = 0.261$), or sex ($p = 0.342$). Dissatisfied patients had more restorations per patient ($p = 0.027$). Clinical complications were documented in 24 patients (11.1%) and were associated with higher odds of dissatisfaction (OR = 19.57, 95% CI 6.71–57.07; $p < 0.001$). Shade discrepancy was the most frequent primary complaint. Conclusions: Patient-reported esthetic satisfaction was high after 5–9 years. Documented complications, particularly shade discrepancy, were associated with dissatisfaction, whereas no statistically significant association was observed for ceramic material, age, or sex.

Keywords: anterior ceramic restorations; patient satisfaction; esthetic dentistry; patient-reported outcomes; lithium disilicate; feldspathic ceramic; zirconia

INTRODUCTION

The increasing demand for esthetic dental treatment has changed the way outcomes of anterior restorative procedures are evaluated. Ceramic restorations are widely used to correct alterations in tooth color, shape, position, proportions, and surface morphology, particularly in patients seeking an improvement in smile appearance. Advances in ceramic materials, adhesive procedures, and laboratory techniques have also made increasingly conservative treatment approaches possible, with greater emphasis on preserving sound dental tissues. Although restoration survival and the occurrence of technical complications remain essential parameters when evaluating treatment, they do not fully describe its success. In the anterior region, where esthetics is often one of the main reasons for intervention, the patient's own perception of the final result represents an important additional outcome.

Clinical assessment and patient perception are closely related, but they cannot be considered equivalent. A restoration may satisfy conventional clinical criteria while the patient remains dissatisfied with certain aspects of the result, such as color, tooth dimensions, symmetry, surface appearance, or integration within the smile. Conversely, minor clinical imperfections may have little influence on the patient's overall perception of treatment. A recent long-term study evaluating ceramic veneers after 9–10 years showed discrepancies between professional clinical assessment and patient-reported outcomes, indicating that restoration survival alone may not reflect the way treatment is experienced by the patient [1].

Esthetic perception is inherently subjective and may also be influenced by individual demographic characteristics. Age and sex are among the factors most frequently investigated in relation to dental appearance. In an observational study conducted in Switzerland, Zaugg et al. found that both age and sex influenced several aspects of orofacial esthetic perception. Women reported lower satisfaction with their dental appearance and showed a greater willingness to undergo corrective treatment, while attitudes toward esthetics also differed between younger and older participants [2]. These findings suggest that apparently similar clinical situations may not necessarily be perceived in the same way by different patients.

The influence of demographic characteristics, however, is not consistent across all populations. Tin-Oo et al. evaluated satisfaction with dental appearance among adult dental patients and reported that women were more likely than men to be dissatisfied with their overall dental appearance. Female participants were also more frequently dissatisfied with tooth color. In contrast, age was not significantly associated with general satisfaction in that population [3]. Such differences between studies indicate that demographic variables should not be regarded as isolated determinants of satisfaction but rather as factors that may interact with individual expectations, previous dental experiences, and the characteristics of the treatment received.

Clinical characteristics of the treated tooth and restoration may have an additional influence on the final esthetic result. Ceramic type, tooth vitality, substrate discoloration, restoration thickness, preparation design, and the amount of preserved enamel may affect both the optical integration and clinical behavior of anterior ceramic restorations. Feldspathic ceramic has traditionally been used for veneers because of its favorable translucency and its ability to reproduce the optical characteristics of natural dental tissues. In a retrospective evaluation of 170 feldspathic ceramic veneers followed for up to seven years, Mihali et al. reported an overall survival rate of 91.77%. Fourteen veneers required replacement because of fracture, while additional cases of ceramic chipping were managed conservatively [4]. These findings illustrate that favorable long-term survival does not exclude the occurrence of events that may influence either the clinical or esthetic perception of the restoration.

The extent of tooth preparation is another relevant consideration in contemporary anterior rehabilitation. Preservation of enamel is particularly desirable for adhesive ceramic restorations, which has led to increased interest in minimally invasive and no-preparation approaches. De Angelis et al. retrospectively evaluated a no-preparation porcelain veneer protocol and reported a survival rate of 97.4% after an observation period ranging from 36 to 60 months. Most restorations were clinically acceptable, although minor fractures, chipping, and limited marginal discoloration were identified in a small number of cases. The authors emphasized that predictable outcomes with a no-preparation approach depend on strict patient selection and appropriate treatment planning [5].

Similar considerations have been reported for ultrathin ceramic veneers. Gonzalez-Martin et al. evaluated 194 ceramic veneers placed using conventional preparation, minimal-preparation, or no-preparation protocols over a 36-month period. Fractures occurred predominantly among minimally prepared restorations, although catastrophic failure was uncommon. Patient satisfaction remained high, and all participants reported that they would not choose a thicker restorative approach merely to reduce the potential risk of fracture [6]. This finding is particularly relevant because it illustrates that the patient's judgment of treatment cannot always be inferred directly from the presence or absence of a clinical complication.

Other clinical factors may be important even when they do not compromise restoration survival. Shade discrepancy, marginal discoloration, chipping, fracture, changes in gingival contour, or periodontal alterations occur in a highly visible region and may therefore influence the patient's perception of treatment. The initial condition of the tooth may also affect the difficulty of achieving an optimal esthetic result. A severely discolored or devitalized substrate, for example, may require greater masking than a tooth with a favorable initial color. Consequently, similar restorative techniques may produce different perceived outcomes depending on the underlying clinical situation.

Despite the extensive literature addressing the survival and technical performance of ceramic veneers and other anterior ceramic restorations, comparatively fewer studies have investigated patient-reported esthetic satisfaction together with demographic and clinical characteristics. Studies focused primarily on restoration survival cannot determine whether clinically successful treatment is perceived equally favorably by all patients. Conversely, investigations of general dental appearance often include individuals who have not undergone a defined restorative intervention and may therefore provide limited information regarding satisfaction after ceramic rehabilitation.

The aim of the present retrospective observational study was to evaluate patient-reported esthetic satisfaction following ceramic restorations in the anterior region and to investigate whether available demographic and clinical factors were associated with the reported outcome. The null hypothesis was that demographic and clinical variables would not be significantly associated with patient-reported esthetic satisfaction following anterior ceramic rehabilitation.

Aim and objectives

The aim of this retrospective observational study was to evaluate patient-reported esthetic outcomes after long-term anterior ceramic rehabilitation and to identify demographic and clinical factors associated with patient satisfaction. The study specifically assessed whether satisfaction differed according to ceramic material, age, sex, tooth vitality, presence of dyschromia, preparation approach, dental arch, number of restorations, and documented clinical complications. A further objective was to determine which clinical events were most closely associated with dissatisfaction and to evaluate the relationship between long-term clinical performance and the patient’s perception of the final esthetic result.

MATERIAL AND METHODS

This retrospective observational study was conducted at Dental Concept by Dr. Mihali, Timişoara, Romania, within the framework of the doctoral research project entitled "Ceramic Restorations in the Anterior Region, Indications, Limitations, Clinical Performance, and Patient Satisfaction." The research project received approval from the Scientific Research Ethics Committee of the "Victor Babeş" University of Medicine and Pharmacy Timişoara (Approval No. 77/14.12.2018, revised 2025). The study was conducted in accordance with the Declaration of Helsinki, and written informed consent was obtained from the participants included in the approved research project. For the present analysis, data were retrospectively extracted from the clinic's electronic patient database during one week in September 2026. No new clinical intervention was performed for the purpose of the present analysis.

The study included patients treated with ceramic restorations in the anterior region with a documented clinical follow-up ranging from 60 to 108 months (5–9 years). The final cohort comprised 217 patients and 667 anterior ceramic restorations. The primary analysis was performed at patient level, regardless of the number of restorations present in the same patient. Patients were eligible if they were at least 18 years old, had one or more ceramic restorations involving maxillary or mandibular anterior teeth, had been treated with lithium disilicate, feldspathic ceramic, or zirconia restorations, and had complete clinical records regarding the restorative material, type of restoration, tooth vitality, dental arch, follow-up period, and recorded clinical complications. Patients were included when at least 60 months of documented clinical follow-up from restoration placement were available.

Patients were excluded if their restorations were located exclusively in the posterior region, the restorative material or relevant clinical information could not be reliably identified, the available follow-up was shorter than 5 years, or the clinical documentation was incomplete. Patients without a completed satisfaction questionnaire available in the study records were also excluded. The occurrence of a complication or restoration failure was not considered an exclusion criterion when sufficient clinical information was available.

The following variables were retrieved from the clinical database: age, sex, ceramic material, restoration type, preparation approach, tooth vitality, presence of dental dyschromia, dental arch, number of restorations, and time in clinical service. All included restorations were clinically evaluated by the same dentist using consistent criteria. Shade discrepancy was defined as a clinically perceptible mismatch in value, chroma, or hue between the restoration and the adjacent dentition. Chipping was defined as a localized loss of ceramic material without complete structural fracture, whereas fracture referred to a structural loss involving a larger portion of the restoration. Gingival recession was recorded when apical displacement of the gingival margin adjacent to the restoration was observed. Debonding was defined as partial or complete loss of restoration retention. Marginal discoloration was recorded when visible pigmentation was present along the tooth–restoration interface, while secondary caries was defined as a newly detected carious lesion adjacent to the restoration margin. A patient was considered to have a clinical complication when at least one of these events was identified in one or more included anterior restorations.

Patient-reported esthetic outcome had been assessed as part of the approved research project using a brief study-specific questionnaire. Patients were asked whether they were satisfied or dissatisfied with the overall esthetic result and were also asked to rate their overall satisfaction on a five-point scale ranging from 1 (very dissatisfied) to 5 (very satisfied). Patients reporting dissatisfaction were asked to indicate the main reason for their response. The questionnaire was used as a study-specific measure of patient satisfaction and was analyzed together with the demographic and clinical variables retrieved from the patient records.

Continuous variables were summarized using mean and standard deviation or median and interquartile range, as appropriate, while categorical variables were presented as absolute frequencies and percentages. Comparisons among the three ceramic material groups were performed using the Kruskal–Wallis test for continuous or ordinal variables. Categorical variables were compared using the Chi-square test when its assumptions were met; for sparse contingency tables, Fisher's exact test or its extension for larger contingency tables was used, as appropriate.

Associations between patient-reported satisfaction and continuous variables were evaluated using the Mann–Whitney U test, while categorical variables were assessed using the Chi-square test or Fisher's exact test, as appropriate. For binary clinical variables, odds ratios (ORs) with 95% confidence intervals (95% CIs) were calculated to estimate the strength of association with dissatisfaction. Ninety-five percent Wilson confidence intervals were calculated for proportions presented graphically. Analyses of individual clinical complications were considered exploratory because of the relatively small number of events. All statistical tests were two-sided, and statistical significance was set at $p < 0.05$. Statistical analyses were performed using Python version 3.13.5 (Python Software Foundation), with SciPy version 1.17.0 and statsmodels version 0.14.6. Custom scripts were used for statistical analysis and figure generation.

RESULTS

The final analysis included 217 patients with 667 anterior ceramic restorations. There were 116 women (53.5%) and 101 men (46.5%), and the mean age was 39.6 ± 10.2 years. Follow-up ranged from 60 to 108 months, corresponding to 5–9 years of clinical service, with a median of 80 months (IQR 73–88). Patients had a mean of 3.1 ± 1.9 restorations each. The material distribution comprised 44 patients treated with lithium disilicate, 105 with feldspathic ceramic, and 68 with zirconia.

The three material groups were not identical with respect to all clinical characteristics. Age differed significantly between groups (Kruskal–Wallis $H = 14.04$, $p < 0.001$), with the zirconia group being older on average. Tooth vitality was also distributed differently ($\chi^2 = 20.93$, $p < 0.001$), as were the preparation approach ($\chi^2 = 44.57$, $p < 0.001$), dental arch ($\chi^2 = 11.53$, $p = 0.003$), and number of restorations per patient ($H = 24.56$, $p < 0.001$). By contrast, sex distribution and follow-up duration were comparable across material groups ($p = 0.857$ and $p = 0.159$, respectively). Feldspathic ceramic was used predominantly for veneers, while zirconia was mainly represented by single crowns and fixed dental prostheses. The main demographic and clinical characteristics of the three material groups are summarized in Table 1.

Table 1. Demographic and clinical characteristics of the study cohort according to ceramic material

Variable	Lithium	Feldspathic	Zirconia (n=68)	Overall (n=217)	p-value
Age, years, mean ± SD	40.8 ± 10.0	36.8 ± 9.4	43.0 ± 10.6	39.6 ± 10.2	<0.001
Female sex, n (%)	25 (56.8%)	56 (53.3%)	35 (51.5%)	116 (53.5%)	0.857
Follow-up, months, median [IQR]	80 [75–94]	79 [71–87]	82 [74–87]	80 [73–88]	0.159
Restorations/patient, mean ± SD	2.6 ± 1.6	3.8 ± 2.2	2.2 ± 1.0	3.1 ± 1.9	<0.001
Restoration type, n (%)					**<0.001**
Veneer	19 (43.2%)	103 (98.1%)	0 (0.0%)	122 (56.2%)	
Single crown	25 (56.8%)	2 (1.9%)	52 (76.5%)	79 (36.4%)	
Fixed dental prosthesis	0 (0.0%)	0 (0.0%)	16 (23.5%)	16 (7.4%)	
Vital teeth, n (%)	33 (75.0%)	90 (85.7%)	37 (54.4%)	160 (73.7%)	<0.001

Dyschromia, n (%)	9 (20.5%)	35 (33.3%)	19 (27.9%)	63 (29.0%)	0.279
No-prep approach, n (%)	2 (4.5%)	39 (37.1%)	0 (0.0%)	41 (18.9%)	<0.001
Maxillary restorations, n (%)	30 (68.2%)	84 (80.0%)	38 (55.9%)	152 (70.0%)	0.003

SD, standard deviation; IQR, interquartile range. Continuous or ordinal variables were compared using the Kruskal–Wallis test. Categorical variables were compared using the Chi-square test or an exact test, as appropriate. The p-value for restoration type was obtained using an exact test because of sparse cells

Patient-reported esthetic satisfaction was high. A total of 198 patients (91.2%) described the final esthetic result as satisfactory, whereas 19 (8.8%) were dissatisfied. The overall satisfaction score was 4.41 ± 0.80 on the five-point scale, with a median of 5 (IQR 4–5). Satisfaction was reported by 41/44 patients with lithium disilicate (93.2%), 94/105 patients with feldspathic ceramic (89.5%), and 63/68 patients with zirconia (92.6%). The differences were not statistically significant (exact test, p = 0.775). Satisfaction scores likewise showed no significant difference between materials (H = 1.14, p = 0.567) (Figure 1).

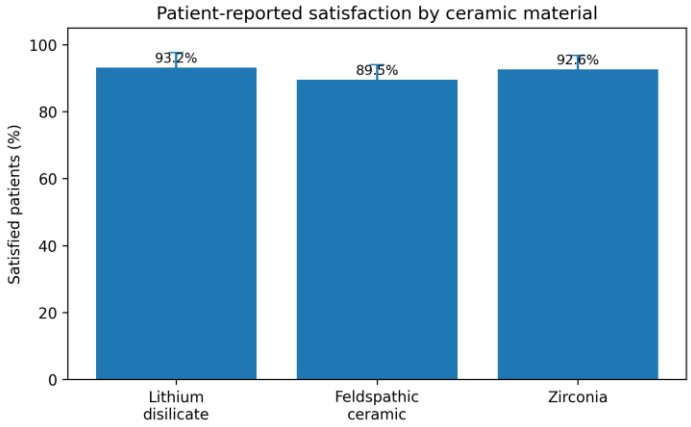


Figure 1. Patient-reported esthetic satisfaction according to ceramic material. Error bars indicate 95% Wilson confidence intervals

The reasons reported by dissatisfied patients were predominantly esthetic rather than mechanical. Shade discrepancy was the most frequent primary complaint, accounting for 8 of the 19 dissatisfied patients (42.1%). Four patients reported another nonspecific esthetic concern, while unmet esthetic expectations and concerns related to shape or contour were each recorded in two patients. Gingival recession, fracture, and chipping were each identified as the main reason for dissatisfaction in one patient. The distribution of patient-reported reasons is shown in Figure 2.

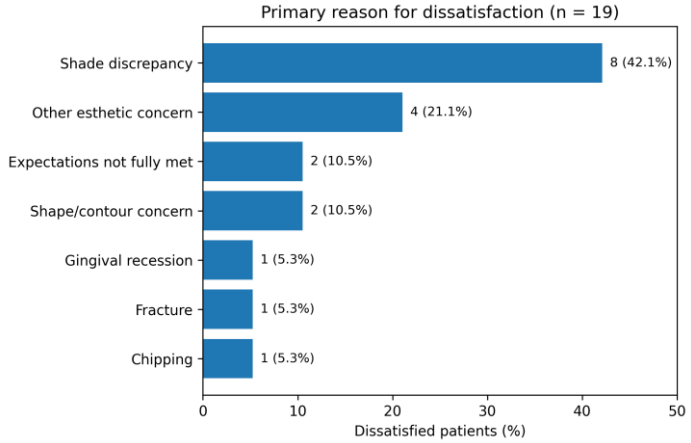


Figure 2. Primary reason for dissatisfaction among the 19 patients who reported an unsatisfactory esthetic outcome

No significant association was identified between satisfaction and either age or sex. The mean age was 39.8 ± 10.3 years among satisfied patients and 36.7 ± 9.3 years among dissatisfied patients (U = 2175, p = 0.261). Among women, 108/116 (93.1%) were satisfied, compared with 90/101 men (89.1%; Fisher's exact test, p = 0.342). Follow-up duration was also similar between the two outcome groups (80.6 ± 11.7 vs. 82.4 ± 9.3 months; p = 0.344). The number of restorations per patient was higher among dissatisfied patients (3.95 ± 1.99) than among satisfied patients (2.99 ± 1.92; U = 1315, p = 0.027). Dyschromia, tooth vitality, preparation approach, dental arch, and restoration type were not significantly associated with the reported satisfaction outcome. These comparisons are summarized in Table 2.

Table 2. Demographic and clinical factors according to patient-reported esthetic satisfaction

Variable	Satisfied (n=198)	Dissatisfied (n=19)	p-value
Age, years, mean ± SD	39.8 ± 10.3	36.7 ± 9.3	0.261
Female sex, n (%)	108 (54.5%)	8 (42.1%)	0.342
Follow-up, months, mean ± SD	80.6 ± 11.7	82.4 ± 9.3	0.344
Restorations/patient, mean ± SD	2.99 ± 1.92	3.95 ± 1.99	0.027
Ceramic material, n (%)			**0.775**
Lithium disilicate	41 (20.7%)	3 (15.8%)	
Feldspathic ceramic	94 (47.5%)	11 (57.9%)	
Zirconia	63 (31.8%)	5 (26.3%)	
Restoration type, n (%)			**0.443**
Veneer	109 (55.1%)	13 (68.4%)	
Single crown	73 (36.9%)	6 (31.6%)	
Fixed dental prosthesis	16 (8.1%)	0 (0.0%)	
Dyschromia, n (%)	58 (29.3%)	5 (26.3%)	1.000
Devitalized teeth, n (%)	54 (27.3%)	3 (15.8%)	0.414
No-prep approach, n (%)	37 (18.7%)	4 (21.1%)	0.763
Maxillary arch, n (%)	139 (70.2%)	13 (68.4%)	1.000
Any clinical complication, n (%)	13 (6.6%)	11 (57.9%)	<0.001

SD, standard deviation. Continuous variables were compared using the Mann–Whitney U test. Binary categorical variables were assessed using Fisher's exact test where appropriate. Ceramic material and restoration type were assessed using the Fisher–Freeman–Halton exact test for 2 × 3 contingency tables

Clinical complications were uncommon overall. At least one complication was documented in 24 patients (11.1%). The corresponding proportions were 13.6% for lithium disilicate, 9.5% for feldspathic ceramic, and 11.8% for zirconia. There was no significant difference in the overall complication rate between the three materials (exact test, p = 0.688). Shade discrepancy was the most frequently recorded individual event (14 patients, 6.5%), followed by gingival recession (9, 4.1%) and marginal discoloration (8, 3.7%). Mechanical events were infrequent: chipping was observed in 4 patients, fracture in 3, and debonding in 3. Secondary caries was recorded in three patients. The distribution of individual complications across ceramic materials is presented in Table 3 and Figure 3. None of the individual complication categories differed significantly between materials. Patients with at least one complication had a somewhat longer mean follow-up than those without complications (83.1 ± 10.4 vs. 80.4 ± 11.6 months), but the difference was not statistically significant (U = 1968, p = 0.231).

Table 3. Distribution of documented clinical complications according to ceramic material

Complication	Lithium disilicate (n=44)	Feldspathic ceramic (n=105)	Zirconia (n=68)	Overall (n=217)	p-value
Shade discrepancy	2 (4.5%)	6 (5.7%)	6 (8.8%)	14 (6.5%)	0.669
Gingival recession	4 (9.1%)	2 (1.9%)	3 (4.4%)	9 (4.1%)	0.109
Marginal discoloration	1 (2.3%)	4 (3.8%)	3 (4.4%)	8 (3.7%)	1.000
Chipping	2 (4.5%)	1 (1.0%)	1 (1.5%)	4 (1.8%)	0.329
Fracture	1 (2.3%)	2 (1.9%)	0 (0.0%)	3 (1.4%)	0.592
Debonding	1 (2.3%)	1 (1.0%)	1 (1.5%)	3 (1.4%)	0.779
Secondary caries	1 (2.3%)	1 (1.0%)	1 (1.5%)	3 (1.4%)	0.779

p-values were obtained using exact tests because of the small number of events in individual complication categories

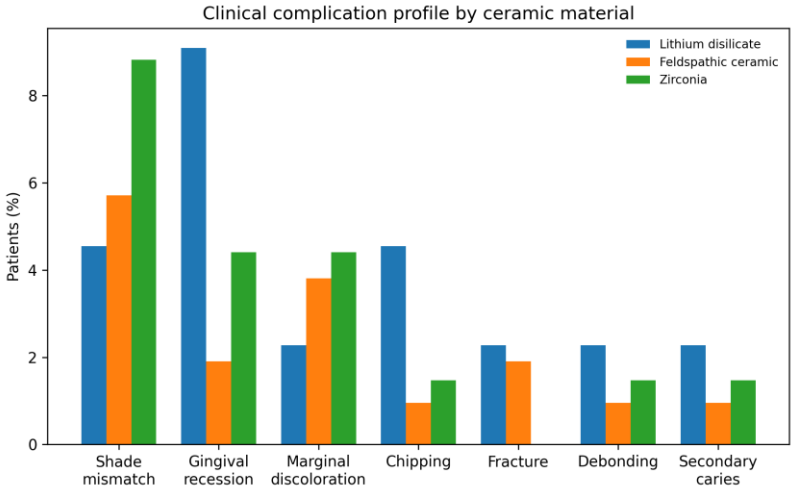


Figure 3. Clinical complication profile according to ceramic material

The presence of a clinical complication was strongly related to the patient-reported outcome. Satisfaction was recorded in 185/193 patients without complications (95.9%), compared with 13/24 patients who had at least one documented complication (54.2%). The odds of dissatisfaction were higher in the presence of a complication (OR = 19.57, 95% CI 6.71–57.07; Fisher's exact test, $p < 0.001$) (Figure 4). Among individual findings, shade discrepancy showed the clearest relationship with dissatisfaction ($p < 0.001$). Chipping, fracture, gingival recession, debonding, marginal discoloration, and secondary caries were also more frequent among dissatisfied patients in exploratory univariable comparisons, although these estimates were based on small numbers of events.

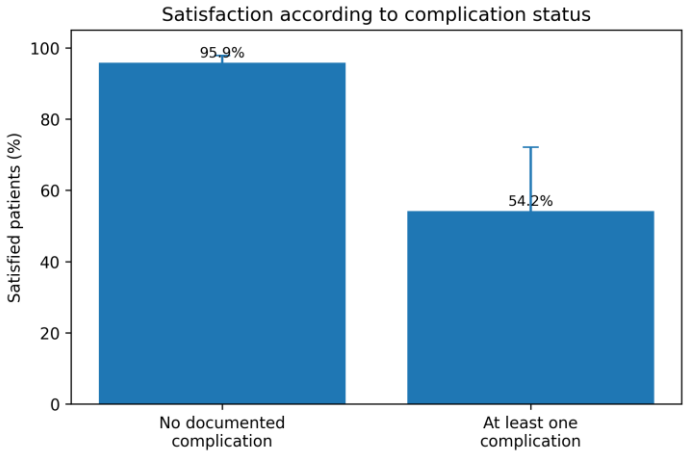


Figure 4. Patient-reported satisfaction according to the presence or absence of a documented clinical complication. Error bars indicate 95% Wilson confidence intervals

Overall, the material used for anterior ceramic rehabilitation was not associated with patient-reported satisfaction, and no meaningful difference was observed according to age or sex. Satisfaction remained above 89% in each material group. The findings instead indicated that dissatisfaction was concentrated among patients with documented esthetic or clinical complications, particularly shade discrepancy, while a greater number of restorations per patient was also associated with lower satisfaction. These results support the use of patient-reported assessment alongside conventional clinical evaluation when judging the long-term outcome of anterior ceramic restorations.

DISCUSSIONS

Patient-reported esthetic outcomes are an important part of the long-term evaluation of anterior ceramic restorations. Clinical survival remains essential, but it does not always reflect how the patient perceives the final result. In our cohort, 91.2% of patients were satisfied after 5–9 years of clinical service. Satisfaction was similar for lithium disilicate, feldspathic ceramic, and zirconia restorations, and no significant association was found with age or sex. The factors that appeared to matter more were the occurrence of clinical complications and the extent of the rehabilitation, as dissatisfied patients had a higher number of restorations per patient.

The generally favorable level of satisfaction observed in this study is in agreement with the good long-term performance usually reported for ceramic restorations. AlJazairy, in a systematic review of porcelain laminate veneers, found high survival and success rates, while also pointing out the considerable heterogeneity among clinical studies [7]. This is relevant for our cohort because the three ceramic groups were not identical. They differed in age, tooth vitality, preparation approach, dental arch, and number of restorations per patient. The materials were used according to the clinical situation rather than being randomly assigned, which needs to be kept in mind when comparing them.

Long-term clinical performance of veneers has also been investigated by Morimoto et al., who reported an estimated cumulative survival of 89% over a median follow-up of 9 years [8]. Fracture and chipping were among the more frequent complications in that analysis. In our study, mechanical complications were less common, with chipping recorded in 1.8% of patients and fracture in 1.4%. Even so, these events occurred more often among patients who were dissatisfied. This illustrates an important difference between restoration survival and treatment success from the patient's point of view. A restoration may still be in place and functioning while a relatively small visible defect is enough to affect satisfaction.

Material choice is another factor frequently discussed in the literature. A recent systematic review and meta-analysis reported long-term survival rates of 96.13% for feldspathic ceramic, 93.70% for leucite-reinforced glass-ceramic, and 96.81% for lithium disilicate [9]. Lower rates of technical, esthetic, and biological complications were reported for lithium disilicate. In our cohort, however, patient satisfaction remained above 89% for all three ceramic groups, and neither satisfaction nor the overall complication rate differed significantly according to ceramic material. For the patients included here, the ceramic material itself therefore did not appear to be the main factor determining how the esthetic result was perceived.

The quality of the substrate and the amount of preserved enamel are also important when planning anterior ceramic restorations. A systematic review and meta-analysis found survival and success rates close to 99% when veneers were bonded predominantly to enamel, while greater dentin exposure was associated with less favorable results [10]. Hong et al. also showed that preparation design may influence veneer prognosis, although the effect varied according to the type of preparation and analytical method used [11]. Similarly, Gurel et al.

reported a survival rate of 99% when preparations remained entirely within enamel and a considerably higher risk of failure when veneers were bonded to dentin [12]. Together, these data support conservative preparation whenever the clinical conditions allow it.

In the present cohort, the preparation approach was not significantly associated with satisfaction. This should not be taken to mean that preparation design is unimportant. Preparation is closely related to tooth position, available restorative space, substrate color, the extent of correction required, and the amount of enamel available for bonding. The fact that most no-prep cases in our sample were treated with feldspathic ceramic also shows that preparation strategy and material choice were linked to the clinical indication.

Color stability is particularly important in the anterior region. Fradeani et al. reported a 94.4% survival probability after 12 years, with favorable long-term evaluations of color match, ceramic surface, marginal discoloration, and marginal integrity [13]. In our study, shade discrepancy was the most frequent individual clinical event, recorded in 14 patients, and it was also the most common reason given by dissatisfied patients. Eight of the 19 dissatisfied patients identified shade discrepancy as their main complaint. This was one of the clearest observations in the present study and underlines how sensitive patients can be to color differences in the anterior region.

Soft tissue changes may be similarly noticeable. D'Arcangelo et al. reported a restoration-level survival rate of 97.5% after seven years, together with satisfactory gingival response and good marginal and color stability [14]. Gingival recession affected only 4.1% of our patients, but it occurred more often among dissatisfied patients. Even when the restoration itself remains intact, a change in gingival level may alter symmetry and make the restoration more visible within the smile.

Patient- and tooth-related variables can also influence long-term outcome. Beier et al. reported an estimated 10-year survival of 93.5% and found a higher risk of failure for nonvital teeth and in patients with bruxism. Marginal discoloration was also more frequent among smokers [15]. Tooth vitality was not associated with satisfaction in our sample. Therefore, although vitality may affect technical prognosis, it did not appear to have an important effect on the patient's overall esthetic assessment in this group.

A similar observation was made for dyschromia. Discolored or devitalized teeth are generally more difficult to mask because the final appearance depends on ceramic thickness, translucency, cement, and the optical characteristics of the substrate. A review of porcelain veneers emphasized the role of enamel preservation, adhesive technique, luting material, and oral hygiene in maintaining favorable esthetic and periodontal outcomes [16]. Dyschromia was present in 29.0% of the patients in our cohort, but it was not associated with lower satisfaction. This may indicate that substrate discoloration can often be managed successfully when the ceramic system and treatment plan are selected appropriately.

Patient satisfaction is also influenced by factors that cannot be fully captured during the clinical examination. Expectations and previous dental experiences differ considerably between patients. Meijering et al. reported that restoration type influenced patient satisfaction, with porcelain veneers producing greater satisfaction than direct composite veneers after two years [17]. In our study, neither age nor sex was related to satisfaction. Demographic characteristics therefore seemed less important than the actual clinical condition of the restorations.

The role of minimally invasive treatment has received increasing attention in recent years. A prospective study comparing prepless and minimally invasive ceramic veneers reported high satisfaction in both groups, with slightly higher satisfaction in the prepless group despite the occurrence of some complications [18]. Our results also showed no significant relationship between preparation approach and satisfaction. From a clinical perspective, this supports the idea that preparation design should not be evaluated on its

own. Tooth position, substrate, available space, material thickness, and the intended esthetic change all influence the final treatment plan.

Shade matching deserves particular attention because it was closely related to dissatisfaction in our study. A clinical comparison of polychromatic feldspathic porcelain and hybrid ceramic laminate veneers found acceptable shade matching, color stability, and high patient satisfaction with both materials after one year [19]. Our results likewise showed high satisfaction with all three ceramic groups, but when a visible shade discrepancy was present, dissatisfaction was considerably more common. In an anterior restoration, even a limited color mismatch can be immediately noticed by the patient despite otherwise satisfactory clinical performance.

Longer follow-up may also reveal differences that are not evident during the first years after treatment. Gresnigt et al. reported 100% cumulative survival for ceramic laminate veneers after up to 10 years, compared with 75% for indirect resin-composite veneers, with ceramic restorations also showing better color match and surface characteristics [20]. The high satisfaction found in our patients after 5–9 years is in line with the generally stable esthetic behavior reported for ceramic restorations. In our cohort, follow-up duration itself was not significantly related to satisfaction.

Layton and Clarke also reported five-year survival above 90% for etchable non-feldspathic porcelain veneers, although they emphasized that long-term evidence remains limited for some ceramic systems [21]. This remains relevant because favorable medium-term results do not remove the need for continued clinical monitoring. In our patients, those with complications had a slightly longer follow-up than patients without complications, but the difference was not statistically significant.

High patient satisfaction with ceramic veneers has also been reported by Galiatsatos and Bergou. In their five-year evaluation of 186 porcelain laminate veneers, 98.4% were satisfactory without intervention and patient satisfaction was very high [22]. The 91.2% satisfaction rate in our cohort is somewhat lower but still confirms a favorable long-term patient perception. Direct comparison between studies is difficult because of differences in restorative materials, clinical indications, follow-up periods, and methods used to assess satisfaction.

The strongest association in our study was observed between clinical complications and dissatisfaction. Satisfaction reached 95.9% among patients without complications but fell to 54.2% when at least one complication was documented. The odds of dissatisfaction were approximately 20 times higher in patients with a complication (OR = 19.57, 95% CI 6.71–57.07). Shade discrepancy showed the clearest relationship, while chipping, fracture, gingival recession, debonding, marginal discoloration, and secondary caries were also more frequent among dissatisfied patients. Because the number of individual events was small, the results for specific complications should be interpreted cautiously. The overall pattern, however, was clear: visible or clinically detectable complications had a much stronger relationship with dissatisfaction than the ceramic material itself.

Another interesting result was the number of restorations per patient. Patients who were dissatisfied had a mean of 3.95 restorations, compared with 2.99 in satisfied patients. More extensive anterior rehabilitations are usually more demanding because color, contour, symmetry, tooth proportions, contact areas, and gingival integration must be controlled across several restorations. Patient expectations may also be higher when treatment involves a larger part of the smile. The retrospective design does not allow us to determine why this association occurred, but it deserves further investigation.

From a clinical point of view, these results highlight several practical aspects. Material selection remains important, but it is only one part of treatment planning. Substrate color, remaining enamel, soft tissue conditions, shade selection, restoration number, and the

patient's expectations should all be considered before treatment. In more extensive cases, communication becomes particularly important. Photographs, diagnostic wax-ups, mock-ups, provisional restorations, and digital simulations can be useful for showing the patient what can realistically be achieved before definitive treatment begins.

There are several limitations to the present study. Its retrospective nature means that the analysis depended on the completeness and accuracy of existing clinical records, and the observed associations cannot be interpreted as causal relationships. The three material groups were also different in several baseline characteristics because ceramic selection followed the clinical indication rather than random allocation. In addition, only 19 patients were dissatisfied, which limits the precision of analyses involving individual complications. Finally, satisfaction was evaluated using a brief study-specific questionnaire rather than a fully validated patient-reported outcome measure.

Prospective studies using validated questionnaires would allow patient satisfaction to be evaluated in greater detail. Larger multicenter samples would also permit more robust analysis of the combined effect of material, preparation design, substrate condition, treatment extent, and clinical complications. It would be particularly useful to record patient expectations before treatment and compare them with the final perceived result, especially in larger anterior rehabilitations.

Overall, anterior ceramic restorations were associated with a high level of patient satisfaction after 5–9 years. Ceramic material, age, sex, tooth vitality, dyschromia, and preparation approach were not significantly associated with the reported outcome. Clinical complications, especially visible esthetic changes such as shade discrepancy, had a much greater impact on satisfaction, while patients with a larger number of restorations were also more likely to report an unfavorable outcome. Long-term evaluation of anterior ceramic rehabilitation should therefore include both conventional clinical examination and the patient's own assessment of the esthetic result.

CONCLUSIONS

Patient-reported esthetic satisfaction after anterior ceramic rehabilitation was high, with more than 90% of patients reporting a satisfactory outcome after 5–9 years of clinical service. Satisfaction did not differ significantly according to ceramic material, age, or sex, indicating that these factors alone were not major determinants of the perceived esthetic result. In contrast, the presence of a documented clinical complication was strongly associated with dissatisfaction, particularly in cases involving shade discrepancy and other visible esthetic changes. Dissatisfied patients also had a greater number of restorations than satisfied patients. These findings suggest that long-term success of anterior ceramic restorations should not be assessed solely by material type or restoration survival, but should also include clinical complications and the patient’s perception of the final esthetic result.

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Conflicts of Interest

The authors declare no conflict of interest.

Author Contributions

Conceptualization, A.J. and S.G.M.; Methodology, A.J., S.G.M. and L.P.; Investigation, A.J. and S.G.M.; Data curation, A.J.; Formal analysis, A.J. and S.G.M.; Writing – original draft

preparation, A.J.; Writing – review and editing, S.G.M. and L.P.; Supervision, S.G.M. and L.P. All authors have read and agreed to the published version of the manuscript.

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