Medicine in Evolution | Volume XXXII | No. 1/2026

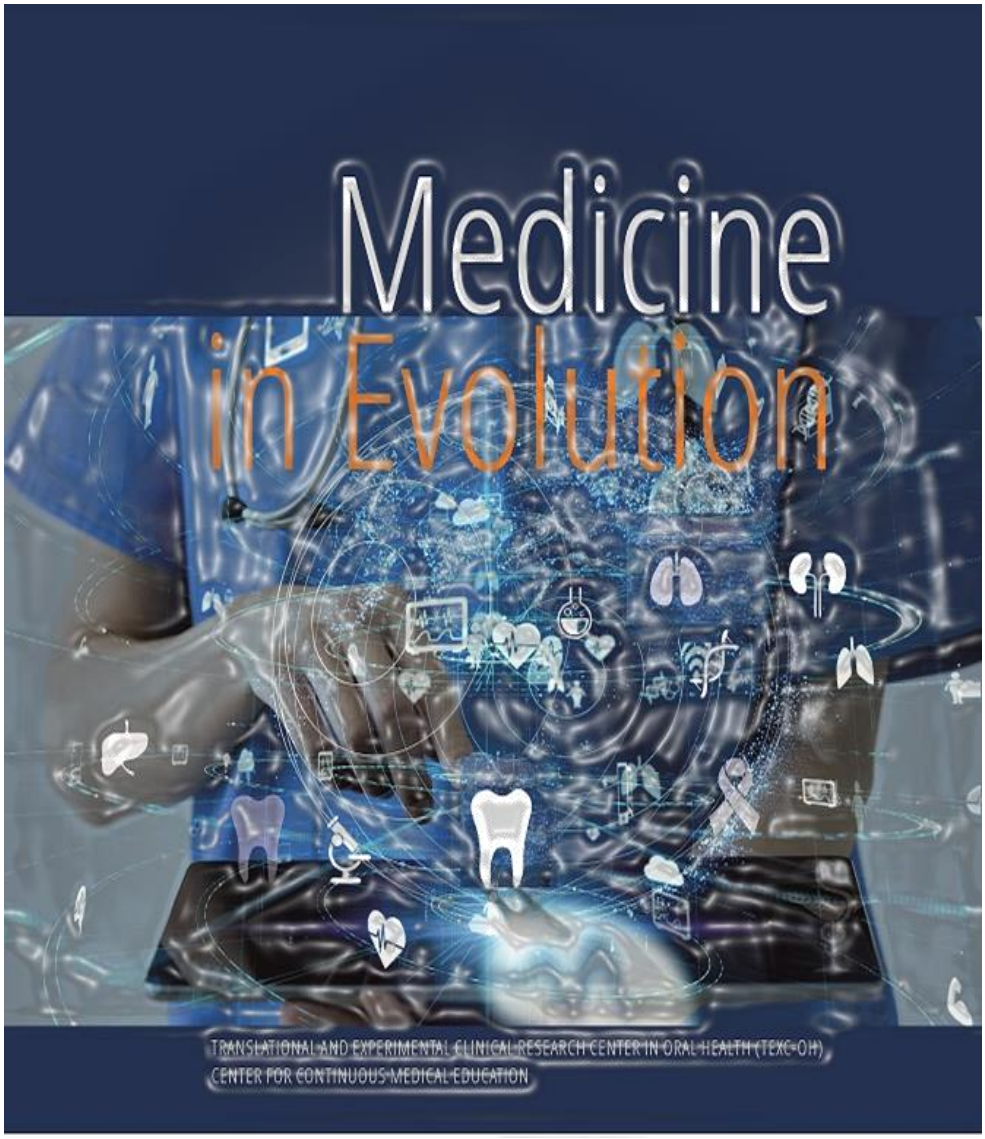
Medicine in Evolution

TRANSLATIONAL AND EXPERIMENTAL CLINICAL RESEARCH CENTER IN ORAL HEALTH (TEXC-OH)
CENTER FOR CONTINUOUS MEDICAL EDUCATION

ISSN 2065-376X medinevolution.umft.ro

Volume XXXII, No. 1, 2026, Timişoara, Romania
ISSN 2065-376X

MEDICINE IN EVOLUTION



TRANSLATIONAL AND EXPERIMENTAL CLINICAL RESEARCH CENTRE IN ORAL HEALTH

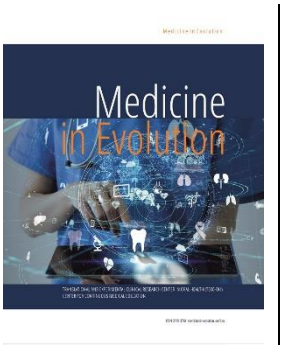
"VICTOR BABEŞ" UNIVERSITY OF MEDICINE AND PHARMACY TIMIŞOARA

https://medicineinevolution.ro/

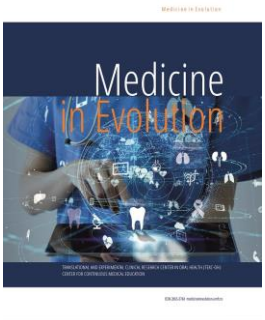
Translational and Experimental Clinical Research Center in Oral Health

https://www.umft.ro/en/research-centres/ccextso/

EDITORIAL BOARD



Background



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.

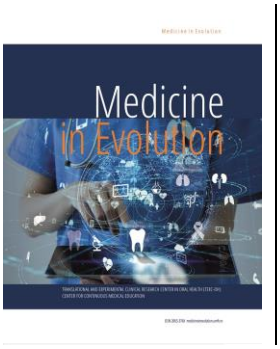
The inception of the journal stemmed from a dedication to exchange experiences in both professional and research domains. It was envisioned to encompass all medical specialties, with the aspiration that the published manuscripts would exhibit exceptional quality, elevating the journal's reputation. Esteemed 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.

CONTENTS

ARTICLES



Vanessa Bolchis, Lucian Floare, Delia Abrudan-Luca, Octavia Balean, Ramona Dumitrescu, Vlad-Tiberiu Alexa, Doina Chioran

Remineralization of Enamel White Spot Lesions Using Plant-Based Agents *1*

Irina Zumbreanu, Valentina Trifan, Sorana Nicoleta Roşu, Daniela Trifan

Biomechanical Strategies and Compliance Monitoring for Orthodontic Treatment in Periodontally Compromised Adults *9*

Sorana Maria Bucur, Dana Cristina Bratu, Remus Christian Bratu, Mariana Păcurar

Alveolar Bone Response to Controlled Orthodontic Maxillary Incisor Vestibularization *22*

Bratu Remus Christian, Sorana Maria Bucur, George Popa, Dana Cristina Bratu

A Retrospective Analysis of Endodontic and Extraction Risk after Orthodontic Treatment *31*

Adina Coman, Daian Ionel Popa, Diana Utu, Florina Buleu, Mihaela Avram, Marius Murariu

Unilateral Focused Parathyroidectomy versus Bilateral Neck Exploration in Primary Hyperparathyroidism: A Retrospective Cohort Study *39*

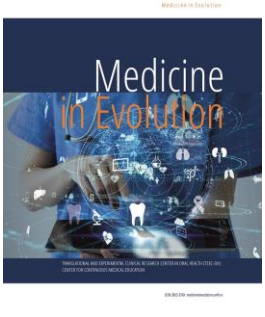
Alexandru Victor Burde, Marius Ciprian Manole, Sorana Baciu, Sabina Gabriela Cretu, Cosmin Sinescu

Dimensional Accuracy of Dental Models Printed with Different Resins Using a Low-Cost LCD 3D Printer *49*

Marius Ciprian Manole, Alexandru Victor Burde, Alexandru Grecu, Mihaela Hedeşiu, Cosmin Sinescu

The Effect of Nozzle Diameter on the Dimensional Accuracy of FDM-Printed Dental Models *59*

Remineralization of Enamel White Spot Lesions Using Plant-Based Agents



https://doi.org/10.70921/medev.v32i1.2015

Vanessa Bolchis[1,2†], Lucian Floare[1,2†], Delia Abrudan-Luca[1,2], Octavia Balean[1,2], Ramona Dumitrescu[1,2], Vlad-Tiberiu Alexa[1, 2], Doina Chioran[3]

[1]*Clinic of Preventive, Community Dentistry and Oral Health," Victor Babes" University of Medicine and Pharmacy, Eftimie Murgu Sq. no. 2, 300041, Timisoara, Romania*
[2]*Translation and Experimental Clincal Research Center in Oral Health (TEXC-OH), Department of Preventive, Community Dentistry and Oral Health," Victor Babes" University of Medicine and Pharmacy, 14 A Tudor Vladimirescu Ave., 300173, Timisoara, Romania*
[3]*Department of Anesthesiology and Oral Surgery, "Victor Babeş" University of Medicine and Pharmacy, Eftimie Murgu Sq. No. 2, 300041 Timisoara, Romania*
[†]*These authors contributed equally to this work.*

Correspondence to:
Name: Vlad-Tiberiu Alexa
E-mail address: vlad.alexa@umft.ro

Received: 11 March 2026; Accepted: 15 March 2026; Published: 31 March 2026

Abstract

1.Background/Objectives: Dental caries is one of the most prevalent chronic diseases worldwide and results from the demineralization of dental hard tissues caused by acids produced by bacterial metabolism of fermentable carbohydrates. Early enamel lesions, known as white spot lesions (WSLs), represent the initial and potentially reversible stage of the caries process. Although fluoride is considered the gold standard for remineralization therapy, increasing attention has been directed toward natural plant-derived agents with antimicrobial and bioactive properties. The aim of this in vitro study was to evaluate the remineralization potential of ginger (*Zingiber officinale*) and rosemary (*Rosmarinus officinalis*) extracts compared with sodium fluoride on artificially induced enamel white spot lesions using laser fluorescence. *2. Methods:* Thirty extracted human teeth were randomly assigned to three groups (n = 10): ginger extract, rosemary extract, and sodium fluoride varnish. Artificial enamel lesions were induced using 37.5% orthophosphoric acid. Laser fluorescence values were measured with a DIAGNOdent device at baseline (T0), after demineralization (T1), and after 10 days of remineralization treatment (T2). *3.Results:* DIAGNOdent values increased after demineralization, confirming successful lesion formation, and decreased after treatment in all groups. The greatest reduction was observed in the ginger extract group. *4. Conclusion:* Plant-based agents demonstrated remineralizing potential on early enamel lesions, with ginger extract showing the most promising effect as a possible complementary alternative to fluoride-based therapies

Keywords: dental caries, enamel remineralization, white spot lesions, plant extracts, laser fluorescence, DIAGNOdent

INTRODUCTION

Dental caries remains one of the most prevalent chronic diseases worldwide and represents a major public health concern. The disease is characterized by the progressive demineralization of dental hard tissues caused by acids produced during the bacterial metabolism of fermentable carbohydrates within the dental biofilm [1,6]. When the balance between demineralization and remineralization shifts toward mineral loss, structural damage to enamel occurs, eventually leading to cavitated lesions [5]. The earliest clinically detectable stage of the caries process is represented by enamel white spot lesions (WSLs), which are characterized by subsurface mineral loss while the superficial enamel layer remains relatively intact [6]. Clinically, these lesions appear as opaque white areas on the enamel surface and represent the initial stage of caries development. White spot lesions are potentially reversible if appropriate preventive strategies are implemented. Consequently, modern preventive dentistry increasingly focuses on non-invasive approaches aimed at enhancing enamel remineralization and preventing lesion progression [8]. Fluoride-based agents are widely considered the gold standard in the prevention and management of dental caries due to their ability to enhance enamel remineralization and increase resistance to acid dissolution [18]. Fluoride promotes the formation of fluorapatite and facilitates the deposition of calcium and phosphate ions in demineralized enamel areas. However, concerns regarding excessive fluoride exposure, particularly the risk of dental fluorosis and other potential adverse effects associated with chronic intake, have stimulated the search for alternative or complementary remineralizing agents [17].

In recent years, natural plant-derived compounds have attracted increasing attention in dental research due to their antimicrobial, antioxidant, and anti-inflammatory properties [19]. Several plant extracts have demonstrated the ability to inhibit the growth and metabolic activity of cariogenic microorganisms, particularly Streptococcus mutans, which plays a key role in the development of dental caries [16]. Among these natural agents, ginger (Zingiber officinale) and rosemary (Rosmarinus officinalis) have been investigated for their potential oral health benefits. Ginger contains biologically active compounds such as gingerols and shogaols that exhibit antimicrobial and anti-inflammatory properties [2,9], while rosemary contains phenolic compounds such as rosmarinic acid and carnosic acid with antibacterial and antioxidant activity [12]. These compounds may contribute to the inhibition of cariogenic bacteria and indirectly support enamel remineralization.

The evaluation of enamel remineralization requires reliable diagnostic methods capable of detecting early structural changes in dental tissues. Laser fluorescence devices, such as DIAGNOdent, are widely used for the detection and monitoring of early enamel lesions due to their ability to quantify changes in tooth structure associated with demineralization [20]. Therefore, the aim of the present in vitro study was to evaluate the remineralization potential of ginger (Zingiber officinale) and rosemary (Rosmarinus officinalis) extracts compared with sodium fluoride on artificially induced enamel white spot lesions using laser fluorescence measurements obtained with the DIAGNOdent system. The working hypothesis was that plant-based extracts may demonstrate measurable remineralizing effects on early enamel lesions and could represent potential complementary alternatives to conventional fluoride-based therapies.

Aim and objectives

The aim of the present study was to evaluate the remineralization potential of plant-based agents on artificially induced enamel white spot lesions using laser fluorescence analysis. Specifically, the study investigated the effectiveness of ginger (Zingiber officinale)

and rosemary (Rosmarinus officinalis) extracts compared with sodium fluoride, a widely used remineralizing agent in preventive dentistry.

The primary objective of the study was to determine the capacity of the tested plant extracts to promote enamel remineralization, assessed through changes in DIAGNOdent values before and after treatment. Secondary objectives included comparing the remineralizing effectiveness of ginger and rosemary extracts with sodium fluoride, as well as evaluating the influence of the duration of agent application on the remineralization process. Additionally, the study aimed to explore the potential of plant-derived agents as complementary or alternative preventive strategies in the management of early enamel lesions.

MATERIAL AND METHODS

This in vitro experimental study was designed to evaluate the remineralization potential of plant-based agents on artificially induced enamel white spot lesions. The remineralizing effects of ginger (*Zingiber officinale*) extract and rosemary (*Rosmarinus officinalis*) extract were compared with those of sodium fluoride varnish using laser fluorescence measurements obtained with the DIAGNOdent device. A total of 30 extracted human teeth were collected from patients who required dental extraction for therapeutic reasons. All patients were informed about the use of the extracted teeth for scientific and educational purposes, and written informed consent was obtained prior to their inclusion in the study. The study protocol followed the ethical principles outlined in the Declaration of Helsinki (2013 revision). Teeth were selected according to strict inclusion criteria in order to ensure sample homogeneity. Only intact teeth without primary or secondary caries, restorative treatments, endodontic therapy, structural defects, or enamel developmental abnormalities were included. Teeth presenting fractures caused during extraction, visible enamel hypoplasia, fluorosis, structural discolorations, or prior bleaching treatments were excluded from the study. After extraction, the teeth were mechanically cleaned to remove calculus deposits and stored in 0.1% thymol solution for five days at room temperature in order to prevent bacterial contamination. To ensure specimen stability during the experimental procedures, the roots of the teeth were embedded in addition silicone impression material (V-Posil Putty Fast, VOCO, Germany). The lingual surfaces of the teeth were covered with two layers of transparent nail varnish, leaving a standardized enamel area measuring approximately 4 × 4 mm exposed on the vestibular surface. This exposed area represented the experimental window used for the induction of artificial enamel lesions and for subsequent remineralization procedures.

After preparation, the specimens were allowed to dry at room temperature for 24 hours and were then stored in distilled water until further use.

Artificial white spot lesions were induced by applying 37.5% orthophosphoric acid gel to the exposed enamel area for 30 seconds. This protocol is frequently used in in vitro studies to simulate early enamel demineralization without causing irreversible structural damage [7,12]**.** The specimens were then rinsed with water for 30 seconds and air-dried for 10 seconds until the characteristic chalky white appearance of early enamel demineralization became visible.

Following the creation of artificial enamel lesions, the specimens were randomly divided into three groups of equal size (n = 10 per group):

Group 1: treatment with ginger extract (0.5% glyceric extract; AdNatura, Romania)
Group 2: treatment with rosemary extract (0.5% extract; PlantExtract, Romania)
Group 3: treatment with sodium fluoride varnish (Fluorodose, 5% NaF; Centrix, USA)

The plant-based extracts were applied to the exposed enamel surfaces using sterile dental applicators for 60 seconds twice daily over a period of 10 consecutive days. A new applicator was used for each specimen in order to prevent cross-contamination. For the control group, the sodium fluoride varnish was applied according to the manufacturer's instructions. After application, the materials were gently removed from the enamel surface without rinsing, and the specimens were returned to distilled water for storage throughout the experimental period.

Enamel mineralization was evaluated using a laser fluorescence device (DIAGNOdent, KaVo, Biberach, Germany), a diagnostic method widely used for the detection and monitoring of early enamel lesions [15,20]**.** The device operates by emitting laser light with a wavelength of approximately 655 nm onto the tooth surface. The fluorescence emitted by bacterial metabolites and altered enamel structures is detected and displayed as numerical values ranging from 0 to 99, corresponding to the degree of enamel demineralization.

Measurements were performed at three time points during the experiment:

- **T0:** baseline measurement before artificial demineralization
- **T1:** after the induction of enamel white spot lesions
- **T2:** after 10 days of remineralization treatment

Prior to each measurement session, the device was calibrated using the ceramic calibration standard supplied by the manufacturer. Each measurement was performed three times on the same area of the enamel surface under standardized conditions, and the mean value of the three readings was recorded for statistical analysis.

Figure 1. DIAGNOdent device used for laser fluorescence evaluation of enamel lesions

All measurements were recorded manually in a data collection table organized according to experimental group and measurement time (T0, T1, and T2). The recorded data were subsequently transferred to a Microsoft Excel spreadsheet for data organization and preparation for statistical analysis.

Statistical analysis was performed using IBM SPSS Statistics software (version 23; IBM Corp., Armonk, NY, USA). Descriptive statistics were calculated as means and standard deviations for each group and measurement time. The normality of the data distribution was assessed using the Shapiro–Wilk test due to the relatively small sample size. Differences between experimental groups were analyzed using one-way analysis of variance (ANOVA). Within-group comparisons across different time points were evaluated using paired t-tests. Non-parametric comparisons of percentage changes were performed using the Kruskal–Wallis test. Additionally, the influence of contact time (1, 3, and 6 minutes) on the remineralization process was analyzed using the Friedman test. The level of statistical significance was set at $p < 0.05$.

RESULTS

The laser fluorescence measurements obtained with the DIAGNOdent device were analyzed at three different time points: baseline (T0), after artificial demineralization (T1), and

after remineralization treatment (T2). These measurements allowed the evaluation of enamel mineralization changes throughout the experimental procedure.

The descriptive statistical analysis showed a clear variation in DIAGNOdent values across the three evaluation stages. The mean value increased markedly from 1.99 at baseline (T0) to 10.97 after demineralization (T1), confirming the successful induction of artificial white spot lesions. After the remineralization phase, the mean value decreased to 2.25 (T2), indicating a partial restoration of enamel mineral content. Although the mean value at T2 did not return completely to the baseline level, the difference between T0 and T2 was relatively small, suggesting a substantial remineralization effect.

Table 1 Descriptive statistics and comparison of overall DIAGNOdent values (repeated measures ANOVA)

Time point	**Mean**	**Standard deviation**	**95% CI lower**	**95% CI upper**	**Minimum**	**Maximum**
T0	1.99	1.03	1.60	2.38	0.55	4
T1	10.97	2.77	9.93	12	6.3	15
T2	2.25	0.64	2.01	2.49	0.66	3.66

Repeated measures ANOVA did not reveal statistically significant differences between the three measurement moments ($p = 0.65$).

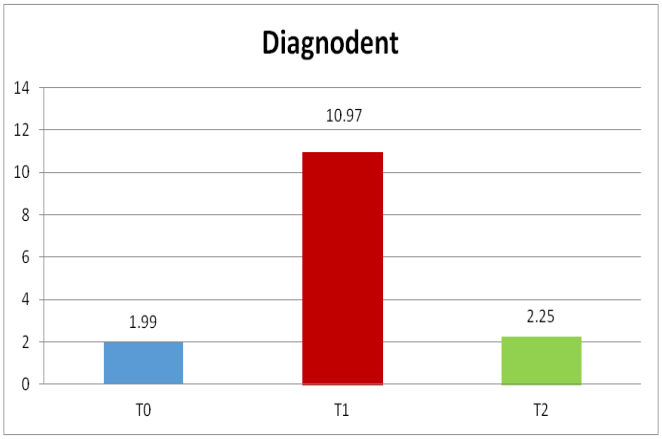


Figure 2. DIAGNOdent values recorded at different observation times (T0, T1, T2)

The comparison of DIAGNOdent values between the experimental groups showed no statistically significant differences at baseline ($p = 0.82$) or after demineralization ($p = 0.48$), indicating that the specimens were comparable prior to treatment.

However, at the end of the remineralization period (T2), differences between groups became evident. The lowest mean DIAGNOdent value was recorded in the ginger extract group (1.7 ± 0.59), followed by the sodium fluoride group (2.29 ± 0.39), while the rosemary extract group presented the highest mean value (2.76 ± 0.41).

The ANOVA test revealed a statistically significant difference between the groups at T2 ($p = 0.0001$).

Table 2. Descriptive statistics and comparison of DIAGNOdent values between groups

Group	**T0 mean ± SD**	**T1 mean ± SD**	**T2 mean ± SD**
Ginger extract	1.81 ± 0.89	10.25 ± 2.74	1.70 ± 0.59
Rosemary extract	2.08 ± 1.18	11.76 ± 2.45	2.76 ± 0.41
Sodium fluoride	2.07 ± 1.11	10.89 ± 3.15	2.29 ± 0.39

Post-hoc analysis using the Bonferroni test demonstrated a statistically significant difference between the ginger and rosemary groups ($p = 0.0002$), while no significant differences were observed between the other comparisons.

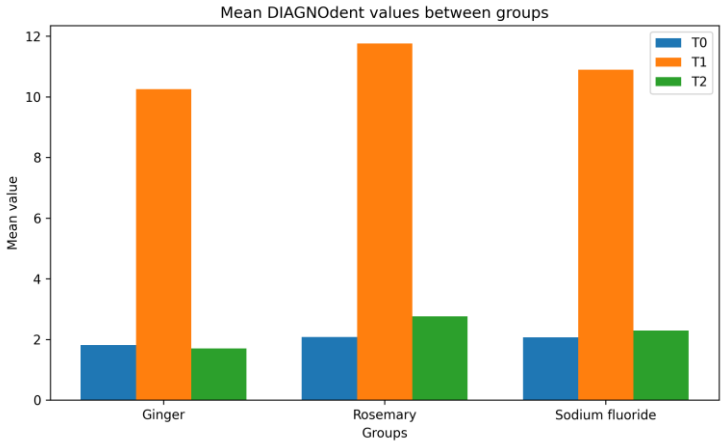


Figure 3. Mean DIAGNOdent values in the experimental groups at the three observation times

The intragroup analysis revealed a significant increase in DIAGNOdent values between T0 and T1 in all groups ($p < 0.001$), confirming the effectiveness of the artificial demineralization protocol. Subsequently, a significant reduction in DIAGNOdent values was observed between T1 and T2 in all groups, indicating the remineralization effect of the applied agents. However, no statistically significant differences were detected between T0 and T2, suggesting a partial recovery of enamel mineralization toward baseline conditions.

Additional analysis evaluated the absolute differences and percentage changes between the experimental stages.

The greatest median increase from T0 to T1 was observed in the rosemary group, followed by the ginger group, while the smallest increase was recorded in the sodium fluoride group. However, these differences were not statistically significant ($p > 0.05$).

Similarly, the analysis of percentage changes showed the highest increase from T0 to T1 in the ginger group, followed by rosemary and sodium fluoride, without statistically significant differences between groups.

To evaluate the influence of the duration of contact with remineralizing agents, additional measurements were performed at 1, 3, and 6 minutes on days 1, 5, and 10 of the treatment protocol. A consistent decreasing trend in DIAGNOdent values was observed with increasing contact time in all groups. The lowest values were generally recorded at 6 minutes, suggesting a stronger remineralization effect with prolonged exposure to the tested agents. In the final evaluation performed on day 10, the lowest mean value was observed at 6 minutes (2.18), compared with 2.25 at 1 minute and 2.26 at 3 minutes. The Friedman test demonstrated a statistically significant difference between the three contact times ($p < 0.000001$).

Table 3. Mean DIAGNOdent values (T2, day 10) according to contact time

Contact time	**Mean DIAGNOdent value**
1 minute	2.25
3 minutes	2.26
6 minutes	2.18

Overall, the results indicate that all tested agents produced measurable remineralization effects on artificially induced enamel lesions. Among the tested agents, ginger extract demonstrated the most favorable results, followed by sodium fluoride and rosemary extract. Additionally, increasing the duration of contact with the remineralizing agents enhanced the effectiveness of the treatment.

DISCUSSIONS

The present in vitro study evaluated the remineralization potential of two plant-based agents, ginger (Zingiber officinale) and rosemary (Rosmarinus officinalis), compared with sodium fluoride on artificially induced enamel white spot lesions using laser fluorescence analysis. The results demonstrated a clear increase in DIAGNOdent values following the demineralization procedure, confirming the successful creation of early enamel lesions. After the remineralization phase, a decrease in fluorescence values was observed in all experimental groups, indicating a partial recovery of enamel mineralization.White spot lesions represent the earliest clinically detectable stage of the caries process and are characterized by subsurface enamel demineralization while the outer enamel layer remains relatively intact [6]. At this stage, the lesion is still reversible if the balance between demineralization and remineralization is shifted toward mineral gain. For this reason, contemporary preventive dentistry increasingly focuses on non-invasive strategies aimed at promoting enamel remineralization and preventing lesion progression [8].

Fluoride remains the most widely used remineralizing agent in clinical dentistry due to its ability to enhance the deposition of calcium and phosphate ions in demineralized enamel and to promote the formation of fluorapatite, a mineral phase that is more resistant to acidic dissolution [18]. However, concerns related to excessive fluoride exposure and the potential risk of dental fluorosis have stimulated interest in alternative or complementary remineralizing agents [17].

In recent years, plant-derived bioactive compounds have attracted considerable attention in dental research due to their antimicrobial, antioxidant, and anti-inflammatory properties [19]. Several plant extracts have demonstrated the ability to inhibit the growth and metabolic activity of cariogenic microorganisms, particularly Streptococcus mutans, which plays a key role in the development of dental caries [16]. By reducing bacterial colonization and acid production within dental biofilms, plant-derived compounds may indirectly contribute to the prevention of enamel demineralization and support remineralization processes. Among the tested agents, the ginger extract group showed the lowest DIAGNOdent values after treatment, suggesting a higher remineralization potential compared with rosemary extract and sodium fluoride. Similar findings have been reported in previous studies that investigated the remineralizing effects of herbal extracts on early enamel lesions [2,9]. Ginger contains several biologically active compounds, such as gingerols and shogaols, which have demonstrated antimicrobial and anti-inflammatory properties. These compounds may inhibit the growth of cariogenic bacteria and reduce acid production within dental biofilms, thereby creating more favorable conditions for enamel remineralization [19]. Additionally, some studies suggest that ginger may contain naturally occurring minerals such as calcium and fluoride, which could further contribute to enamel remineralization processes [9]. The antibacterial activity of ginger against Streptococcus mutans may also play an important role in reducing the cariogenic potential of dental biofilms [16].

The rosemary extract group also demonstrated a reduction in DIAGNOdent values following treatment, although the remineralization effect appeared to be less pronounced than that observed in the ginger group. Rosemary contains phenolic compounds such as rosmarinic acid and carnosic acid, which have been shown to exhibit antibacterial and antioxidant properties [12]. These compounds may inhibit the growth of cariogenic bacteria and reduce oxidative stress in the oral environment, indirectly supporting the remineralization process.The results obtained in the present study are partially consistent with previous investigations that explored the potential of natural plant extracts in the prevention of dental caries. Several studies have demonstrated that herbal compounds can reduce bacterial adhesion, inhibit biofilm formation, and decrease the metabolic activity of

cariogenic microorganisms [11,12]. However, the magnitude of the remineralization effect may vary depending on factors such as extract concentration, treatment duration, and experimental conditions.

In the present study, although descriptive analysis suggested a more pronounced remineralization effect in the ginger group, some comparisons between experimental groups did not reach statistical significance. This may be attributed to the relatively small sample size and the controlled conditions of the in vitro experimental design. While in vitro studies provide a controlled environment for evaluating the direct effects of therapeutic agents, they cannot fully replicate the complex biological conditions of the oral cavity, where saliva composition, dietary habits, oral hygiene practices, and microbial diversity play important roles in the caries process. Another important aspect investigated in this study was the influence of contact time between the remineralizing agents and the enamel surface. The results indicated that longer exposure times were associated with lower DIAGNOdent values, suggesting enhanced remineralization. The lowest values were generally observed after six minutes of contact, and statistical analysis confirmed that contact duration significantly influenced the outcome of the remineralization process. These findings highlight the importance of adequate exposure time when applying remineralizing agents, particularly those based on natural extracts.

Despite the promising findings, several limitations should be considered when interpreting the results of this study. First, the relatively small sample size may limit the statistical power of the analysis and reduce the ability to detect subtle differences between treatment groups. Second, the in vitro design does not fully replicate the dynamic conditions of the oral environment, where saliva, biofilm interactions, and dietary factors significantly influence remineralization processes. Additionally, the experimental protocol lasted only ten days, which may not fully reflect the long-term effects of remineralizing agents. Future research should aim to validate the findings of the present study through in vivo investigations involving larger sample sizes and longer observation periods. Further studies could also explore the remineralization potential of other plant-derived compounds such as green tea, honey, or aloe vera, as well as combinations of natural extracts that may produce synergistic effects. Moreover, incorporating plant-based remineralizing agents into oral hygiene products such as toothpastes, mouth rinses, or topical gels could represent a promising direction for preventive dentistry.

Overall, the findings of the present study suggest that plant-derived agents, particularly ginger extract, may exhibit measurable remineralization effects on early enamel lesions. These results support the potential role of natural compounds as complementary strategies in the prevention and management of early dental caries.

CONCLUSIONS

Within the limitations of this in vitro study, the tested remineralizing agents demonstrated the ability to reduce DIAGNOdent values after the induction of artificial enamel lesions, indicating a measurable remineralization effect. Among the evaluated agents, ginger extract showed the most favorable results, presenting the lowest DIAGNOdent values after treatment compared with rosemary extract and sodium fluoride. These findings suggest that plant-derived compounds may contribute to the remineralization of early enamel lesions. The results also highlighted the importance of the duration of contact between the remineralizing agents and the enamel surface, with longer application times leading to improved remineralization outcomes. This observation may have practical implications for the clinical use of topical remineralizing treatments. Although the differences between some experimental groups were not statistically significant, the overall trend indicates that natural

plant extracts may represent promising complementary agents in preventive dentistry. Further in vivo studies with larger sample sizes and longer observation periods are necessary to confirm these findings and to better understand the clinical applicability of plant-based remineralizing therapies.

Conflicts of Interest

The authors declare no conflict of interest.

REFERENCES

[1] Hassan S, Hassan A, El-Masry E. Effectiveness of natural remineralizing agents on initial enamel caries: an in vitro study. Ahram Canadian Dental Journal. 2022.

[2] Shaker AM, El-Wahab SA, El-Sayed D. Effectiveness of ginger-honey mixture and rosemary on remineralization and prevention of enamel white spot lesion measured by color change. Al-Azhar Dental Journal for Girls. 2022.

[3] Popa E, Sorin A. Strategii actuale de remineralizare a cariilor și eroziunilor incipiente. București: Editura Universitară; 2019.

[4] American Dental Federation. Preventive strategies adapted to oral disease risk groups. Social European Program; 2013.

[5] Grohe B, McKee MD. Advanced non-fluoride approaches to dental enamel remineralization: the next level in enamel repair management. Oxford: Elsevier; 2021.

[6] Pathak S, Ranjan K, Prakash P. White spot lesions: a literature review. Journal of Pediatric Dentistry. 2015.

[7] Holmen L, Bjørndal L, Tveit AB. The microflora associated with the development of initial enamel decalcification below orthodontic bands. Journal of Dental Research. 1989.

[8] Farooq I, Bugshan A. The role of salivary contents and modern technologies in the remineralization of dental enamel: a review. F1000Research. 2020;9:171.

[9] Hassan S, Hassan A, El-Masry E. Remineralization potential of ginger and rosemary herbals versus sodium fluoride in treatment of white spot lesions. Egyptian Dental Journal. 2021.

[10] Abd El Aziz K, El-Gendy R. Remineralization and antibacterial efficacy of ginger-based mouthwashes versus fluoride-based mouthwash on initial enamel caries: an in vitro study. 2024.

[11] Abdo R, Nagy M, Ghanem N. The remineralizing potential of some natural materials alone or combined with Zamzam water on demineralized enamel. Al-Azhar Dental Journal for Girls. 2021.

[12] Bilgin Gocmen G, Yildirim F. Effectiveness of some herbals on initial enamel caries lesions. Asian Pacific Journal of Tropical Biomedicine. 2016.

[13] Roushdy RZ, Sayed M. Remineralizing effect of white tea, green tea and CPP-ACP on artificially demineralized enamel: an in vitro study. ACDJ. 2023.

[14] Shayegan A, Moradi M. Comparative evaluation of remineralizing efficacy of calcium sodium phosphosilicate, ginger, turmeric, and fluoride. 2024.

[15] Yazicioglu O, Ulukapi H. Investigation of non-invasive techniques for treating early approximal carious lesions: an in vivo study. International Dental Journal. 2014.

[16] Al-Lafi T. Antimicrobial activity of vegetables, herbs and spices against cariogenic bacteria. Research Journal of Biology. 2016.

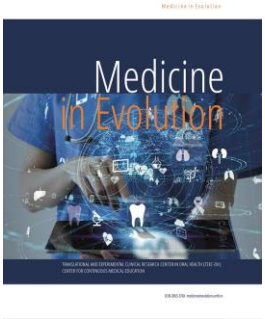
[17] Lins R, Araujo D. Influence of treatment protocols for dental fluorosis on enamel surface: an in vitro study. Rio de Janeiro Dental Journal. 2019.

[18] Dai Z, Liu M, Zhang Y. Effects of fluoride and calcium phosphate materials on remineralization of mild and severe white spot lesions. BioMed Research International. 2019.

[19] Sharma D, Jain A. Role of plant extracts in the inhibition of dental caries. Life. 2018.

[20] Khushboo S, Singh A. DIAGNOdent in detection of dental decay: a systematic review. Journal of Pearldent. 2013.

Biomechanical Strategies and Compliance Monitoring for Orthodontic Treatment in Periodontally Compromised Adults



https://doi.org/10.70921/medev.v32i1.2022

Irina Zumbreanu[1], Valentina Trifan[1], Sorana Nicoleta Roşu[2], Daniela Trifan[1]

[1]*Department of Orthodontics, State University of Medicine and Pharmacy "Nicolae Testemiţanu", Chişinău, Republic of Moldova*
[2]*Department of Surgery (Dentoalveolar and Maxillofacial Surgery), "Grigore T. Popa" University of Medicine and Pharmacy, Iaşi, România*

Correspondence to:
Name: Irina Zumbreanu
E-mail address: irina.zumbreanu@usmf.md

Received: 23 December 2025; Accepted: 10 January 2026; Published: 31 March 2026

Abstract

Background: Orthodontic treatment in adults with reduced periodontal support requires interdisciplinary sequencing and strict plaque control; however, heterogeneity of periodontal phenotypes, biomechanics, and adjunctive therapies makes standardized clinical outcome evaluation challenging. This study therefore prioritised clinical compliance and cooperation as key modifiable determinants of safe treatment delivery. Biomechanical strategies are presented to contextualize clinical management and were not evaluated as study endpoints. Objective: To assess patient cooperation during late active orthodontic therapy and clinical compliance during early retention in adults with stage I–II periodontitis. Materials and methods: A prospective clinical study was conducted in 25 adults (17 women, 8 men; 29–51 years) diagnosed with stage I–II periodontitis. Following periodontal stabilisation (non-surgical therapy in all cases; adjunctive periodontal surgery in 12%), orthodontic treatment was delivered using individualised, low-force biomechanics with periodic periodontal monitoring. Cooperation was assessed using the Orthodontic Patient Cooperation Scale (OPCS). Compliance during retention was assessed using a Clinical Compliance Evaluation (CCE) form at 6 months (T1) and 12 months (T2) after transition to retention. Non-parametric tests were used to compare timepoints and sex-based differences. Results: Women showed higher compliance scores for motivation/enthusiasm and fewer complaints about wearing appliances. CCE total scores improved significantly from T1 to T2 (86.20±14.73 vs 96.20±2.96; p=0.001), with a concurrent improvement in the oral hygiene subscore (23.12±1.64 vs 23.60±0.82; p=0.010). Conclusions: Structured compliance monitoring can support adherence during retention in periodontitis-susceptible adults undergoing orthodontic treatment. Larger controlled studies integrating standardised periodontal endpoints are required to clarify how compliance trajectories translate into long-term periodontal stability and orthodontic outcomes.

Keywords: periodontitis, orthodontic treatment, patient compliance, cooperation, retention, interdisciplinary car

INTRODUCTION

Periodontal disease is a common chronic condition in adults that leads to progressive loss of the tooth's supporting structures, often resulting in gingival recession, alveolar bone loss, tooth mobility, and pathologic tooth migration [5; 15]. In its advanced form (Stage IV periodontitis), the disease can cause secondary malocclusions such as flaring and drifting of incisors, bite collapse from posterior tooth loss, and occlusal trauma, all of which impair function and aesthetics [5; 29]. With the rising demand for adult orthodontic treatment and the prevalence of periodontitis in middle-aged populations, clinicians are increasingly managing complex cases of malocclusion associated with reduced periodontal support [16; 21]. Orthodontic intervention in periodontitis patients is no longer contraindicated per se – on the contrary, it is often an integral part of comprehensive rehabilitation aimed at restoring a stable occlusion and improving oral health-related quality of life [15; 16]. Recent consensus guidelines emphasize that orthodontic treatment can be performed safely in patients with a history of periodontitis, provided the periodontal inflammation is first controlled and the disease stabilized [3; 16]. Orthodontic realignment in these cases may facilitate better plaque control, redistribute occlusal forces, and aid in periodontal maintenance, thereby potentially improving long-term outcomes [9; 21].

Despite these potential benefits, the scientific evidence on orthodontic outcomes in periodontally compromised adults remains difficult to interpret. Every patient presents a unique combination of disease severity, anatomical bone loss patterns, and treatment needs, making standardized protocols and outcome measures challenging to establish [17; 30]. Traditional orthodontic success metrics (e.g., tooth movement achieved or occlusal indices) may be less meaningful in this context than periodontal stability and tooth survival – outcomes which are multifactorial and heavily influenced by patient behavior. Research shows that when periodontal health is stabilized, orthodontic tooth movement usually does not exacerbate attachment loss [3; 17]. However, variability in case presentations and the necessity of individualized biomechanics have led to heterogeneous study designs and often inconclusive or low-quality evidence [17; 19]. Considering these challenges, the present study focuses on a critical modulator of success that transcends individual techniques or appliances: patient cooperation and clinical compliance. We hypothesize that in periodontally compromised adults, adherence to oral hygiene and maintenance regimens, as well as compliance with orthodontic instructions, are pivotal determinants of favorable outcomes, potentially outweighing the choice of specific biomechanical strategies. This article outlines the rationale and aims of our investigation into biomechanical approaches for these patients, and why patient cooperation was chosen as a central variable of interest. Biomechanical considerations are therefore included as background to the clinical pathway; the present study does not compare specific mechanics or quantify orthodontic tooth movement as an endpoint. This rationale is based on the fact that methodologically, "outcomes" in periodontal-orthodontic care are rarely comparable across patients because both orthodontic objectives and periodontal baselines (defect morphology, tooth mobility, and selectively indicated adjunctive procedures) are case-specific. Pooling periodontal endpoints would require extensive stratification by phenotype and planned movements/anchorage, which quickly becomes underpowered and drives heterogeneity in the evidence base [17; 30]. Therefore, we treated biomechanics as individualized clinical context (after periodontal stabilisation) and prioritised cooperation/compliance as the cross-cutting endpoint enabling safe execution of the interdisciplinary plan.

Orthodontic treatment and periodontal health are deeply interrelated, especially in adult patients. Active periodontitis causes attachment loss and often leads to pathologic tooth

migration – for example, flared or extruded anterior teeth and formation of diastemas as bone support is lost [5; 29]. These changes can further impair oral function and aesthetics, creating a clear indication for orthodontic intervention once the disease is controlled. Conversely, malocclusion itself can exacerbate periodontal problems: crowding and malpositioned teeth hinder oral hygiene, and deep overbites or traumatic occlusion can injure the periodontium [16]. A synergistic approach has therefore emerged in which combined periodontal-orthodontic therapy is employed to restore oral health. After initial periodontal therapy to eliminate inflammation, gentle orthodontic forces are applied to reposition teeth in more favorable alignment, which can reduce plaque stagnation areas, distribute forces evenly, and facilitate restorative procedures [16; 21]. Recent systematic reviews have indeed noted that periodontitis patients treated with integrated orthodontic therapy show improved clinical parameters compared to periodontal treatment alone, although the gains tend to be modest [19; 29]. Importantly, long-term follow-up studies up to 10 years demonstrate that such interdisciplinary treatment can achieve stable outcomes, with minimal recurrence of periodontal breakdown when maintenance care is rigorous [3; 13]. These findings underscore that orthodontic treatment, when performed on a stabilized periodontium, is not only safe but can also enhance overall prognosis of a compromised dentition [3; 15].

Performing orthodontics on a reduced periodontium necessitates special biomechanical considerations and presents several challenges. By definition, periodontally compromised adults have lost varying amounts of alveolar bone support, which alters the center of resistance of teeth and makes them more susceptible to damage from excessive forces. Therefore, light and controlled forces, longer pauses between activations, and shorter treatment phases are generally recommended to minimize risks such as orthodontic-induced root resorption or further bone loss [7; 23]. The presence of infrabony defects or furcation involvements adds complexity: certain movements (for instance, uncontrolled tipping or extrusion of teeth with vertical defects) can aggravate periodontal breakdown if done improperly or in the presence of inflammation [15; 26]. Biomechanical strategies in these patients often include using sectional mechanics or splints to stabilize teeth with reduced support, intrusion of supra-erupted teeth to level the occlusal plane (only after inflammation is resolved), and skeletal anchorage devices (TADs) or splinted anchorage to distribute forces more safely [11; 14]. Each case must be planned individually: for example, pathologically migrated anterior teeth in a patient with Stage IV periodontitis may require intrusion and retraction with very mild continuous forces, whereas a different patient might need molar uprighting using a segmented arch to avoid stressing adjacent periodontally involved teeth (Chele 2016; 11). This individualized planning is compounded by patient-specific factors (age, smoking status, systemic health, etc.) that affect healing and tissue response. Because of these variables, research gaps remain in our knowledge – there is a lack of high-level evidence (few randomized trials) and existing studies are hard to compare due to inconsistent case selection and outcome measures [17; 30]. A systematic review by Kloukos et al. (2022) highlighted that evidence on combined ortho-perio treatment in severe periodontitis is limited and heterogenous, with many studies being retrospective or case series prone to bias [17]. Similarly, a 2016 review by Zasčiurinskienė et al. noted that while numerous case reports document successful outcomes, there was insufficient standardized data to quantify the periodontal effects of orthodontics in periodontitis-susceptible patients [30]. Key questions – such as the optimal timing of orthodontics relative to periodontal therapy, or the extent to which orthodontic movement can regenerate bone in vertical defects – are still difficult to answer definitively due to these research challenges [16; 25].

On balance, current knowledge supports the notion that orthodontic treatment is feasible and beneficial in periodontally compromised adults under certain conditions. First and foremost, the periodontal disease must be stabilised: clinicians agree that active

periodontal inflammation is a contraindication to orthodontic force, because moving teeth in the presence of uncontrolled periodontitis can accelerate attachment loss [15; 16]. The European Federation of Periodontology S3 guidelines [16] stipulate that orthodontic therapy should commence only after successful initial periodontal therapy – defined by the absence of deep pockets and bleeding on probing – and this often involves re-evaluating the patient after each phase of periodontal treatment. Studies have explored different sequencing; for example, one clinical trial found that starting orthodontics concurrently with cause-related periodontal therapy yielded similar attachment level gains as waiting until after periodontal treatment, though pockets tended to heal slightly better when orthodontics was deferred [28]. Another multicenter trial examined timing orthodontics after periodontal regenerative surgery and reported no significant difference in outcomes whether orthodontic movement began 1 month versus 6 months post-surgery [16; 25]. These findings suggest a degree of flexibility in treatment timing, provided that meticulous plaque control is maintained. Nonetheless, a common theme is that supportive periodontal therapy (maintenance) is essential throughout orthodontic care and beyond. Patients must be kept on a strict maintenance schedule (e.g., professional cleanings every 3–4 months) to monitor periodontal indices and address any signs of recurrence immediately [2]. Indeed, a 30-year follow-up study demonstrated that with regular supportive periodontal care, even patients with initially advanced periodontitis could retain the vast majority of their teeth, whereas those who became erratic in maintenance had significantly higher risk of tooth loss [2]. Thus, while biomechanical techniques (such as force selection, anchorage methods, and use of adjunctive surgery) are important, they operate on a foundation that is fundamentally biological and patient dependent.

Given the multifactorial nature of these cases, one of the most decisive factors is the patient's own cooperation. Successful periodontal-orthodontic treatment requires the patient to maintain impeccable daily oral hygiene, comply with periodontal maintenance visits, and follow orthodontic instructions [3; 4]. Poor plaque control will quickly negate any potential benefit of orthodontic alignment by allowing gingival inflammation to recur, potentially leading to progressive bone loss even during treatment. Similarly, if patients do not attend regular maintenance or if they smoke or neglect risk factor modification, the carefully calibrated orthodontic movements could result in undesired outcomes like increased pocket depths or recession [3; 15]. On the orthodontic side, compliance may involve wearing elastics or removable aligners as instructed, avoiding detrimental habits or excessive forces on teeth, and generally engaging with the treatment process. Adults with periodontal histories may have complex treatment plans (for instance, alternating periodontal surgeries with orthodontic adjustments), which absolutely require the patient's understanding and cooperation to succeed [26]. Unfortunately, clinical studies that focus on hard outcomes (attachment level changes, bone fill on radiographs, etc.) often cannot fully capture this human element. The decision to center our study on clinical compliance and patient cooperation arises from both clinical experience and evidence in the literature: high compliance has been correlated with favorable long-term results in periodontally compromised cases. For example, Aimetti et al. (2022) reported that in a cohort of severe periodontitis patients treated with combined orthodontics, all the teeth with initial "hopeless" prognoses remained stable over 10–15 years if the patients were highly compliant with maintenance – a remarkable outcome attributed to strict plaque control and maintenance care. By contrast, teeth in non-compliant patients or those lost to follow-up were far more likely to be lost (3). This aligns with earlier observations that orthodontics in periodontitis patients "improves the possibilities of saving a deteriorated dentition" only when periodontal support is meticulously preserved by the patient's and clinician's efforts [15]. Thus, focusing on compliance is not to downplay the importance of biomechanics, but rather to acknowledge that even the best biomechanical plan will falter in the absence of patient cooperation. Our

study aims to explore this often-under-emphasized aspect, examining how different strategies to engage and motivate patients – as well as the design of treatment plans those patients can realistically adhere to – might influence overall treatment success.

MATERIAL AND METHODS

A prospective clinical investigation was conducted within the Department of Orthodontics at University Dental Clinic No. 2 of "Nicolae Testemitanu" State University of Medicine and Pharmacy (Ethics Committee approval – no. 1 of 08.11.2024). The study evaluated patient compliance in adults undergoing periodontal-orthodontic management. Orthodontic therapy was delivered only after periodontal stabilization, and adjunctive prosthodontic and/or implantological interventions were performed when clinically indicated as part of comprehensive rehabilitation.

The study group comprised 25 adult patients (17 women and 8 men) aged 29–51 years. All participants were diagnosed with Stage I or Stage II periodontitis according to the 2017 classification of periodontal diseases and presented orthodontic treatment needs related to dento-maxillary anomalies (e.g., crowding, interdental spacing, and/or pathological tooth migration). Given the multifactorial nature of clinical outcomes in periodontal patients receiving orthodontic treatment, the present investigation focused on clinical compliance as the primary study endpoint rather than on heterogeneous clinical outcomes. This methodological choice is supported by evidence showing that, even among adult orthodontic patients in general, cooperation/compliance and—critically—oral-hygiene maintenance varies across treatment stages and tend to deteriorate as treatment progresses, which can directly affect the risk profile and management needs during mechanotherapy [20].

Consequently, standard clinically investigated periodontal variables (probing data) were used for eligibility and safety monitoring (confirmation of stabilisation before appliance placement and periodic surveillance), but changes in periodontal indices were not modelled as primary endpoints because baseline- and intervention-related variability would confound between-patient comparisons. By contrast, adherence behaviours – plaque control, appointment attendance, appliance wear and maintenance – are required in all cases and directly determine whether the planned low-force biomechanics and supportive periodontal therapy can be delivered as intended. For this reason, validated compliance instruments (OPCS and CCE) were selected as the primary outcome measures.Moreover, the periodontal–orthodontic interface is particularly sensitive to plaque-mediated inflammation: fixed appliances favor biofilm retention and shifts in periodontal conditions, and the literature emphasizes completing periodontal therapy and maintaining strict inflammation control before and throughout orthodontic tooth movement to reduce the likelihood of periodontal breakdown [18].

Accordingly, structured compliance monitoring and reinforcement (including targeted communication strategies shown to improve oral-hygiene adherence) represent a clinically justified approach for standardizing follow-up in a cohort where clinical outcome variability is intrinsically high [8]. Prior to initiation of orthodontic therapy, each patient underwent comprehensive periodontal evaluation and a treatment protocol aimed at controlling inflammation and stabilizing the periodontal condition. This phase included individualized oral-hygiene instruction, professional plaque and calculus removal by scaling, and root surface debridement. In 3 out of 25 cases (12%), deep periodontal pockets and persistent inflammation required surgical intervention; these patients received flap surgery combined with root planning to improve access for decontamination and to facilitate periodontal healing. Periodontal monitoring included periodontal probing, assessment of tooth mobility, evaluation of plaque and calculus indices, and documentation of gingival recession. The

periodontal status was reassessed after initial therapy to confirm resolution of active inflammation before orthodontic planning and appliance placement.

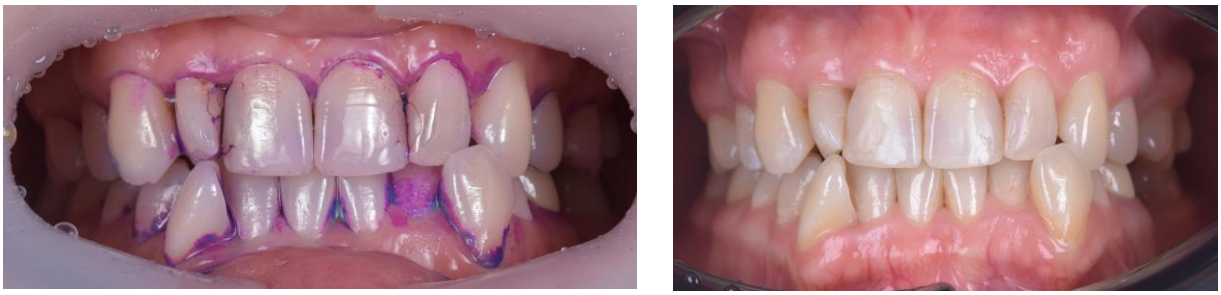
Orthodontic treatment was initiated using individualized biomechanical strategies adapted to each patient's periodontal status. Anchorage planning, force calibration, and appliance selection were tailored to minimize stress on compromised periodontal structures. Throughout treatment, patients were periodically re-evaluated to monitor periodontal stability and to ensure that orthodontic forces remained within biologically acceptable limits. These biomechanical strategies were individualized as part of routine care and are reported descriptively only; no standardized or comparative biomechanical analysis was undertaken.Orthodontic documentation and baseline characterization included medical history and standard extraoral and intraoral clinical examination, extraoral photostatic assessment, and paraclinical investigations (panoramic radiography/OPG, computed tomography/CT when indicated, cephalometry including lateral cephalogram/TRG, and study model analysis).

Study design and outcome focus

Participants were evaluated in both the active phase (fixed appliance therapy) and the passive phase (retention). At the end of the active phase, overall adherence was assessed using the Orthodontic Patient Cooperation Scale (OPCS). After transition to retention, patients were followed for 12 months, and compliance was longitudinally recorded using the Clinical Compliance Evaluation (CCE) instrument. Compliance levels were compared at 12 months (T2) versus 6 months (T1), both for the overall CCE score and across its specific domains. Patient cooperation throughout orthodontic therapy was measured using the OPCS (Orthodontic Patient Cooperation Scale), developed by Slakter et al. (1980) [24]. The instrument comprises 10 items capturing distinct behavioral aspects and is rated on a 5-point Likert scale (Never, Rarely, Sometimes, Frequently, Always). OPCS includes five positively worded and five negatively worded items; negatively phrased items are reverse scored, such that higher total scores indicate better compliance. The scale can be applied at different time points during treatment as clinically indicated. Clinical compliance during retention was assessed using the Clinical Compliance Evaluation (CCE) instrument proposed by Richter et al. (1998) [22]. The CCE provides a quantitative appraisal of patient compliance across four determinants of treatment success: oral hygiene status, appointment punctuality, adherence to prescribed appliance wear, and maintenance of orthodontic devices. The four compliance domains are equally weighted, yielding similar maximum domain scores (approximately 24–25 points each), for a maximum total score of 99 points; the CCE wording was adapted to the retention appliances used. Oral hygiene was evaluated using a modified version of the Simplified Oral Hygiene Index (OHI-S; Green–Vermillion) with a dental mirror, dental probe, and plaque-disclosing agent (Plaquefinder, Curaprox, Switzerland). The buccal surfaces of the maxillary permanent first molars, the maxillary right permanent central incisor, the mandibular left permanent central incisor, and the lingual surfaces of both mandibular permanent molars were examined. Scoring reflected the location and extent of plaque at the tooth/retainer interface (4 points: no deposits; 3 points: <1/3; 2 points: >1/3 to ≤2/3; 0 points: >2/3), with a maximum total hygiene score of 24 points. Appointment punctuality was scored on a five-level scale (25 points for delay <15 minutes; 20 points for 15–30 minutes; 15 points for >30 minutes; 10 points for rescheduling within 24 hours; 0 points for non-attendance). Retainer wear was scored on a nine-level scale based on the percentage of prescribed wear time achieved, and retainer maintenance was scored on a four-level defect scale. For each CCE domain, raw scores were additionally converted into grades.

Patient data were entered into a tabular database using Microsoft Excel 2019 (Microsoft, USA). Statistical analyses were performed in RStudio (Posit Software, USA), including descriptive statistics, between-group comparisons using Student's t-test (Welch

modification), and repeated-measurement analyses using the paired Wilcoxon test. Statistical significance was set at $p < 0.05$.



A B

Figure 1. Example of plaque control and patient instruction before orthodontic treatment (A. Result after application of plaque revealer (Plaquefinder, Curaprox, Switzerland); B. Result after oral hygienization procedure)

RESULTS

The study enrolled 25 adult patients (women: n=17, 68%; men: n=8, 32%) with stabilized Stage I–II periodontitis who had completed the active phase of orthodontic treatment; retention was initiated. Participants were aged 29–51 years. The evaluated patients were examined using the OPCS (*Orthodontic Patient Cooperation Scale*) questionnaire at the end of active orthodontic treatment (Table 1). Based on this instrument, the patient's behaviors and their degree of compliance were assessed by the orthodontist. Thus, in general, we observe that according to the total OPCS score, the given patients had a fairly high level of compliance (34.08±6.714 points), but the analysis of individual cases revealed that compliance was quite variable (range of values from 23-40 points). Women generally demonstrated a higher level of compliance than men (35.82±5.434 vs. 30.38±7.99 points), but this trend did not approach statistical significance ($p = 0.111$). Comparable scores were observed in men and women for most of the items, without any statistical significane, such as appointment adherence and punctuality; family/support network involvement; family-related problems/strained relationships; complaints about treatment procedures. Although non-significant, per case scoring showed that men have a trend in lower compliance scores regarding appliance integrity, hostile attitude, cooperation with adjuncts to treatment (eg. elastics) and oral hygiene quality. It is to be noted that statistically significant sex-related differences were identified for patient enthusiasm/motivation in treatment ($p = 0.046$) and complaints about wearing appliances ($p = 0.045$), with women demonstrating higher compliance scores on both items, while men showing lower compliance on these items.

Table 1. OPCS (Orthodontic Patient Cooperation Scale) questionnaire scores administered at the end of active orthodontic treatment

	Gender	Mean±SD	Minimum	Maximum	Statistic (Welch t)	*p*
OPCS Item 1. **Appointments/punctuality**	M (n = 8)	3.75±0.707	2	4	0.5123	.616
	F (n = 17)	3.59±0.795	1	4		
OPCS Item 2. **Appliance integrity (damage/loose components)**	M (n = 8)	2.88±1.126	1	4	-1.3709	.201
	F (n = 17)	3.47±0.717	2	4		
OPCS Item 3. **Support-person engagement (partner/family/caregiver involved)**	M (n = 8)	3.50±0.926	2	4	-0.4220	.683
	F (n = 17)	3.65±0.493	3	4		
OPCS Item 4. **Family/relationship stressors affecting cooperation**	M (n = 8)	3.88±0.354	3	4	-0.0494	.961
	F (n = 17)	3.88±0.332	3	4		
OPCS Item 5.	M (n = 8)	2.38±1.408	1	4	-2.3662	**.046**

Motivation/enthusiasm for treatment	F (n = 17)	3.59±0.507	3	4		
***OPCS Item 6*. Negative/hostile demeanor (sad, sullen, rude, aggressive)**	M (n = 8)	2.88±1.246	1	4	-1.5589	.157
	F (n = 17)	3.59±0.507	3	4		
***OPCS Item 7.* Cooperation with auxiliaries (e.g., elastics/headgear)**	M (n = 8)	2.13±1.553	1	4	-1.6231	.134
	F (n = 17)	3.12±1.111	1	4		
***OPCS Item 8*. Complaints about procedures**	M (n = 8)	3.13±0.835	2	4	-1.0089	.333
	F (n = 17)	3.47±0.717	2	4		
***OPCS Item 9.* Oral hygiene quality (excellent hygiene).**	M (n = 8)	3.38±0.916	2	4	-1.3285	.220
	F (n = 17)	3.82±0.393	3	4		
***OPCS Item 10*. Complaints about wearing appliances**	M (n = 8)	2.50±1.309	1	4	-2.3257	**.045**
	F (n = 17)	3.65±0.702	2	4		
OPCS Total Score	M (n = 8)	30.38±7.999	23	40	-1.7463	.111
	F (n = 17)	35.82±5.434	26	40		

At the start of the retention (passive) phase, appliances were prescribed on an individual clinical basis. Overall, combined retention involving a fixed retainer and at least one removable appliance was used in 17/25 patients (68%), fixed-only retention was used in 7/25 patients (28%), and removable-only retention was used in 1/25 patients (4%). After fabrication and application of these devices, at repeated follow-up visits (6 and 12 months), patients were assessed for their degree of compliance with the retention phase using the CCE (Clinical Compliance Assessment) tool. The comparison was made from the perspective of the degree of change in parameters at visit 2 (T2 – 12 months of retention) compared to visit 1 (T1 - 6 months of retention). Regarding the Oral Hygiene section of the CCE, at visit T1 adequate hygiene was observed for the first molars assessed within the CCE (16, 26, 36, 46), and the same level was maintained at T2 (all four teeth had a mean score of 4.00 at both time points; $p = 1.000$ for each paired comparison). In contrast, hygiene issues during the intermediate retention period were predominantly identified in the frontal region. Within the CCE, the central incisors 11 and 31 showed greater variability at T1 (mean 3.56 ± 0.821) than at T2 (mean 3.80 ± 0.408), consistent with the clinical observations. The paired comparisons demonstrated a statistically significant improvement in hygiene for both incisors between T1 and T2 ($p = 0.010$ for 11; $p = 0.010$ for 31). Accordingly, the total hygiene score (Igiena_T) increased at T2 compared with T1 (23.60 ± 0.816 vs. 23.12 ± 1.641), and this change was statistically significant ($p = 0.010$). We assume that this improvement may reflect reinforcement of oral-hygiene instruction at the intermediate visit (T1) and increased patient motivation as treatment progresses toward completion.

Device wearing scores improved significantly at T2 compared with T1 (22.80 ± 2.236 vs. 20.68 ± 4.697; Wilcoxon $W = 6.00$; $p = 0.003$), with reduced variability at T2. Maintenance scores improved markedly between visits (25.00 ± 0.000 at T2 vs. 19.00 ± 7.071 at T1; $p < 0.001$), consistent with the absence of detected device defects at T2 following replacements when indicated. Punctuality/appointments also improved significantly from T1 to T2 (24.80 ± 1.000 vs. 23.40 ± 3.136; $p = 0.013$), again with lower variability at T2. These dynamics are broadly consistent with reports that compliance can vary across treatment stages and may deteriorate over time if not actively reinforced [20]. Overall, the total CCE score increased significantly, with 96.20 ± 2.958 at T2 vs. 86.20 ± 14.725 at T1 ($W = 1.00$; $p = 0.001$).

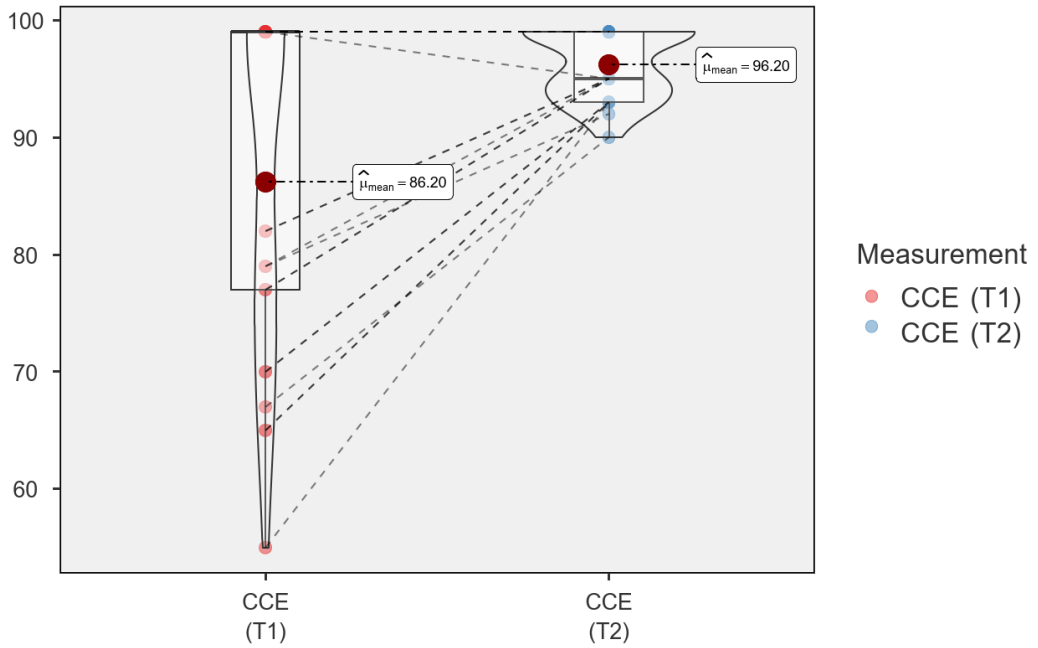


Figure 2. Total CCE score at different time periods (T1/T2) in the examined patients

We assume that this high level of compliance is due to several factors: the impact of the extended approach at visit T1 (additional patient education, patient verification according to the CCE), as well as the psycho-emotional aspect of awareness of treatment completion. In this context, our preliminary results reveal the usefulness of applying these tools both for documenting patient compliance with treatment, and for detecting gaps during treatment and correcting patient behaviors.

DISCUSSIONS

The present study followed 25 adults with stage I–II periodontitis who required orthodontic correction and were managed through a structured, interdisciplinary sequence (periodontal stabilisation followed by orthodontic treatment and retention). The primary observation was an improvement in clinical compliance during early retention, accompanied by improved oral-hygiene scores and significant gains in device-wearing behaviour, device maintenance, and appointment punctuality. In a complex periodontal–orthodontic context, this suggests that monitoring and reinforcing patient behaviour can produce measurable short-term gains in adherence. The feasibility of orthodontic tooth movement in a reduced periodontium is well supported when inflammation is controlled and biomechanics are adapted, with particular emphasis on low forces, careful anchorage management, and close periodontal surveillance. Contemporary reviews and clinical guidance highlight plaque control and supportive periodontal therapy as prerequisites for safe treatment progression in periodontitis-susceptible adults [11; 12; 14; 17].

A major methodological challenge in periodontal–orthodontic research is the heterogeneity of clinical presentations and treatment protocols (periodontitis stage/grade, defect morphology, tooth migration patterns, adjunctive regenerative or restorative procedures, appliance systems, and differing maintenance regimens). This heterogeneity limits the comparability of conventional periodontal or orthodontic endpoints across cohorts and explains why compliance and cooperation—high-impact, modifiable determinants of treatment safety—were selected as the principal endpoint in this investigation [11; 17; 19]. In our cohort, the biomechanical approach was deliberately individualised (force calibration,

anchorage strategy, and sequencing with periodontal care) with the primary aim of maintaining periodontal stability. The scientific question was therefore not whether one mechanics protocol outperforms another, but whether patients can adhere to the strict behavioural requirements that make any protocol safe in a reduced periodontium. This distinction is clinically relevant because even optimally planned low-force mechanics cannot compensate for inadequate plaque control or irregular maintenance attendance – factors repeatedly linked with long-term tooth retention in periodontitis-susceptible patients managed within supportive care programmes [2; 3].

Cooperation and compliance are inherently multidimensional constructs. The OPCS and the CCE operationalise these domains by capturing appointment adherence, fixed-appliance maintenance, removable-appliance wear, and oral hygiene. While these instruments do not replace objective measures, they provide a pragmatic framework for structured chairside appraisal and targeted behavioural reinforcement—an approach supported by behavioural-modification trials in orthodontics and by studies showing that cooperation and oral hygiene can fluctuate across treatment stages in adults [1; 8; 20; 22; 24]. Retention represents a particularly vulnerable period for periodontitis-susceptible patients because relapse control relies on a combination of fixed and removable protocols, and plaque accumulation around retainers can jeopardise periodontal stability if hygiene is suboptimal. Evidence from randomised studies indicates that adherence to retainer wear can be improved through structured reminders and patient education, supporting the clinical value of ongoing reinforcement beyond active therapy [6; 27].

This study is limited by its small sample size, single-centre design, and the absence of a group for comparison. In addition, periodontal clinical endpoints were not standardised as primary outcomes, and compliance instruments, while practical, remain partly subjective. Nonetheless, the findings support systematic compliance monitoring as a low-cost, clinically actionable strategy in interdisciplinary periodontal–orthodontic care. Future controlled studies should combine behavioural metrics with standardised periodontal and orthodontic outcomes to identify which compliance trajectories best predict long-term stability [10,11]. According to the present design, periodontal indices were monitored primarily to confirm disease control and to ensure safe treatment delivery within individualised protocols; therefore, the analysis cannot quantify baseline-to-end periodontal changes attributable to specific biomechanics or compare such changes across patients.

Given the multifactorial nature of periodontal–orthodontic rehabilitation and the ongoing refinement of interdisciplinary guidance, future research should be designed with explicit, a priori consideration of key sources of clinical heterogeneity (baseline periodontal phenotype and defect morphology, case-specific orthodontic objectives, anchorage/force systems, adjunctive periodontal procedures, and maintenance intensity). In this context, strict standardization and fully balanced sampling across all relevant strata may be difficult to achieve in prospective clinical cohorts; therefore, pragmatic study designs with robust phenotyping and transparent reporting are essential to ensure interpretability and external validity.

CONCLUSIONS

In this prospective cohort of 25 adults with stage I–II periodontitis treated with orthodontics after periodontal stabilisation, clinical compliance during early retention improved significantly over time, with significant gains in the total CCE score and in the oral-hygiene, device-wearing, device-maintenance, and appointment-punctuality domains. Sex-based differences in cooperation were limited to two OPCS items (motivation/enthusiasm and complaints about wearing appliances), with women demonstrating higher compliance

scores in this sample. These findings support the routine incorporation of structured compliance monitoring tools, reinforced oral-hygiene education, and periodontal maintenance when delivering orthodontic therapy in a reduced periodontium. Future studies should employ larger, controlled designs with standardised periodontal and orthodontic outcome measures to reduce heterogeneity and to identify which compliance trajectories best predict long-term stability.

Conflicts of Interest

The authors declare no conflicts of interest.

REFERENCES

[1] Acharya, A., Bhattarai, B., Giri, D., & Bhagat, T. (2018). Relationship between Patient Cooperation and Treatment Result among Orthodontic Patients in Biratnagar, Nepal. Orthodontic Journal of Nepal, 8(1), 11–13. https://doi.org/10.3126/ojn.v8i1.21337

[2] Agudio G, et al. Longevity of teeth in patients susceptible to periodontitis: clinical outcomes and risk factors associated with tooth loss after active therapy and 30 years of supportive periodontal care. J Clin Periodontol. 2023;50(4):520-532. doi:10.1111/jcpe.13770

[3] Aimetti M, et al. Combined periodontal and orthodontic treatment of severely compromised teeth in stage IV periodontitis patients: how far can we go? Int J Periodontics Restorative Dent. 2022;42(6):731-738. doi:10.11607/prd.6247.

[4] Avornic L. Factori etiologici şi de risc ai anomaliilor dento-maxilare. Chişinău: Tipografia „Paradis Media"; 2019. 26 p. ISBN: 978-9975-3345-1-8.

[5] Caton JG, Armitage G, Berglundh T, et al. A new classification scheme for periodontal and peri-implant diseases and conditions—Introduction and key changes from the 1999 classification. J Clin Periodontol. 2018;45(Suppl 20):S1-S8. doi:10.1111/jcpe.12935.

[6] Cerroni A, Pasquantonio G, Condò R, Cerroni L. Orthodontic fixed appliance and periodontal status: an updated systematic review. Open Dent J. 2018;12:614-622. doi:10.2174/1745017901814010614.

[7] Ciobanu S, Vovc M. Etiologia şi patogenia bolii parodontale. Medicina Stomatologică. 2020;2(55):51-57.

[8] Cozzani M, Ragazzini G, Delucchi A, et al. Oral hygiene compliance in orthodontic patients: a randomized controlled study on the effects of a post-treatment communication. Prog Orthod. 2016;17(1):41. doi:10.1186/s40510-016-0154-9.

[9] Crego-Ruiz M, Jorba-García A. Assessment of the periodontal health status and gingival recession during orthodontic treatment with clear aligners and fixed appliances: a systematic review and meta-analysis. Med Oral Patol Oral Cir Bucal. 2023;28(4):e330-e340. doi:10.4317/medoral.25760.

[10] El-Naghy R, Al-Qawasmi R, Hasanin M. Does orthodontic treatment using clear aligners and fixed appliances affect periodontal status differently? Evid Based Dent. 2023;24(2):73-74. doi:10.1038/s41432-023-00719-z.

[11] Erbe C, et al. Orthodontic treatment in periodontally compromised patients: a systematic review. Clin Oral Investig. 2023;27(1):79-89. doi:10.1007/s00784-022-04822-1.

[12] Fleming PS, Andrews J. Periodontitis: orthodontic implications and management. Br Dent J. 2024;237(5):334-340. doi:10.1038/s41415-024-7789-6.

[13] Garbo D, et al. Periodontal and orthodontic synergy in the management of stage IV periodontitis: challenges, indications and limits. Life (Basel). 2022;12(12):2131. doi:10.3390/life12122131.

[14] Gehlot M, et al. Effect of orthodontic treatment on periodontal health of periodontally compromised patients. Angle Orthod. 2022;92(3):324-332. doi: 10.2319/022521-156.1

[15] Hazan-Molina H, et al. Aggressive periodontitis diagnosed during or before orthodontic treatment. Acta Odontol Scand. 2013;71(5):1023-1031. doi:10.3109/00016357.2012.749515.

[16] Jepsen K, et al. Synergy of regenerative periodontal surgery and orthodontics improves quality of life of patients with stage IV periodontitis: 24-month outcomes of a multicenter RCT. Bioengineering (Basel). 2023;10(6):695. doi:10.3390/bioengineering10060695.
[17] Kloukos D, et al. Effect of combined periodontal and orthodontic treatment of tilted molars and of teeth with intra-bony and furcation defects in stage-IV periodontitis patients: a systematic review. J Clin Periodontol. 2022;49(Suppl 24):121-148. doi:10.1111/jcpe.13509.
[18] Luchian I, et al. The influence of orthodontic treatment on periodontal health between challenge and synergy: a narrative review. Dentistry Journal. 2024;12(4):112. doi:10.3390/dj12040112.
[19] Papageorgiou SN, Antonoglou GN, Eliades T, Martin C, Sanz M. Orthodontic treatment of patients with severe (stage IV) periodontitis. InSeminars in orthodontics 2024 May 1 (Vol. 30, No. 2, pp. 123-134). WB Saunders.
[20] Qabool H, Sukhia RH, Fida M. Assessment of cooperation and compliance in adult patients at three stages of orthodontic treatment at a tertiary care hospital: a cross-sectional study. Int Orthod. 2020;18(4):794-800. doi:10.1016/j.ortho.2020.09.004.
[21] Ren C, et al. Low-level laser-aided orthodontic treatment of periodontally compromised patients: a randomised controlled trial. Lasers Med Sci. 2020;35(3):729-739. doi:10.1007/s10103-019-02923-0.
[22] Richter DD, Nanda RS, et al. Effect of behavior modification on patient compliance in orthodontics. Angle Orthod. 1998;68(2):123-132.
[23] Sîrbu D, Topalo V, Strîşca S, Mighic A, Gheţiu A, Sîrbu V, Bostan C. Aspecte ale tratamentului chirurgical în afecţiunile parodonţiului marginal. Medicina Stomatologică. 2016;1-2(38-39):24-32.
[24] Slakter MJ, Albino JE, Fox RN, Lewis EA. Reliability and stability of the orthodontic patient cooperation scale. Am J Orthod. 1980;78(5):559-563. doi:10.1016/0002-9416(80)90306-1.
[25] Tietmann C, et al. Regenerative periodontal surgery and orthodontic tooth movement in stage IV periodontitis: a retrospective practice-based cohort study. J Clin Periodontol. 2021;48(5):668-678. doi:10.1111/jcpe.13442.
[26] Trifan V. Impactul medico-social al anomaliilor dento-maxilare asupra sănătăţii orale şi calităţii vieţii pacienţilor. Chişinău: Tipografia Sirius; 2024. 186 p. ISBN: 978-9975-82-338-8.
[27] Wafaie K, et al. Compliance with retainer wear using audiovisual integration and reminder: a randomized clinical trial. Sci Rep. 2023;13:8543. doi:10.1038/s41598-023-35686-4.
[28] Zasčiurinskienė E, Basevičienė N, Lindsten R, Slotte C, Jansson H, Bjerklin K. Orthodontic treatment simultaneous to or after periodontal cause-related treatment in periodontitis susceptible patients. Part I: Clinical outcome. A randomized clinical trial. J Clin Periodontol. 2018;45(2):213-224. doi:10.1111/jcpe.12835.
[29] Zasčiurinskienė E, et al. Malocclusions, pathologic tooth migration, and the need for orthodontic treatment in subjects with stage III–IV periodontitis: a cross-sectional study. Eur J Orthod. 2023;45(4):418-429. doi: 10.1093/ejo/cjad003.
[30] Zasčiurinskienė E, et al. Orthodontic treatment in periodontitis-susceptible subjects: a systematic literature review. Clin Exp Dent Res. 2016;2(2):162-173. doi:10.1002/cre2.28.

Alveolar Bone Response to Controlled Orthodontic Maxillary Incisor Vestibularization

https://doi.org/10.70921/medev.v32i1.2025

Sorana Maria Bucur[1], Dana Cristina Bratu[2*], Remus Christian Bratu[3*], Mariana Păcurar[4]

[1]*Department of Dentistry, Faculty of Medicine, Dimitrie Cantemir University of Târgu Mureş, 3-5 Bodoni Sandor Street, 540545 Târgu Mureş, Romania*
[2]*Department of Orthodontics II, Orthodontic Research Centre, Faculty of Dental Medicine, "Victor Babes" University of Medicine and Pharmacy of Timisoara, 2 Eftimie Murgu Square, 300041 Timişoara, Romania*
[3]*Faculty of Dental Medicine, "Victor Babes" University of Medicine and Pharmacy of Timisoara, 2 Eftimie Murgu Square, 300041 Timişoara, Romania*
[4]*Department of Orthodontics, Faculty of Dental Medicine, George Emil Palade University Medicine, Pharmacy, Science, and Technology of Târgu Mureş, 38 Gh. Marinescu Str., 540139 Târgu Mureş, Romania*

Correspondence to:
Name: Dana Cristina Bratu
E-mail address: bratu.cristina @umft.ro

Name: Remus Christian Bratu
E-mail address: remus.bratu@student.umft.ro

Received: 08 February 2026; Accepted: 11 March 2026; Published: 31 March 2026

Abstract

1. Background/Objectives: Orthodontic proclination of retroclined maxillary incisors is frequently required for functional and esthetic correction; however, excessive movement may exceed the biological limits of the alveolar housing and compromise periodontal health. Understanding alveolar bone remodeling in response to controlled incisor vestibularization is essential for safe orthodontic planning. This study aimed to quantitatively assess alveolar bone thickness changes associated with controlled orthodontic vestibularization of retroclined maxillary incisors using standardized cephalometric and CBCT measurements, and to analyze the relationship between these changes, incisor displacement, and skeletal stability.*2. Methods*: Nineteen patients presenting with retroclined maxillary incisors underwent orthodontic treatment involving controlled incisor vestibularization. Cephalometric and CBCT-derived measurements were standardized using the SN–7° reference plane and perpendicular orientation to the incisor long axis (⊥U1). ABT was assessed at the cementoenamel junction, 3 mm, and 6 mm apical levels on both labial and lingual surfaces. Dental and skeletal parameters including U1–SN, U1–NA, L1–NB, and SN–MP were recorded pre- and post-treatment. Paired statistical comparisons were performed. 3. *3. Results:* Maxillary incisor proclination increased significantly, as demonstrated by substantial rises in U1–SN and U1–NA values. Labial alveolar bone thickness showed significant increases at mid-root and apical levels, indicating adaptive bone apposition on the tension side. In contrast, lingual ABT decreased significantly at corresponding levels, reflecting pressure-side resorption. No significant changes were observed in skeletal parameters, confirming predominantly dentoalveolar effects. Crestal bone thickness remained stable, suggesting a low periodontal risk. *4. Conclusions:* Controlled vestibularization of retroclined maxillary incisors induces predictable alveolar remodeling characterized by labial bone apposition and lingual resorption without compromising skeletal balance or crestal periodontal support. When performed within biological limits, incisor proclination appears to be a safe and effective orthodontic strategy.

Keywords: orthodontic vestibularization, alveolar bone, incisors, skeletal parameters

INTRODUCTION

Class II Division 2 malocclusion represents a relatively common dentofacial anomaly among Caucasian populations, with a reported prevalence ranging between 2.3% and 5%, according to data from the literature [1,2]. The classical classification of malocclusions proposed by Edward Angle defines Class II by a distal positioning of the mandibular first molar relative to the maxillary first molar. At the same time, Division 2 is clinically characterized by retroclination of the maxillary incisors and the presence of an increased deep overbite, features currently regarded as defining characteristics of this malocclusion type [1,2]. Although the dental manifestations are readily apparent, numerous authors have emphasized the complex and multifactorial etiology of Class II Division 2 malocclusion, suggesting the presence of an associated skeletal component [2-4]. The mandible may exhibit insufficient growth or a posterior positioning relative to the maxilla and cranial base, contributing to the sagittal discrepancy observed in these patients [4,5]. In this context, Class II Division 2 malocclusion is understood as the result of interactions among dental, skeletal, and muscular factors [1-5]. The maxillary incisors occupy a central position in the anterior region of the oral cavity and play a crucial role in both function and dentofacial aesthetics. They influence upper lip support, phonetics, masticatory efficiency, and facial profile harmony, exerting a major impact on smile perception and patient self-image [6]. Studies have shown that the primary motivation for seeking orthodontic treatment is often aesthetic in nature, with patients associating dental appearance with social integration and professional success [7,8].

Within this framework, establishing an appropriate inclination of the anterior incisors represents a fundamental objective of orthodontic treatment, as their faciolingual angulation affects smile contour, anterior guidance, and the stability of Class I canine and molar relationships [9,10]. In the management of Class II Division 2 malocclusion, treatment frequently involves controlled proclination of both maxillary and mandibular incisors to reduce deep overbite and achieve functional occlusal relationships [2,4,9,10,11]. However, such movements must remain within the biological limits of the alveolar bone to prevent periodontal complications. The literature reports variable findings regarding the relationship between incisor proclination and periodontal health. Kloukos and Kobylyanskyy associated excessive proclination of the mandibular incisors with a higher incidence of periodontal problems [9,12], while Pilloni demonstrated through computed tomography that significant changes in tooth inclination may predispose to alveolar bone dehiscences and fenestrations, particularly in adult patients [13]. Conversely, Celis et al. showed that in children and adolescents, incisor proclination is not necessarily associated with gingival recession [14], although patients with severe Class II malocclusion may present an increased risk due to reduced apical base dimensions [14,15]. These conclusions are supported by the studies of Morris et al., who reported that orthodontic treatment itself does not constitute a major determinant for gingival recession and that the clinical impact of extensive maxillary expansions is generally limited [16]. Similarly, Colet et al. observed an absence of gingival recession in patients treated with the Twin Force appliance, emphasizing the importance of biomechanical control in preserving periodontal health [17].

Advances in imaging techniques have further elucidated the relationship between orthodontic tooth movement and alveolar bone remodeling. Sarikaya et al. demonstrated that incisor retraction may be associated with alveolar bone loss, particularly on the lingual surface, and highlighted the limitations of two-dimensional radiographs in detecting dehiscences [18]. Comparable findings were reported by Hong et al., who observed minor, clinically insignificant changes in labial alveolar bone thickness [19], as well as by Elnagar et

al., who documented a reduction in lingual bone thickness following incisor retraction using skeletal anchorage [20]. A particularly relevant contribution to understanding alveolar remodeling in Class II Division 2 malocclusion was provided by Kang et al., who analyzed alveolar bone changes following correction of initially retroclined incisors using cone-beam computed tomography (CBCT) [21]. The authors reported that an average proclination of approximately 15° of the maxillary incisors did not result in significant changes in facial alveolar bone height, although a reduction in palatal bone height and thickness was observed. Similar results were described by Chen et al., who demonstrated through three-dimensional CBCT analyses a differential alveolar bone response depending on the surface examined and the treatment modality employed, with a potential biological advantage associated with clear aligner therapy [22].

Overall, the available evidence suggests that the relationship between incisor proclination and alveolar bone remodeling is complex and influenced by multiple variables, including the type of tooth movement, biomechanical control, patient age, and initial alveolar morphology.

Aim and objectives

This study aimed to investigate, using standardized cephalometric and CBCT analysis, the dentoalveolar changes induced by controlled vestibularization of retroclined maxillary incisors. Specifically, the study sought to quantify variations in labial and lingual alveolar bone thickness at different root levels and to evaluate their correlation with incisor inclination, positional changes, and skeletal parameters before and after orthodontic treatment.

MATERIALS AND METHODS

Study Sample and Selection Criteria

This retrospective study included 19 patients treated at the Department of Orthodontics between 2021 and 2024. The orthodontic treatments were conducted over a mean duration of approximately 18–24 months, and radiographic records were obtained at two standardized time points: before treatment initiation (T0) and immediately after completion of active orthodontic therapy (T1). The sample consisted of patients diagnosed with Class II Division 2 malocclusion presenting retroclined maxillary incisors requiring orthodontic vestibularization.

The inclusion criteria comprised the presence of permanent dentition, retroclined maxillary incisors (U1–SN < 100°), the availability of both pre-treatment and post-treatment cephalometric radiographs and CBCT scans, the absence of any previous orthodontic treatment, and good periodontal health at baseline.

The exclusion criteria included the presence of craniofacial anomalies, systemic conditions that could affect bone metabolism, periodontal disease, and incomplete radiographic records

All patients underwent comprehensive orthodontic treatment involving controlled vestibularization of the maxillary incisors using fixed appliances.

To ensure measurement reproducibility, cephalometric and CBCT analyses were performed using stable anatomical landmarks and standardized reference planes.

Cephalometric Reference Planes and Skeletal Angles

The Sella–Nasion (SN) plane, defined by the line connecting Sella (S) and Nasion (N), was used as a cranial reference due to its post-childhood stability [23]. To reduce variability related to head positioning and approximate the functional horizontal plane, measurements were oriented to SN–7°, a commonly applied correction in contemporary cephalometric

studies [23,24]. Sagittal skeletal relationships were assessed using SNA, SNB, and ANB angles. SNA evaluated maxillary position relative to the cranial base (normal ≈82° ± 2°), SNB assessed mandibular position (≈80° ± 2°), and ANB classified skeletal relationships as Class I (2° ± 2°), Class II (>4°), or Class III (<0°) [24]. The stability of these parameters confirmed that observed changes were predominantly dentoalveolar rather than skeletal. Vertical facial pattern was evaluated using the SN–mandibular plane (SN–MP) angle, with higher values indicating hyperdivergent growth and lower values indicating hypodivergence, a factor known to influence anterior alveolar bone morphology.

Dental Cephalometric Measurements

The maxillary central incisor (U1) was analyzed due to its key role in aesthetics and occlusal function [25]. Axial inclination was assessed using the U1–SN angle (normal ≈102° ± 5.5°), where reduced values indicated retroclination and increased values indicated proclination. This parameter served as both an inclusion criterion and the primary indicator of treatment-induced decompensation. Incisor position and torque were further evaluated using U1–NA angular and linear measurements. Increases in U1–NA (°) and U1–NA (mm) reflected labial movement of the incisor and allowed differentiation between tipping and bodily movement [25]. Mandibular incisor position was monitored using the linear measurement L1–NB (mm), a classical Steiner parameter used to assess dental compensation during orthodontic treatment [26].

Alveolar Bone Thickness Assessment

Alveolar bone thickness (ABT) was evaluated to determine the biological limits of incisor proclination and the risk of periodontal complications such as dehiscence, fenestration, and attachment loss [13]. ABT was defined as the distance between the root surface and the cortical plate of the alveolar bone and was measured on both labial and palatal/lingual surfaces. Measurements were obtained at three standardized levels: at the cementoenamel junction (CEJ), 3 mm apical to the CEJ, and 6 mm apical to the CEJ, corresponding to crestal, mid-root, and apical regions, respectively. This protocol enabled site-specific evaluation of alveolar remodeling [27].

Reference Systems for ABT Measurement

ABT measurements were performed using two perpendicular reference orientations:

(1) perpendicular to the SN–7° plane to ensure cranial standardization and interindividual comparability, and

(2) perpendicular to the long axis of the maxillary incisor (⊥U1) to reflect biologically relevant root–bone relationships. The combined approach minimized orientation bias and enhanced measurement validity.

Examiner Reliability

Intra-examiner reliability was assessed using the intraclass correlation coefficient (ICC) to ensure measurement consistency and reduce systematic error.

RESULTS

Intra-examiner reliability analysis demonstrated excellent measurement reproducibility, with intraclass correlation coefficients (ICCs) ranging from 0.89 to 0.96, indicating high consistency of repeated cephalometric and CBCT measurements. A total of 19 patients met the inclusion criteria and were analyzed in this study. The sample consisted of 10 male patients (mean age: 14.3 years) and 9 female patients (mean age: 15.2 years).

The initial descriptive cephalometric values indicated a predominantly skeletal Class I pattern, with retroclined maxillary incisors, in accordance with the selection criteria. The mean values and standard deviations for the main pre-treatment skeletal and dental parameters were as follows:

- SNA: 79.48° ± 4.48
- SNB: 77.08° ± 3.51
- ANB: 2.39° ± 2.19
- U1–SN: 92.03° ± 2.74
- U1–NA: 12.56° ± 5.85
- U1–NA (mm): 1.97 ± 2.44
- L1–NB (mm): 1.35 ± 1.96
- SN–MP: 32.87° ± 6.83

Table 1. Cephalometric and alveolar bone thickness measurements before and after orthodontic treatment (N= 19)

Parameter	Pre-treatment Mean ± SD	Post-treatment Mean ± SD	Change (Δ)
Alveolar bone thickness — labial (SN–7°)			
CEJ level (a)	0.60 ± 0.49 mm	0.32 ± 0.36 mm	−0.28
3 mm apical (b)	1.11 ± 0.36 mm	1.42 ± 0.58 mm	+0.31
6 mm apical (c)	1.19 ± 0.47 mm	2.02 ± 1.39 mm	+0.83
Alveolar bone thickness — lingual (SN–7°)			
CEJ level (a)	0.52 ± 0.70 mm	0.51 ± 0.86 mm	−0.01
3 mm apical (b)	3.07 ± 1.03 mm	2.66 ± 1.11 mm	−0.41
6 mm apical (c)	5.37 ± 1.26 mm	4.15 ± 1.71 mm	−1.22
Alveolar bone thickness — labial (⊥U1)			
CEJ level (a)	0.63 ± 0.53 mm	0.38 ± 0.41 mm	−0.25
3 mm apical (b)	1.10 ± 0.36 mm	1.28 ± 0.56 mm	+0.18
6 mm apical (c)	1.13 ± 0.49 mm	1.70 ± 1.19 mm	+0.57
Alveolar bone thickness — lingual (⊥U1)			
CEJ level (a)	0.49 ± 0.62 mm	0.26 ± 0.49 mm	−0.23
3 mm apical (b)	2.75 ± 0.83 mm	1.94 ± 0.72 mm	−0.81
6 mm apical (c)	4.85 ± 0.96 mm	3.19 ± 1.31 mm	−1.66
Dental and skeletal parameters			
U1–SN (°)	92.03 ± 2.74	102.09 ± 8.63	+10.06
U1–NA (°)	12.56 ± 5.85	22.16 ± 7.66	+9.60
U1–NA (mm)	1.97 ± 2.44	3.88 ± 2.78	+1.91
L1–NB (mm)	1.35 ± 1.96	4.25 ± 2.78	+2.90
SN–MP (°)	32.87 ± 6.83	31.82 ± 8.11	−1.05

Orthodontic treatment induced significant dentoalveolar changes, characterized by a marked increase in the angulation and protrusion of the maxillary incisors. This was evidenced by increases in U1–SN (from 92.03° ± 2.74 to 102.09° ± 8.63) and U1–NA values, as well as by a linear advancement of the incisors from 1.97 ± 2.44 mm to 3.88 ± 2.78 mm. Labial alveolar bone thickness demonstrated adaptive remodeling, with a slight reduction at the crestal level and a significant increase at the mid-root and apical levels, suggesting localized bone apposition in response to tooth movement. In contrast, lingual alveolar bone thickness decreased significantly across all measured levels, particularly at the mid-root and apical regions, reflecting root displacement toward the palatal cortical plate and pressure-side bone resorption. Skeletal parameters remained stable throughout treatment, with no statistically significant changes observed in SNA, SNB, or ANB angles, confirming the absence of major skeletal modifications. Vertical skeletal relationships were also preserved, as indicated by minimal variation in the SN–MP angle.

Collectively, these findings confirm that the orthodontic corrections achieved were predominantly dentoalveolar in nature and occurred within the physiological limits of alveolar bone remodeling, without compromising skeletal harmony. Correlation analysis indicated a positive association between the degree of maxillary incisor proclination (U1–SN, U1–NA) and increases in labial alveolar bone thickness at mid-root and apical levels, while a negative correlation was observed with lingual bone thickness reduction, reflecting the biological pattern of tension-side apposition and pressure-side resorption.

DISCUSSIONS

The primary aim of this study was to evaluate changes in labial and lingual alveolar bone thickness associated with the vestibularization of retroclined maxillary incisors using lateral cephalometric analysis. A secondary objective was to correlate these changes with dental movements and skeletal stability to determine whether orthodontic tooth movement remained within the biological limits of the alveolar housing.

The results allow an integrated dentoalveolar interpretation and provide clinically relevant orthodontic and periodontal insights, consistent with biomechanical and biological principles described in the literature.

One of the most important findings was the significant increase in U1–SN and U1–NA values, both angularly and linearly. These changes indicate substantial proclination and labial displacement of the maxillary incisors, confirming the effectiveness of orthodontic treatment in correcting initial retroclination.

The mean increase in U1–SN of approximately 8–10° and in U1–NA of around 7–9° falls within the limits reported by Lanteri et al., who described such values as compatible with controlled dental decompensation without inducing skeletal or periodontal instability [28]. Moreover, the significant increase in U1–NA (mm) confirms true anterior bodily movement rather than mere torque alteration. Clinically, these modifications are essential for correcting dental inclination, achieving functional occlusion, and improving anterior facial aesthetics. Skeletal parameters (SNA, SNB, and ANB) did not show statistically significant changes throughout treatment. This is particularly relevant, as it confirms that the observed modifications were predominantly dentoalveolar rather than the result of orthopedic or growth-related skeletal changes. The stability of the ANB angle indicates preservation of sagittal maxillomandibular relationships, supporting the concept that incisor proclination was achieved without compromising facial skeletal balance. The literature emphasizes that alveolar changes should always be interpreted within the context of skeletal stability to avoid misattributing biological remodeling to dental movement alone [29].

A key outcome of this study was the significant increase in labial alveolar bone thickness, particularly at mid-root and apical levels (b and c), measured both relative to the SN–7° plane and perpendicular to the incisor long axis. These findings support the concept of adaptive bone remodeling, extensively described by Kalina et al., whereby alveolar bone responds favorably to controlled orthodontic forces through apposition on the tension side. The increase in labial bone thickness suggests that incisor vestibularization occurred within an alveolar envelope capable of biological adaptation [30]. Importantly, no significant changes were observed at the CEJ level, a region considered critical from a periodontal perspective. This suggests that treatment did not increase the risk of gingival recession, a conclusion consistent with the findings of Verdecchia et al., who reported that apical bone changes are more frequent and biologically safer than coronal alterations [31].

In contrast, lingual alveolar bone thickness decreased significantly at mid-root and apical levels, particularly when measurements were taken perpendicular to the incisor long axis. This observation aligns with biomechanical principles of orthodontic tooth movement, whereby root displacement toward the palatal cortical plate induces bone resorption on the pressure side. The literature confirms that lingual bone reduction is an expected response during incisor proclination, provided that movement remains within biological limits and does not result in direct root–cortical contact. The values obtained in this study suggest controlled remodeling rather than pathological bone loss [13]. A notable methodological strength of this study is the use of two reference orientations for ABT measurement: SN–7° and perpendicular to the incisor long axis (⊥U1). The differences observed between these methods support recent literature emphasizing that tooth-axis–oriented measurements

provide a more realistic assessment of root–bone relationships. The fact that the most pronounced and statistically significant changes were detected using ⊥U1 reinforces the biological validity of this approach and justifies its inclusion in alveolar bone assessment protocols. The significant increase in L1–NB (mm) reflects mandibular incisor protrusion, suggesting a global dental compensation mechanism. Clinically, this demonstrates that treatment was not confined to the maxillary arch but involved coordinated alignment of both arches.

Orthodontic studies highlight the importance of evaluating mandibular incisor response during maxillary decompensation to ensure occlusal stability and a harmonious facial profile. From a periodontal standpoint, the findings are encouraging. The absence of significant labial bone reduction at the CEJ suggests a low risk of post-treatment gingival recession. This is particularly relevant, as recession is frequently associated with excessive labial movement of incisors within thin alveolar envelopes. Bucur et al. demonstrated that tooth position plays a more critical role in recession development than gingival biotype [32]. The present results suggest that incisor positioning remained within safe biological limits. Study limitations include the use of two-dimensional cephalometric analysis, which does not allow full three-dimensional evaluation of the alveolar housing, the relatively small sample size, and the absence of direct clinical periodontal assessment. Nevertheless, the standardized methodology and rigorous comparative analysis enhance the validity of the findings.

Overall, this study demonstrates that controlled vestibularization of retroclined maxillary incisors can be performed safely within biological limits when closely monitored through alveolar bone assessment. The integration of dental, alveolar, and skeletal parameters provides a valuable predictive model for individualized orthodontic treatment planning.

CONCLUSIONS

This study demonstrates that orthodontic vestibularization of retroclined maxillary incisors produces significant dentoalveolar changes while preserving skeletal stability and periodontal safety. The observed increase in labial alveolar bone thickness at mid-root and apical levels confirms the capacity of the alveolar process for adaptive remodeling in response to controlled orthodontic forces. Conversely, the reduction in lingual alveolar bone thickness reflects expected pressure-side resorption associated with anterior tooth movement, without evidence of pathological bone loss or breach of biological limits. The stability of crestal bone thickness further supports the periodontal safety of the treatment protocol applied.

The absence of significant skeletal changes emphasizes that the observed effects were primarily dental and alveolar in nature. The use of dual reference orientations for ABT measurement enhanced the biological validity of the analysis and highlighted the clinical relevance of tooth-axis–based assessment. Overall, these findings support the concept that carefully planned and biologically guided incisor proclination can be safely achieved within the alveolar envelope. Integrating cephalometric, alveolar, and skeletal parameters offers a reliable framework for individualized orthodontic treatment planning and risk assessment.

Future research incorporating three-dimensional imaging and larger sample sizes is recommended to further refine predictive models of alveolar remodeling and periodontal response.

Conflicts of Interest

The authors declare no conflict of interest.

REFERENCES

[1] Hirani S, Hirani T, Shah A, Patel S, Mehta M, Patel P, Kumar S, Haque M. Morphogenetic Expression of Genes in Class II Division 2 Malocclusion: A Pedigree Study. Cureus. 2025 May 7;17(5):e83647. doi: 10.7759/cureus.83647.

[2] Ma Y, Zhao W, Zhang S, et al. Treatment decisions of patients with Class II Division 2 malocclusion and severe tooth wear: a systematic review. BDJ Open. 2024;10(1):65. Published 2024 Aug 13. doi:10.1038/s41405-024-00248-x.

[3] Shukla M, Reddy M, Singh K, Saini R, Raghav P, Nasser K, Sharma N, Kamrani A, Rafique S, Shair T. Genetic association between Class II division 1 and division 2 malocclusions with PAX9 (rs8004560) gene polymorphism in a tertiary care hospital. Dental Press J Orthod. 2024 Dec 16;29(6):e2424128. doi: 10.1590/2177-6709.29.6.e2424128.oar.

[4] Lone IM, Zohud O, Midlej K, Proff P, Watted N, Iraqi FA. Skeletal Class II Malocclusion: From Clinical Treatment Strategies to the Roadmap in Identifying the Genetic Bases of Development in Humans with the Support of the Collaborative Cross Mouse Population. J Clin Med. 2023 Aug 6;12(15):5148. doi: 10.3390/jcm12155148.

[5] Bozkaya E, Kaygısız E, Tortop T, Güray Y, Yüksel S. Mandibular posterior space in class II division 1 and 2 malocclusion in various age groups. Posteriores Platzangebot im Unterkiefer bei Klasse-II/1- und -II/2-Malokklusion in verschiedenen Altersgruppen. J Orofac Orthop. 2020;81(4):249-257. doi:10.1007/s00056-020-00230-w.

[6] Nguyen KT, Farella M, Bennani V, Mei L. Effect of Biomechanical Properties of Perioral Soft Tissues on Lip Response to Simulated Protraction of Upper Front Teeth. J Oral Rehabil. 2025 May;52(5):632-640. doi: 10.1111/joor.13941.

[7] Santana LG, Gatti-Reis L, Paiva SM, Ramos-Jorge ML, Marques LS. Patient-centered factors associated with orthodontic treatment success: a scoping review. Braz Oral Res. 2025 Feb 21;39:e020. doi: 10.1590/1807-3107bor-2025.vol39.020.

[8] Bahar AD, Sagi MS, Mohd Zuhairi FA, Wan Hassan WN. Dental Aesthetics and Self-Esteem of Patients Seeking Orthodontic Treatment. Healthcare (Basel). 2024 Aug 8;12(16):1576. doi: 10.3390/healthcare12161576.

[9] Kloukos D, Koukos G, Doulis I, Stavropoulos A, Katsaros C. Does incisor inclination change during orthodontic treatment affect gingival thickness and the width of keratinized gingiva? A prospective controlled study. Eur J Orthod. 2025 Feb 7;47(2):cjaf001. doi: 10.1093/ejo/cjaf001.

[10] Tomaru H, Tachiki C, Nakamura Y, Ariizumi D, Matsunaga S, Sugahara K, Watanabe A, Katakura A, Nishii Y. Anterior Tooth Inclination Between Skeletal Class II and III Malocclusions After Surgical Orthodontic Treatment. Diagnostics (Basel). 2025 Jun 18;15(12):1553. doi: 10.3390/diagnostics15121553.

[11] Alkhamees A. Treatment of adult class II division 2 with deep bite using Forsus appliance and intrusion with TADs. J Orthod Sci. 2024 Nov 25;13:56. doi: 10.4103/jos.jos_214_23.

[12] Kobylyanskyy O, Rausch MA, Kobylyanska A, Andrukhov O, Rausch-Fan X. Relationship Between the Changes in the Inclination of the Incisors and Soft Gingival Tissue Remodeling During the First Phase of Orthodontic Treatment Without Premolar Extraction. Dent J (Basel). 2025 Dec 8;13(12):587. doi: 10.3390/dj13120587.

[13] Pilloni A, Rotundo R, Gambarini G, Testarelli L, Dell'olmo F. Bone dehiscences and fenestrations of the anterior mandibular facial bone wall: a retrospective cone beam computed tomography study. Minerva Stomatol. 2018;67(3):86-95. doi:10.23736/S0026-4970.18.04099-2.

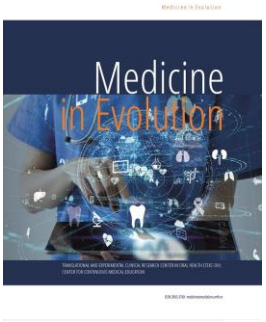
[14] Celis B, Sanz-Esporrin J, Verdasco C, Yañez-Vico RM, Martin C. Incidence of Gingival Recessions in Adolescent Orthodontic Patients Treated With Fixed Appliances and Lingual Retainer. J Clin Periodontol. 2025 Apr;52(4):589-598. doi: 10.1111/jcpe.14097.

[15] Ruf S, Hansen K, Pancherz H. Does orthodontic proclination of lower incisors in children and adolescents cause gingival recession?. Am J Orthod Dentofacial Orthop. 1998;114(1):100-106. doi:10.1016/s0889-5406(98)70244-6.

[16] Morris JW, Campbell PM, Tadlock LP, Boley J, Buschang PH. Prevalence of gingival recession after orthodontic tooth movements. Am J Orthod Dentofacial Orthop. 2017;151(5):851-859. doi:10.1016/j.ajodo.2016.09.027.

[17] Colet R, Cotrin P, Oliveira RC, et al. Gingival recession in mandibular anterior teeth in patients with Class II malocclusion treated with elastics and Twin Force appliance. Am J Orthod Dentofacial Orthop. 2022;162(4):529-537. doi:10.1016/j.ajodo.2021.05.015.
[18] Sarikaya S, Haydar B, Ciğer S, Ariyürek M. Changes in alveolar bone thickness due to retraction of anterior teeth. Am J Orthod Dentofacial Orthop. 2002;122(1):15-26. doi:10.1067/mod.2002.119804.
[19] Hong SY, Shin JW, Hong C, Chan V, Baik UB, Kim YH, Chae HS. Alveolar bone remodeling during maxillary incisor intrusion and retraction. Prog Orthod. 2019 Dec 23;20(1):47. doi: 10.1186/s40510-019-0300-2.
[20] Elnagar MH, Handelman CS, Lippincott JS, Kim MR, BeGole E. Alveolar cortical plate changes associated with incisor retraction and its influence on the limits of orthodontic tooth movement. Orthod Craniofac Res. 2021;24(4):536-542. doi:10.1111/ocr.12469.
[21] Kang HK, Guo J, Kaczynski R, Liu C, Zhou Z. Effects of maxillary incisor inclination on dentoalveolar changes in class II division 1 and 2 non-extraction treatment for Caucasian children - A retrospective study using CBCT. Int Orthod. 2021;19(1):51-59. doi:10.1016/j.ortho.2020.11.003.
[22] Chen H, Liu L, Han M, et al. Changes of maxillary central incisor and alveolar bone in Class II Division 2 nonextraction treatment with a fixed appliance or clear aligner: A pilot cone-beam computed tomography study. Am J Orthod Dentofacial Orthop. 2023;163(4):509-519. doi:10.1016/j.ajodo.2022.02.015.
[23] Guarnieri R, Squillace F, Podda R, Monterossi AS, Galluccio G, Di Giorgio R, Barbato E. Three-Dimensional Dental Analysis in Subjects with Skeletal Malocclusion: A Retrospective Observational Study. Dent J (Basel). 2025 Jun 22;13(7):280. doi: 10.3390/dj13070280.
[24] Mourgues T, González-Olmo MJ, Martel-Lambert M, Nieto-Moraleda C, Romero M. Proposal of a Protocol for Adjusting the Value of the SN-GoGn Angle in Steiner Cephalometry. J. 2024; 7(3):385-392. https://doi.org/10.3390/j7030022.
[25] Zarif Najafi H, Oshagh M, Khalili MH, Torkan S. Esthetic evaluation of incisor inclination in smiling profiles with respect to mandibular position. Am J Orthod Dentofacial Orthop. 2015;148(3):387-395. doi:10.1016/j.ajodo.2015.05.016.
[26] Liu J, Zhang C, Shan Z. Application of Artificial Intelligence in Orthodontics: Current State and Future Perspectives. Healthcare (Basel). 2023 Oct 18;11(20):2760. doi: 10.3390/healthcare11202760.
[27] Al-Somairi MAA, Yan Y, Alhammadi MS, ALshoaibi LH, Abdulghani EA, Al-Balaa M, Alhashimi N, Farea K, Al-Tayar B, Sharhan HM, Zheng B, Liu Y. Three-dimensional alveolar bone changes and root resorption in Class I malocclusion treated with extraction and non-extraction protocols: a comparative study of fixed appliances and clear aligners. BMC Oral Health. 2025 Dec 6;26(1):64. doi: 10.1186/s12903-025-07435-8.
[28] Lanteri V, Abate A, Donelli M, et al. Comparison of the Skeletal and Dento-Alveolar Changes Obtained with a Customized Elastodontic Appliance and Twin Block: A Prospective Investigation. Children (Basel). 2025;12(9):1147. Published 2025 Aug 28. doi:10.3390/children12091147.
[29] Boccalari, E., Rossi, O., Baldini, B., Tripicchio, C., Serafin, M., & Caprioglio, A. (2025). The Maxillomandibular Sagittal Assessment: The ABwise Appraisal and Its Correlation with ANB Angle. Journal of Clinical Medicine, 14(4), 1379. https://doi.org/10.3390/jcm14041379.
[30] Kalina E, Grzebyta A, Zadurska M. Bone Remodeling during Orthodontic Movement of Lower Incisors-Narrative Review. Int J Environ Res Public Health. 2022;19(22):15002. Published 2022 Nov 15. doi:10.3390/ijerph192215002.
[31] Verdecchia A, Suárez-Fernández C, Miquel A, Bardini G, Spinas E. Biological Effects of Orthodontic Tooth Movement on the Periodontium in Regenerated Bone Defects: A Scoping Review. Dent J (Basel). 2024;12(3):50. Published 2024 Feb 26. doi:10.3390/dj12030050.
[32] Bucur SM, Bud E, Decusară M, Olteanu CD. Retrospective Study on Orthodontic Gingival Recession Correction Using Clear Aligners. Medicina (Kaunas). 2024;60(12):2024. Published 2024 Dec 8. doi:10.3390/medicina60122024.

A Retrospective Analysis of Endodontic and Extraction Risk after Orthodontic Treatment



https://doi.org/10.70921/medev.v32i1.2026

Bratu Remus Christian[1], Sorana Maria Bucur[2*], George Popa[3*], Dana Cristina Bratu[3]

[1]Faculty of Dental Medicine, "Victor Babes" University of Medicine and Pharmacy of Timisoara, 2 Eftimie Murgu Square, 300041 Timişoara, Romania
[2]Department of Dentistry, Faculty of Medicine, Dimitrie Cantemir University of Târgu Mureş, 3-5 Bodoni Sandor Street, 540545 Târgu Mureş, Romania
[3]Department of Orthodontics II, Orthodontic Research Centre, Faculty of Dental Medicine, "Victor Babes" University of Medicine and Pharmacy of Timisoara, 2 Eftimie Murgu Square, 300041 Timişoara, Romania

Correspondence to:
Name: Sorana Maria Bucur
E-mail address: bucursoranamaria@gmail.com

Name: George Popa
E-mail address: popa.george@umft.ro

Received: 08 February 2026; Accepted: 11 March 2026; Published: 31 March 2026

Abstract

1.Background/Objectives*:** To evaluate the risk of root canal therapy and tooth extraction in anterior teeth following orthodontic treatment in adolescents. ***2. Methods: This retrospective study analyzed electronic dental records of 186 patients treated between 2021 and 2025. Permanent anterior teeth (maxillary #6–11, mandibular #22–27) were followed longitudinally. Adverse outcomes included endodontic treatment or tooth extraction. Kaplan–Meier survival analysis and Cox regression were used, with orthodontic treatment modeled as a time-dependent variable. ***3. Results:*** The mean age at treatment initiation was 12.93 ± 1.64 years. Root canal therapy occurred in 3.0% of anterior teeth and extractions in 0.1%. Maxillary central incisors showed the highest failure rate (12.2%) and the lowest 10-year survival (82.04%). Overall survival was 99.52% at 1 year, 97.59% at 5 years, and 95.20% at 10 years. Female patients had a lower risk of adverse outcomes (HR = 0.66, $p < 0.001$). Orthodontic treatment did not significantly increase overall risk, although a temporary increase in root canal therapy was observed 2–3 years after treatment initiation. ***4. Conclusions:*** Orthodontic treatment in adolescents does not significantly increase severe adverse outcomes in anterior teeth, supporting its generally favorable safety profile.

Keywords: Orthodontic treatment, Malocclusion, Root canal therapy, Tooth extraction, Anterior teeth Dental trauma, Tooth survival

INTRODUCTION

Malocclusion is one of the most prevalent oral health conditions worldwide, ranking after dental caries and periodontal disease [1]. It is commonly defined as an abnormal relationship between the maxillary and mandibular dentition when the jaws are closed. Moderate to severe forms affect approximately one-third of the population and often warrant treatment due to their impact on craniofacial growth, facial appearance, and oral function. Comprehensive orthodontic treatment is a well-established approach for correcting malocclusion, typically initiated after eruption of the permanent dentition unless significant skeletal discrepancies necessitate earlier intervention [2]. Orthodontic therapy relies on controlled mechanical forces applied to teeth and supporting structures to achieve alignment. These forces, however, are associated with potential adverse effects, including periodontal injury, pain, enamel damage, root resorption, caries, temporomandibular disorders, and possible pulpal complications [3]. Given the medicolegal importance of informed consent, clinicians must disclose not only the benefits of orthodontic treatment but also its risks and alternatives, including no treatment [1]. While several adverse outcomes are well documented, uncertainty remains regarding whether orthodontic forces can result in pulpal necrosis requiring endodontic treatment or tooth extraction [3]. Consequently, this study aimed to assess the likelihood of anterior teeth requiring root canal therapy or extraction following orthodontic treatment, as such outcomes may represent relevant risk factors for inclusion in informed consent discussions.

Malocclusion classification originated with Angle's molar-based system in 1899, later expanded by Ackerman and Proffit to incorporate dental relationships across multiple planes and facial profile analysis [4]. While Angle's classification remains foundational, contemporary indices such as the Index of Orthodontic Treatment Need provide a more comprehensive assessment by evaluating abnormalities, including missing teeth, overjet, crossbite, contact point displacement, and overbite [5]. Orthodontic treatment is indicated not only for functional correction but also for prevention of dental trauma, normalization of facial growth, and mitigation of psychosocial effects associated with malocclusion [6]. Children with untreated Class II malocclusions, particularly those with protrusive maxillary incisors, face a significantly increased risk of dental trauma, with studies reporting pulpal devitalization or fracture in approximately one-third of affected cases [7]. Additionally, facial disharmony has been shown to negatively influence social perception and psychological well-being, further supporting orthodontic intervention when appropriate [8]. Malocclusions often develop between ages 6 and 12, with treatment timing determined by severity and etiology [9]. Phase I treatment is initiated during the primary or mixed dentition to guide skeletal and dental development, particularly in cases involving crossbites, open bites, or skeletal Class III relationships. Phase II treatment, or comprehensive orthodontics, is typically undertaken once permanent dentition is established and generally lasts 12 to 36 months [10].

Comprehensive treatment progresses through stages of alignment, correction of occlusal relationships, space closure, and final detailing [1]. Tooth movement occurs through biologic remodeling of alveolar bone and periodontal tissues, mediated by osteoclast and osteoblast activity in response to sustained mechanical forces [11]. Orthodontic therapy carries recognized risks, including periodontal damage, root resorption, pulpal alterations, and enamel defects [3]. Ethical practice requires clinicians to clearly communicate these risks to patients before treatment initiation [12]. Root resorption is defined as the pathological loss of dental hard tissues unrelated to caries or trauma [13]. External apical root resorption is the most frequently associated form in orthodontic patients and results from a combination of biological susceptibility and treatment-related factors [14]. Excessive or prolonged forces,

particularly involving rapid tooth movement, are strongly linked to apical cementum loss [13,14].

While severe root resorption is relatively uncommon, occurring in approximately 1–5% of cases, it disproportionately affects maxillary incisors [15]. Histologic studies indicate that minor resorption occurs in over 90% of orthodontically treated teeth, suggesting that radiographs may underestimate its prevalence [15,16]. Severity is commonly classified using the Levander and Malmgren system, ranging from minor apical irregularities to extensive loss exceeding one-third of the root length [17]. The long-term prognosis of teeth affected by resorption remains unclear. Invasive cervical resorption represents a less common but clinically significant condition linked to orthodontic treatment, trauma, bleaching, and idiopathic causes [18]. Orthodontic therapy has been identified as a predisposing factor in nearly one-quarter of affected cases, predominantly involving maxillary anterior teeth [15]. Advanced lesions may necessitate endodontic therapy or extraction. Dental pulp is highly susceptible to ischemic injury due to its confined environment, and inflammatory pressure increases may compromise vascular supply, leading to necrosis. Orthodontic forces have been shown to induce transient molecular and vascular changes within the pulp-dentin complex. Histologic studies report varying degrees of pulpal inflammation, circulatory disturbances, and cellular degeneration following orthodontic force application [19].

Some evidence suggests an association between orthodontic movement, particularly in impacted teeth, and reduced pulp vitality or increased need for root canal treatment [19,20]. However, other investigations demonstrate reversible pulpal changes, with blood flow returning to baseline within days of force application and no detectable long-term structural damage [20]. Pulpal complications appear more likely when preexisting irritation from trauma, caries, or restorations is present [19,20].

Aim and objectives

This study aimed to evaluate the incidence and risk of root canal therapy and tooth extraction in anterior teeth following comprehensive orthodontic treatment, and to determine whether orthodontic therapy constitutes a clinically relevant risk factor for pulpal complications that should be addressed during informed consent.

MATERIAL AND METHODS

This retrospective observational study was conducted at the two University Clinics, using institutional electronic dental records collected between 2021 and 2025. This was a retrospective observational study without a non-orthodontic control group. Therefore, causal relationships between orthodontic treatment and adverse outcomes cannot be established.

Patients who initiated orthodontic treatment during adolescence were identified from the department's clinical database. A total of 186 patients met the inclusion criteria and were included in the analysis. Orthodontic treatment initiation was defined as the first documented placement of a fixed or interceptive orthodontic appliance, recorded using internal institutional procedure identifiers (ORTH-A for comprehensive treatment and ORTH-B for interceptive treatment).

All permanent anterior teeth were evaluated, including maxillary teeth #6–11 and mandibular teeth #22–27. Teeth were followed from baseline until the occurrence of an adverse dental outcome or the end of the observation period. Adverse outcomes were defined as either endodontic intervention (pulp therapy) or tooth removal, as documented in the patient record. Teeth without recorded adverse outcomes were considered event-free. For statistic al purposes, contralateral teeth were grouped, and teeth were further categorized as maxillary or mandibular anterior teeth.

Because multiple teeth from the same patient were included, the teeth were not statistically independent. No adjustment for intra-patient clustering was performed, and hazard ratios should therefore be interpreted cautiously. Baseline tooth status (previous trauma, vitality testing, restorations, or caries) was not systematically documented in the electronic records and was therefore assumed based on the absence of recorded treatment. This may introduce misclassification bias. Descriptive statistics were calculated for patient demographics, treatment type, and outcome frequency. Survival analysis was performed using Kaplan–Meier estimates, with survival time defined as the interval from baseline assessment to the first recorded adverse event. Because Kaplan–Meier methods account for censoring, survival probabilities beyond the observed follow-up period represent statistical projections rather than actual observed long-term outcomes. The proportional hazards assumption was not formally tested and represents a limitation of the study. Cox proportional hazards regression models were applied to assess associations between orthodontic treatment timing, tooth location, gender, and failure risk. Statistical significance was set at $p < 0.05$. All analyses were performed using SAS version 9.4.

Hazard ratios were reported as point estimates derived from Cox proportional hazards models. Confidence intervals were not available in the original institutional dataset because survival outputs were exported as aggregated summary statistics. Consequently, the precision of the hazard ratio estimates cannot be formally quantified, and results should be interpreted with caution. Orthodontic treatment exposure was modelled as a time-dependent covariate, with teeth contributing person-time to the non-exposed period before appliance placement and to the exposed period thereafter.

RESULTS

The study included 186 patients, with a mean age at orthodontic treatment initiation of 12.93 ± 1.64 years. The majority of patients (89.4%) began treatment between 10 and 15 years of age. Comprehensive orthodontic therapy (ORTH-A) accounted for 95.5% of treatments, while interceptive therapy (ORTH-B) represented 4.5% (Table 1).

Table 1. Patient Characteristics and Orthodontic Treatment Type

Variable	Total (n = 186)
Age at treatment initiation (years)	
Mean ± SD	12.93 ± 1.64
Median (Range)	12.8 (10–20)
Age group	
10–<11	11.5%
11–<12	19.3%
12–<13	24.9%
13–<14	21.8%
14–<15	11.9%
≥15	10.6%
Treatment type	
ORTH-A (comprehensive)	95.5%
ORTH-B (interceptive)	4.5%

A total of 2,232 anterior teeth were evaluated across all patients. Among these, 69 teeth experienced adverse outcomes, including 67 teeth requiring root canal therapy (3.0%) and 2 teeth extracted (0.1%). Endodontic treatment accounted for 3.0% of teeth, whereas extractions accounted for 0.1%. The highest frequency of adverse outcomes occurred in the maxillary central incisors (#8 and #9), which represented 12.2% of all failures. Teeth #7 and #10 accounted for 3.6%, while #6 and #11 showed a failure rate of 0.5%. Mandibular anterior teeth demonstrated substantially lower failure rates, ranging from 0.1% to 1.6% (Table 2).

Table 2. Distribution of Adverse Events by Tooth Group

Tooth Group	Failure (%)	Endodontic (%)	Extraction (%)
#6 / 11	0.5	0.4	0.1
#7 / 10	3.6	3.4	0.1
#8 / 9	12.2	12.0	0.2
#22 / 27	0.1	0.1	0.0
#23 / 26	0.5	0.5	0.0
#24 / 25	1.6	1.6	0.0

Overall tooth survival remained high throughout the observation period. Kaplan–Meier estimates showed survival probabilities of 99.52% at 1 year, 98.67% at 3 years, 97.59% at 5 years, and 95.20% at 10 years (Table 3).

Table 3. Survival Probabilities for All Anterior Teeth

Time Point	Survival Probability (%)
1 year	99.52
3 years	98.67
5 years	97.59
10 years	95.20

Female patients exhibited consistently higher survival rates than male patients. Cox regression analysis demonstrated a 34% reduction in failure risk among females compared to males (HR = 0.66, $p < 0.001$). Confidence intervals were not available for hazard ratio estimates. Tooth-specific analysis revealed significantly lower survival in maxillary central incisors (#8/9) than in all other anterior teeth. Their survival probabilities declined to 82.04% at 10 years. Mandibular anterior teeth demonstrated a 87–99% lower hazard of failure than maxillary central incisors, while teeth #7 and #10 showed a 72% lower hazard. Overall, mandibular anterior teeth had a markedly lower failure risk than maxillary anterior teeth (HR = 0.13). When comparing periods before and after orthodontic treatment initiation, no statistically significant difference in overall failure risk was observed (HR = 1.11, $p = 0.122$). However, a significant increase in adverse events occurred during years 2–3 following treatment initiation (HR = 1.38, $p = 0.015$). This association remained significant when considering endodontic treatment alone (HR = 1.33, $p = 0.031$). Confidence intervals were not available for these estimates.

When extractions were analyzed separately, orthodontic treatment was associated with a significantly increased hazard at all post-treatment time intervals, with hazard ratios ranging from 4.50 to 7.20. Because only two extraction events occurred, these estimates are unstable and should be interpreted cautiously.

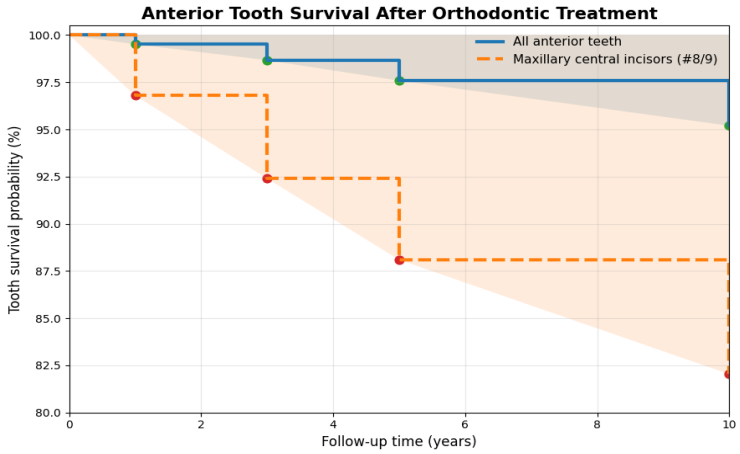


Figure 1. Kaplan–Meier survival curves for anterior teeth following orthodontic treatment. Overall, anterior tooth survival remained high throughout follow-up, while maxillary central incisors (#8/9) demonstrated a markedly lower long-term survival probability, consistent with their increased susceptibility to trauma and biologic risk factors

DISCUSSIONS

This study evaluated the occurrence of serious adverse dental outcomes—root canal therapy and tooth extraction—following orthodontic treatment of the anterior dentition in adolescent patients treated between 2021 and 2025. The findings indicate that orthodontic therapy is a generally safe treatment modality, with a low overall incidence of severe complications affecting anterior teeth. Orthodontic tooth movement is achieved through biologic remodeling of the periodontal ligament and alveolar bone in response to sustained mechanical forces [11]. Although these forces are necessary for occlusal correction, they have been associated with several potential adverse effects, including root resorption and transient pulpal changes [3]. Whether such biologic responses translate into irreversible pulpal damage requiring endodontic treatment or extraction remains clinically relevant, particularly for informed consent discussions. In the present cohort, orthodontic treatment did not result in a statistically significant increase in overall adverse outcomes when comparing periods before and after treatment initiation (HR = 1.11, p = 0.122). Root canal therapy accounted for 3.0% of evaluated teeth, while extractions were rare (0.1%), supporting previous reports that severe pulpal or structural complications following orthodontic therapy are uncommon [19,20]. These findings reinforce the notion that orthodontic forces alone do not typically compromise long-term tooth vitality.

A transient increase in adverse events was observed during years two to three after treatment initiation, with a significant rise in root canal therapy (HR = 1.33, p = 0.031). This period coincides with the average duration of comprehensive orthodontic treatment, which commonly lasts approximately two years [10]. One possible interpretation is that orthodontic correction of increased overjet may reduce post-treatment trauma risk, while pulpal sequelae from pre-existing injuries become clinically evident during or shortly after treatment completion. Maxillary central incisors (#8 and #9) demonstrated the lowest survival rates, with a 10-year survival probability of 82.04%, and accounted for the highest proportion of adverse outcomes (12.2%). This distribution mirrors the well-established vulnerability of these teeth to traumatic dental injuries and orthodontically induced root resorption [7,15]. Children between 7 and 12 years of age experience the highest incidence of dental trauma, with maxillary central incisors most frequently affected [5,7]. Previous studies have also shown that untreated Class II malocclusions with increased overjet substantially elevate the risk of incisor trauma, pulpal devitalization, and fracture [7,16].

Gender-related differences observed in this study further support a trauma-associated explanation. Female patients exhibited a 34% lower hazard of adverse outcomes compared to males (HR = 0.66, p < 0.001), consistent with earlier reports demonstrating higher trauma prevalence among boys [7]. These findings suggest that patient-specific risk factors, rather than orthodontic mechanics alone, significantly influence pulpal outcomes. Biological mechanisms may also contribute to the observed pattern. Severe external apical root resorption occurs in approximately 1–5% of orthodontic patients and is most frequently reported in maxillary incisors [15,17]. Excessive or prolonged orthodontic forces can disrupt cementum integrity and alter pulpal blood flow, particularly in teeth with pre-existing inflammation or trauma [13,14,19]. Although many pulpal changes induced by orthodontic forces appear reversible, compromised teeth may progress to necrosis, necessitating endodontic intervention [19,20].

Invasive cervical resorption represents another potential pathway linking orthodontic treatment and adverse outcomes. Orthodontics has been identified as a predisposing factor in a substantial proportion of cases, predominantly involving maxillary anterior teeth [18]. Advanced lesions may ultimately require root canal therapy or extraction, further explaining the higher failure rates observed in this region.

Several limitations must be acknowledged. The study population was derived from a single academic institution, which may limit generalizability. The retrospective design did not allow control over confounding factors such as oral hygiene, caries history, or undocumented dental trauma. Additionally, it was assumed that all evaluated anterior teeth were present and untreated at baseline and that orthodontic therapy had not been initiated before age 10. The absence of a non-orthodontic control group limits causal inference. Observed associations may reflect underlying patient risk factors rather than treatment effects. The analysis treated teeth as independent observations despite clustering within patients, which may have led to underestimated standard errors and overestimated statistical significance. Reported survival estimates up to 10 years reflect statistical projections derived from Kaplan–Meier modeling rather than direct observation, as the study follow-up period extended from 2021 to 2025.

Additionally, confidence intervals for hazard ratios were not available due to the aggregated nature of the exported survival data, limiting assessment of the estimate's precision. In summary, orthodontic therapy did not significantly increase the overall risk of root canal therapy or extraction in this adolescent population. Maxillary central incisors and male patients demonstrated higher susceptibility to adverse outcomes, likely reflecting the combined effects of trauma exposure, biologic vulnerability, and pre-existing conditions rather than orthodontic forces alone. Given the low overall incidence of severe complications, orthodontic treatment remains a safe and effective modality for managing malocclusion in children and adolescents. Given the retrospective observational design and potential residual confounding, these findings should be interpreted as associative rather than causal.

CONCLUSIONS

Orthodontic treatment was not associated with a sustained increase in overall risk of root canal therapy or tooth extraction, although a transient increase in adverse events was observed during years 2–3 after treatment initiation. Maxillary central incisors and male patients exhibited a higher susceptibility to adverse outcomes, likely reflecting trauma-related and biologic factors rather than orthodontic forces alone. Overall, the low incidence of severe complications supports orthodontic therapy as a safe treatment modality in children and adolescents.

Conflicts of Interest

The authors declare no conflict of interest.

REFERENCES

[1] Alhammadi MS, Halboub E, Fayed MS, Labib A, El-Saaidi C. Global distribution of malocclusion traits: A systematic review. Dental Press J Orthod. 2018;23(6):40.e1-40.e10. doi:10.1590/2177-6709.23.6.40.e1-10.onl.

[2] Silva DBHD, Gonzaga AS. Importance of orthodontic intervention of the Class III malocclusion in mixed dentition. Dental Press J Orthod. 2020 Sep-Oct;25(5):57-65. doi: 10.1590/2177-6709.25.5.057-065.bbo. PMID: 33206830; PMCID: PMC7668065.

[3] Wishney M. Potential risks of orthodontic therapy: a critical review and conceptual framework. Aust Dent J. 2017;62 Suppl 1:86-96. doi:10.1111/adj.12486.

[4] Ackerman JL, Proffit WR. The characteristics of malocclusion: a modern approach to classification and diagnosis. Am J Orthod. 1969;56(5):443-454. doi:10.1016/0002-9416(69)90206-1.

[5] Negri P, Vena F, Lomurno G, et al. Index of Orthodontic Treatment Need (IOTN) and distribution of malocclusion traits in a population of growing patients attending a public

orthodontic service in Perugia (Italy). Eur J Paediatr Dent. 2021;22(4):303-308. doi:10.23804/ejpd.2021.22.04.8.

[6] Ben Gassem AA, Aldweesh AH, Alsagob EI, et al. Psychosocial Impact of Malocclusion and Self-Perceived Orthodontic Treatment Need among Young Adult Dental Patients. Eur J Dent. 2023;17(3):713-719. doi:10.1055/s-0042-1753452.

[7] Di Venere D, Rapone B, Corsalini M. Dental trauma in the anterior sector: an analysis of the predisposing factors in a group of orthodontic patients. Clin Ter. 2020;171(6):e481-e485. doi:10.7417/CT.2020.2261.

[8] Sicari F, Merlo EM, Gentile G, Nucera R, Portelli M, Settineri S, Myles LAM, Militi A. Body Image and Psychological Impact of Dental Appearance in Adolescents with Malocclusion: A Preliminary Exploratory Study. Children. 2023; 10(10):1691. https://doi.org/10.3390/children10101691.

[9] Berry S, Javed F, Rossouw PE, Barmak AB, Kalogirou EM, Michelogiannakis D. Influence of thyroxine supplementation on orthodontically induced tooth movement and/or inflammatory root resorption: A systematic review. Orthod Craniofac Res. 2021;24(2):206-213. doi:10.1111/ocr.12428.

[10] English JD, Akyalcin S, Peltomaki T, and Litschel K. Mosby's Orthodontic Review, 2nd ed. St. Louis: Elsevier; 2015:24-35.

[11] Profitt WR, Fields HW. Contemporary Orthodontics. 3rd ed. Missouri: Mosby; 2000:296-313.

[12] Bucur SM, Chibelean M, Pacurar M, Sita DD, Zetu IN. (2014). Ethical considerations in Orthodontics and Dentofacial Orthopaedics. Rev Rom Bioet, 12(1): 80–84.

[13] Heboyan A, Avetisyan A, Karobari MI, Marya A, Khurshid Z, Rokaya D, Zafar MS, Fernandes GVO. Tooth root resorption: A review. Sci Prog. 2022 Jul-Sep;105(3):368504221109217. doi: 10.1177/00368504221109217. PMID: 35759366; PMCID: PMC10358711.

[14] Patel S, Saberi N, Pimental T, Teng PH. Present status and future directions: Root resorption. Int Endod J. 2022 Oct;55 Suppl 4(Suppl 4):892-921. doi: 10.1111/iej.13715.

[15] Liu Z, Ouyang Y, Lou Y, Han Y, Lu M, Yu M, Wang H, Ding W. Orthodontically induced root resorption in endodontically treated and vital teeth: a cone beam computer tomographic study. Prog Orthod. 2025 Feb 27;26(1):8. doi: 10.1186/s40510-025-00553-7. PMID: 40011294; PMCID: PMC11865387.

[16] Topkara A, Karaman AI, Kau CH. Apical root resorption caused by orthodontic forces: A brief review and a long-term observation. Eur J Dent. 2012 Oct;6(4):445-53.

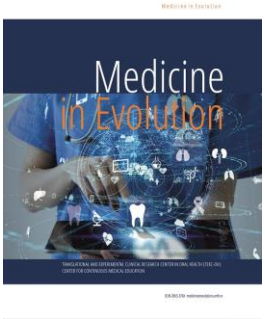
[17] Levander E, Malmgren O. Evaluation of the risk of root resorption during orthodontic treatment: a study of upper incisors. Eur J Orthod. 1988;10(1):30-38. doi:10.1093/ejo/10.1.30.

[18] Jeng PY, Lin LD, Chang SH, Lee YL, Wang CY, Jeng JH, Tsai YL. Invasive Cervical Resorption-Distribution, Potential Predisposing Factors, and Clinical Characteristics. J Endod. 2020;46:475-482.

[19] Golež A, Ovsenik M, Cankar K. The effect of orthodontic tooth movement on the sensitivity of dental pulp: A systematic review and meta-analysis. Heliyon. 2023 Mar 24;9(4):e14621. doi: 10.1016/j.heliyon.2023.e14621. PMID: 37025792; PMCID: PMC10070381.

[20] Parashos P. The orthodontic-endodontic interface: trauma and pulpal considerations. Br Dent J. 2024;237(5):389-397. doi:10.1038/s41415-024-7786-9.

Unilateral Focused Parathyroidectomy versus Bilateral Neck Exploration in Primary Hyperparathyroidism: A Retrospective Cohort Study



https://doi.org/10.70921/medev.v32i1.2028

Adina Coman[1,2], Daian Ionel Popa[1], Diana Utu[3], Florina Buleu[4], Mihaela Avram[2,5], Marius Murariu[2,5]

[1]*Doctoral School, Victor Babes University of Medicine and Pharmacy Timisoara, E. Murgu Square, No. 2,300041 Timisoara, Romania;*
[2]*Department X, Discipline of General Surgery I, Faculty of Medicine, Victor Babes University of Medicine and Pharmacy Timisoara, E. Murgu Square, No. 2, 300041 Timisoara, Romania;*
[3]*Department II, Discipline of Pharmacology-Pharmacotherapy, Faculty of Pharmacy, Victor Babes University of Medicine and Pharmacy Timisoara, E. Murgu Square, No. 2, 300041 Timisoara, Romania;*
[4]*Department VI, Discipline of Internal Medicine and Ambulatory Care, Prevention and Cardiovascular Recovery, Faculty of Medicine, Victor Babes University of Medicine and Pharmacy Timisoara, E. Murgu Square, No. 2, 300041 Timisoara, Romania;*
[5]*Center for Research in Abdominal Surgery and Flebology – CCCAF, UMF Victor Babes Timisoara*

Correspondence to:
Name: Mihaeala Avram
E-mail address: avram,mihaela@umft.ro

Received: 23 February 2026; Accepted: 11 March 2026; Published: 31 March 2026

Abstract

1.Background: Primary hyperparathyroidism (pHPT) is cured by parathyroidectomy. Bilateral neck exploration (BNE) has been the historical standard, whereas improved preoperative imaging and intraoperative parathyroid hormone (IOPTH) monitoring support unilateral focused parathyroidectomy (UFP) in selected patients. This study compared UFP and BNE. *2.Methods:* We conducted a single-center retrospective cohort study of adults undergoing initial surgery for sporadic pHPT between 2012 and 2023 with ≥6 months follow-up. Diagnosis was biochemical (hypercalcemia with inappropriately high/unsuppressed PTH). Localization used cervical ultrasound and technetium-99m sestamibi; IOPTH was used when available to confirm adequate resection and prompt conversion to wider exploration if needed. *3.Results*: Of 84 operated patients, 72 met inclusion criteria (mean age 51.9±14.1 years; 77.8% female). UFP was performed as the first operation in 54 patients (75%) and BNE in 18 (25%). Pathology revealed single adenoma in 66 cases (91.7%), multiple adenomas in 3 (4.2%), and hyperplasia in 3 (4.2%). Eight patients (11.1%) required reoperation, and persistent disease without further surgery occurred in 2 (2.8%). One patient later developed parathyroid carcinoma with bone metastasis and died. No significant differences at 6 months follow-up between the two procedures. *4.Conclusions:* In a cohort largely characterized by single-gland disease, UFP was the predominant approach with low clinical recurrence; BNE remained essential for non-localizing or complex disease.

Keywords: Primary hyperparathyroidism, Unilateral focused parathyroidectomy, Bilateral neck exploration, Intraoperative parathyroid hormone (IOPTH) monitoring, Parathyroid adenoma

INTRODUCTION

Primary hyperparathyroidism (pHPT) is a common endocrine disorder in which excessive parathyroid hormone causes hypercalcemia. If left untreated, this may lead to nephrolithiasis, osteoporosis, and fragility fractures, with variable neurocognitive and gastrointestinal manifestations. Parathyroidectomy is the only definitive cure and is recommended for symptomatic patients and for selected asymptomatic patients meeting established guideline criteria [1-5]. For decades, the standard surgical treatment for pHPT has been a bilateral neck exploration (BNE). In a traditional BNE, a cervical incision is used to identify all four parathyroid glands and excise abnormal tissue. This comprehensive approach achieves very high initial cure rates in experienced hands and reduces the likelihood of missing multigland disease, but it requires broader dissection and may increase operative duration and the risk of transient hypocalcemia or recurrent laryngeal nerve injury compared with more limited approaches. [6-8]

In the last two decades, advances in preoperative localization and intraoperative monitoring have enabled a focused, minimally invasive surgical approach for many patients. High-resolution ultrasound and sestamibi-based imaging can localize a dominant hyperfunctioning gland, while rapid intraoperative parathyroid hormone (IOPTH) assays allow biochemical confirmation of adequate resection by demonstrating an appropriate decline in PTH during the operation. Together, these developments support unilateral focused parathyroidectomy targeted at the suspected lesion, avoiding routine four-gland exploration when it is unlikely to add value [9-12].

A unilateral focused approach offers advantages in appropriately selected cases. By limiting dissection to one side, the procedure can shorten operative time, reduce tissue trauma, and facilitate faster recovery, often allowing short hospital stays. Limiting exploration may also reduce the risk of postoperative hypocalcemia and bilateral nerve injury. When a solitary adenoma is the cause of pHPT, focused surgery can achieve cure rates comparable to BNE, and contemporary series and meta-analyses support its effectiveness when localization is concordant and surgical expertise is available. Recent single-center experiences have similarly reported high cure rates with selective use of focused exploration alongside BNE for complex presentations [2,3,9,13-18].

However, focused parathyroidectomy is not appropriate for every case. A clinically important minority of patients have multigland disease (multiple adenomas or parathyroid hyperplasia), and limited exploration may fail if additional hyperfunctioning tissue is left in situ. Accordingly, when preoperative imaging is negative or discordant, when intraoperative findings are inconsistent with a single-gland process, or when PTH fails to decline appropriately after targeted excision, surgeons often proceed with BNE to ensure that all hyperfunctioning tissue is addressed. These trade-offs underpin an ongoing debate about the optimal extent of exploration in routine pHPT surgery [2,3,9,12,13].

In light of these considerations, we conducted a single-center retrospective cohort study to compare the two surgical approaches for pHPT. The objective was to evaluate and contrast the outcomes of unilateral focused parathyroidectomy versus bilateral neck exploration in patients with primary hyperparathyroidism – specifically examining cure rates, disease recurrence, and complications – in order to inform optimal surgical management of this condition.

Aim and objectives

In light of these considerations, we conducted a single-center retrospective cohort study to compare the two surgical approaches for pHPT. The objective was to evaluate and

contrast the outcomes of unilateral focused parathyroidectomy versus bilateral neck exploration in patients with primary hyperparathyroidism – specifically examining cure rates, disease recurrence, and complications – in order to inform optimal surgical management of this condition.

MATERIAL AND METHODS

This study is a retrospective cohort analysis conducted at a single tertiary care academic hospital. We reviewed the medical records of all patients who underwent parathyroidectomy for primary hyperparathyroidism (pHPT) between January 2012 and December 2023. The study obtained approval from the institutional ethics committee, with a waiver of individual consent due to its retrospective design. Multiple endocrine surgeons at the centre performed the operations over the study period. All available perioperative and follow-up data were collected, including patient demographics, clinical presentation, laboratory results, imaging findings, surgical details, and pathology reports.

Inclusion and Exclusion Criteria

Inclusion criteria were defined to capture patients with sporadic pHPT undergoing curative surgery: adult patients (age ≥18) with biochemically confirmed primary hyperparathyroidism who underwent initial parathyroidectomy at our institution during the study period. Exclusion: no postoperative follow-up of at least 6 months to ensure outcome assessment.

Preoperative Evaluation

All patients underwent a standardized preoperative evaluation by an endocrinologist and a surgeon. The diagnosis of primary hyperparathyroidism was confirmed biochemically by the finding of elevated serum calcium levels in conjunction with inappropriately high or unsuppressed intact parathyroid hormone (PTH) concentrations. Additional laboratory assessments included serum phosphate, 25-hydroxyvitamin D, and creatinine to assess kidney function. Patients with very low vitamin D levels were repleted prior to surgery, in order to minimize post-parathyroidectomy hypocalcemia risk. The presence of end-organ effects of pHPT was documented, including a history of nephrolithiasis, osteoporosis or fragility fractures, and neurocognitive or gastrointestinal symptoms [1-5].

Indications for surgery followed contemporary consensus guidelines for pHPT. All symptomatic patients (e.g. those with kidney stones, bone disease, or significant hypercalcemic symptoms) were offered surgery. Asymptomatic patients were considered surgical candidates if they met at least one guideline criterion, such as: serum calcium more than 1.0 mg/dL above the upper normal limit, reduced bone mineral density (T-score ≤ –2.5 or prior fragility fracture), evidence of nephrolithiasis/nephrocalcinosis, impaired renal function (glomerular filtration rate < 60 mL/min), or age under 50 years. These criteria ensured that all patients had a clear indication for parathyroidectomy [4,5].

Preoperative localization studies were obtained for all patients to guide the surgical approach. High-resolution cervical ultrasound was performed to identify enlarged parathyroid glands and evaluate thyroid pathology. In addition, to some cases a technetium-99m sestamibi scintigraphy was conducted to localize hyperfunctioning parathyroid tissue. All patients were assessed to be fit for surgery, and any coexisting medical conditions (such as hypertension or cardiac issues) were optimized preoperatively [9-11,19,20].

Surgical Technique

All parathyroidectomies were performed under general anesthesia with endotracheal intubation. Patients were positioned with neck extension, and a sterile low transverse cervical incision (approximately 3–4 cm, along a skin crease) was utilized in all cases. In each operation, the surgeon identified and preserved the recurrent laryngeal nerve on the side of

exploration and took care to maintain intact parathyroid blood supply for any glands left in situ. A rapid intraoperative PTH (IOPTH) assay was employed in every case to guide the extent of resection whenever available at the hospital laboratory. Baseline PTH levels were drawn after induction of anesthesia (prior to incision), and subsequent samples were obtained 5 and 10 minutes after removal of suspected abnormal parathyroid tissue. The criterion for biochemical cure during surgery was a drop in IOPTH level of ≥50% from the pre-excision baseline and into the normal PTH reference range by 10 minutes post-excision (Miami criterion). If this criterion was met, it indicated that all hyperfunctioning tissue had likely been removed [9,12].

Unilateral focused parathyroidectomy: patients with preoperative imaging localizing a single parathyroid adenoma underwent a unilateral focused parathyroidectomy. In these cases, the operation was targeted to the region of the identified abnormal gland (typically one side of the neck). Intraoperative frozen-section pathology was occasionally utilized to confirm that the resected tissue was indeed parathyroid gland. After removal, IOPTH levels were checked as described if available (due to availability at the hospital laboratory). If the PTH dropped appropriately (≥50% and into normal range), no further gland exploration was performed. The wound was then closed without routine drain placement, and the patient was observed for the standard postoperative period. This focused approach minimized dissection and operative time while achieving cure in patients with single-gland disease [9,12].

Bilateral neck exploration: If preoperative imaging was negative, if it suggested multiglandular disease, or if the intraoperative findings/IOPTH results did not meet cure criteria after a focused resection, a bilateral neck exploration (BNE) was undertaken. In a planned BNE, the incision was typically slightly longer to allow access to both sides of the neck. The surgeon systematically identified all four parathyroid glands. Any grossly enlarged or abnormal-appearing glands were resected. In patients with multigland hyperplasia (suspected when more than one gland appeared enlarged or hormone levels failed to drop after a single adenoma removal), a subtotal parathyroidectomy was performed: usually three and a half glands were removed, leaving a small remnant of the most normal-appearing gland in situ to prevent permanent hypoparathyroidism. Alternatively, in a few cases of multigland disease, one entire gland was left in situ or a portion of a gland was autotransplanted into a forearm or sternocleidomastoid muscle, according to surgeon preference. All resected specimens were sent for histopathological examination to confirm the presence of parathyroid adenoma or hyperplasia and to rule out rare parathyroid carcinoma. Postoperatively, all patients received standard care including calcium level monitoring and calcium/vitamin D supplementation as necessary to prevent symptomatic hypocalcemia (especially in those with significant bone disease preoperatively) [6-9].

Postoperative Follow-Up and Outcome Measures

Postoperative follow-up was conducted by the endocrinology clinic. Patients were typically seen at approximately 1 month after surgery for an initial evaluation, then at 6 months, 12 months, and annually up to 36 months postoperatively or whenever addressed the clinic. At each follow-up visit, a thorough clinical assessment and laboratory tests were performed. Serum calcium and PTH levels were measured at each visit to monitor residual or recurrent hyperparathyroidism. Additional assessments included serum phosphate. Patients were also queried about the resolution or persistence of hypercalcemia-related symptoms and the occurrence of any new symptoms (such as bone pain, kidney stones, or neuromuscular symptoms) during follow-up.

The primary outcome measure was surgical cure rate, defined as the achievement of normocalcemia after surgery that persisted through the early postoperative period. Operationally, we considered a patient “cured” if they had a normal serum calcium level at the 6-month follow-up visit without intervening hypercalcemia. Persistent pHPT was defined

as failure to normalize calcium levels after surgery, or a return of hypercalcemia (accompanied by elevated PTH) within the first six months postoperatively. Recurrent pHPT was defined as the reappearance of hypercalcemia due to hyperparathyroidism after an initial period of normocalcemia, occurring beyond 6 months post-surgery. All cases of persistence or recurrence were verified by biochemical testing and, when appropriate, confirmatory imaging for localization of any remnant or regrown parathyroid lesion [17,18].

Secondary outcome measures included surgical and postoperative complications and other relevant clinical outcomes. We tracked any occurrences of hypocalcemia and recurrent laryngeal nerve (RLN) injury.

RLN injury: Vocal cord function was assessed by clinical exam (and laryngoscopy if vocal symptoms were present). Transient RLN palsy was defined as voice changes or endoscopic vocal cord paralysis that resolved within 6–12 months, whereas permanent RLN injury was defined by persistent vocal cord paralysis beyond 12 months or requiring intervention (voice therapy or medialization surgery).

All patients who were identified to have persistent or recurrent disease were evaluated for potential re-operation. The timing and success of any remedial parathyroid surgery during the follow-up period were documented, but these re-operations were not counted as new index cases in the cohort (they were considered outcomes of the initial surgery).

Statistical Analysis

All data collected were entered into a secure database and analyzed using statistical software (IBM SPSS Statistics, Version 26.0). Descriptive statistics were used to summarize the patient cohort and surgical outcomes. Continuous variables were reported as mean ± standard deviation (SD) if normally distributed, or as median with interquartile range (IQR) if the distribution was skewed. Categorical variables were summarized as frequencies and percentages. We compared baseline characteristics and outcomes between the two surgical approach groups (unilateral focused parathyroidectomy vs. bilateral neck exploration). For continuous variables, the Student's t-test was used for group comparisons when data were approximately normally distributed; otherwise, the Mann–Whitney U test was employed. Categorical variables (such as cure rates and complication incidences) were compared using the chi-square test or Fisher's exact test, as appropriate. The threshold for statistical significance was set at a two-tailed p value < 0.05.

All statistical analyses adhered to the intention-to-treat principle with respect to the planned surgical approach. The cohort's data analysis followed STROBE guidelines for observational studies, aiming to provide transparent and comprehensive reporting of findings.

RESULTS

During the study period 84 patients were operated on; 12 were excluded from the study population and 72 were included in the analysis. 56 were females (77.78%), 16 were males (22.22%). In the table 1 are the demographics data of the patients included in the study.

Table 1. Demographics of the patients included in the study

Variable	n=72
Age (years)	51.9±14.1
Calcium (mg/dL)	10.9±0.98
Phosphate (mg/dL)	2.8±0.8
Creatinine (mg/dL)	0.7 ±0.3
Alkaline phosphatase (u/L)	112±65
Parathormone (pg/mL)	282.63± 321.48
Bone and muscle pain	58 (80.55%)

Fatigue	**17 (23.61%)**
Kidney stones	**27 (37.50%)**
Gastrointestinal symptoms	**22 (30.55%)**
Osteoporosis	**21 (29.16%)**
Arterial hypertension	**38 (52.77%)**
Depression	**9 (12.5%)**

UFP was employed in 54 patients (75%), whereas BNE in the remaining 18 (25%). Some patients needed another procedure after the recurrence of the disease, 8 of them, while another patient developed parathyroid cancer and needed another surgery. Surgical procedures, findings and pathology are illustrated in table 2.

Table 2. Surgical variables

Variables	**N=72**
First surgery	
UFP	**54 (75%)**
BNE	**18 (25%)**
Second surgery due to recurrence	**8 (11.11%)**
UFP	**4 (5.56%)**
BNE	**4 (5,56%)**
Second surgery due to cancer	**1 (1.38%)**
IOPTH assay performed	**54 (75%)**
Pathology	
Single adenoma	**66 (91.67%)**
Multiple adenoma	**3 (4.16%)**
Hyperplasia	**3 (4.16%)**

Eight patients were reoperated for recurrence of the disease, four from each group.

After UFP 4 patients have persistent HPT, despite initial drop in PTH values, three cases underwent reoperation with BNE, and one of them with right thyroid lobectomy and BNE. Four cases from the 18 of BNE needed second surgery: the missing gland was in the thorax in one case; one had a persistence due to implantation in the forearm, two had the gland inside the thyroid gland and had lobectomy for the removal. One case of hyperplasia evolved after 5 years in a parathyroid cancer with bone metastasis and patient death; first surgery pathology report did not mention malignancy.

No conversion from UFP to BNE was reported at index surgery.

At 6 months postoperatively, cure defined as normocalcemia was high in both groups (UFP 52/54 [96.3%] vs BNE 18/18 [100.0%]). Table 3 summarizes complications and 6-month laboratory values. Bleeding was uncommon (UFP 2/54 [3.7%] vs BNE 1/18 [5.6%]). Transient hypocalcemia occurred in 2/54 (3.7%) after UFP and 2/18 (11.1%) after BNE. Temporary unilateral vocal cord paralysis occurred in 1/54 (1.9%) vs 1/18 (5.6%). Six-month calcium and phosphate values were similar between groups. Reoperation during follow-up occurred in 4/54 (7.4%) after UFP and 4/18 (22.2%) after BNE. Two patients had persistent HPT at six months follow-up, but no clinical symptoms and refused further surgeries.

Table 3. Short-term results and follow-up at six months UFP versus BNE

Variables	**UFP (n=54)**	**BNE (n=18)**	**p**
Bleeding	2	1	1.000
Transient hypocalcemia	2	2	0.259
Temporary unilateral vocal cord paralysis	1	1	0.444
PTH pg/ml	61.80±32.4	60.80±34.6	0.915
Ca at 6 months (mg/dL)	8.9 ±1.15	8.8 ±1.23	0.764
Phosphate at 6 months (mg/dL)	3.30 ±0.4	3.32±0.28	0.816
Reoperation	4	4	0.101
Cure rate at six months	52	18	1.000

DISCUSSIONS

In this single-center retrospective cohort covering 2012–2023, surgery for primary hyperparathyroidism (PHPT) achieved favorable overall outcomes in a predominantly symptomatic population. Of 72 included patients (mean age 51.9 years; 78% female), unilateral focused parathyroidectomy (UFP) was the most frequently employed initial approach (75%), while bilateral neck exploration (BNE) was used in 25%. Pathology demonstrated a predominance of single adenoma (91.7%), with a small proportion of multiple adenomas (4.2%) and hyperplasia (4.2%). Reoperation was required in 11.1% of patients, whereas clinically defined persistent disease without further surgery was observed in 2.8%. One patient developed parathyroid carcinoma with bone metastasis and died, highlighting the clinical impact of rare but aggressive disease.

The clinical profile of our cohort suggests a substantial symptomatic burden at presentation, with bone and muscle pain reported by over 80% of patients, nephrolithiasis in 37.5%, gastrointestinal symptoms in 30.6%, and osteoporosis in 29.2%. This pattern is consistent with "classical" pHPT, where skeletal and renal involvement remain common drivers for surgical referral, and it underscores that pHPT in real-world settings may still present beyond incidentally detected hypercalcemia. Contemporary reviews and guidelines emphasize that parathyroidectomy is the only curative therapy and is appropriate for symptomatic patients and for selected asymptomatic patients meeting guideline criteria [1-5].

A key observation from our series is that a focused approach was feasible in the majority of cases, which is biologically plausible given the predominance of single-gland disease. The proportion of single adenoma in our pathology results parallels large surgical series and supports a strategy of targeted exploration when preoperative localization is concordant and surgical expertise is available [2,6-9]. In the study by Unlu and colleagues, minimally invasive strategies (unilateral neck exploration or focused parathyroid surgery) were used in about two-thirds of patients, with an overall cure rate approaching 98% and low recurrence during follow-up [17]. Similarly, Demir and colleagues reported a single-center experience in which adenoma was the dominant pathology and perioperative outcomes were favorable, reinforcing that contemporary pHPT surgery can be highly effective when supported by systematic preoperative assessment and intraoperative decision-making. [18] Our results align with this overall narrative: most patients can be treated effectively with UFP, while BNE remains essential for selected situations.

Despite the generally favorable outcomes, the need for reoperation in 11.1% of our cohort warrants focused interpretation. In our series, reoperation was most often linked to failure to excise hyperfunctioning tissue at the index operation, ectopic gland location, and complex disease biology such as multiglandular disease or double adenomas [21-25]. Consistent with prior reports, Unlu et al. highlight double adenoma and ectopic localization as important contributors to persistent disease after initial surgery and describe how repeat imaging and tailored reoperative planning can restore high cure rates in experienced centers [17]. This framework helps explain our reoperative cases: four patients required additional surgery after BNE because a missing gland was in the thorax in one case, two in the thyroid gland and because of implantation-related disease in another, illustrating both ectopic pathology and the challenge of surgically distributed parathyroid tissue.

Ectopic and mediastinal disease is particularly relevant when interpreting failures and the need for additional procedures. Persistent hypercalcemia after an apparently adequate cervical exploration should prompt renewed localization efforts with attention to ectopic sites, including the mediastinum. Advanced imaging, particularly 4D-CT, can improve preoperative localization in difficult or reoperative settings and can inform the choice between repeat focused exploration and broader re-exploration [19,20,21,23]. Although some

mediastinal lesions remain approachable from the neck, others may require thoracic access depending on their location and the prior operative field [21-23]. These observations reinforce the need for a structured algorithm for persistent disease that incorporates repeat imaging, multidisciplinary discussion, and individualized operative strategy [22,23].

The low prevalence of multigland disease in our pathology results (8.3% combined multiple adenomas and hyperplasia) likely supported the high effectiveness of focused surgery overall. Nevertheless, multigland disease remains clinically important because it is a consistent driver of persistence and recurrence, and it can be difficult to identify when imaging is discordant or when a dominant adenoma suppresses smaller hyperfunctioning glands [2,3,24,25]. Demir et al. discuss that advanced imaging, including selective use of 4D-CT in difficult cases, can assist localization, particularly in patients with multigland disease or persistent/recurrent pHPT [18-20].

A distinctive operational limitation in our cohort was the inconsistent availability of intraoperative PTH (IOPTH) monitoring during the study period. IOPTH is widely used to biochemically confirm removal of hyperfunctioning tissue during focused operations and to signal the need for further exploration when the expected hormone decline does not occur [12]. In settings where IOPTH is unavailable or results are not rapid, surgeons may rely more heavily on concordant imaging, intraoperative findings, and adjuncts such as frozen section. Unlu et al. describe a setting where PTH measurements were obtained but were not available intraoperatively, limiting their immediate utility for guiding the extent of exploration [17]. Demir et al. discuss the practical barrier of cost and report using frozen section confirmation rather than IOPTH in their cohort [18]. In our series, inconsistent IOPTH availability likely contributed to heterogeneity in intraoperative decision-making across surgeons and years, and it may partially explain the proportion of patients requiring reoperation, especially those with occult additional glands [21-23].

The single case of parathyroid carcinoma emerging after initial hyperplasia is uncommon. Although carcinoma represents a very small fraction of PHPT etiologies, it carries a markedly different prognosis and can manifest with severe skeletal disease and metastasis. This case emphasizes the importance of long-term biochemical follow-up and careful reassessment of patients with atypical courses, recurrent hypercalcemia, or unusually aggressive clinical features, even when the initial histology is not malignant. It also reinforces the value of specialized endocrine follow-up, which in our cohort was provided for up to three years postoperatively.

Strengths of this study include the single-center design, real-world inclusion of both UFP and BNE across a contemporary period, and clinically meaningful follow-up by endocrinologists. Nevertheless, several limitations should be acknowledged. The retrospective design introduces risks of missing data, unmeasured confounding, and selection bias—particularly in how patients were assigned to UFP versus BNE (for example, based on imaging concordance, surgeon preference, or disease severity). The sample size is modest, limiting statistical power for subgroup comparisons. Surgical practice also evolved over the long study interval, and multiple surgeons contributed, which may have increased variability in operative technique, conversion thresholds, and use of adjuncts such as IOPTH.

CONCLUSIONS

Our findings support a selective strategy for pHPT surgery: unilateral focused parathyroidectomy is effective for most patients with concordant localization and an anticipated single adenoma, while BNE remains necessary when localization is negative or discordant, when multigland disease is suspected. The reoperation rate and the occurrence of rare malignant evolution in our cohort underscore the importance of meticulous operative

technique, access to reliable localization and intraoperative confirmation where feasible, and long-term endocrine follow-up to detect persistence, recurrence, and uncommon aggressive disease.

Acknowledgments NA

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

Conflicts of Interest

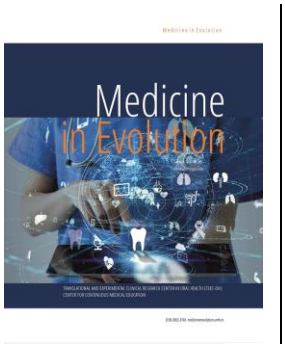
The authors declare no conflict of interest.

REFERENCES

[1] Walker MD, Bilezikian JP. Primary hyperparathyroidism: recent advances. Curr Opin Rheumatol. 2018;30:427–439.
[2] Madkhali T, Alhefdhi A, Chen H, Elfenbein D. Primary hyperparathyroidism. Ulus Cerrahi Derg. 2016;32:58–66.
[3] Bilezikian JP, Silverberg SJ. Clinical practice: asymptomatic primary hyperparathyroidism. N Engl J Med. 2004;350:1746–1751.
[4] Bilezikian JP, Brandi ML, Eastell R, Silverberg SJ, Udelsman R, Marcocci C, et al. Guidelines for the management of asymptomatic primary hyperparathyroidism: summary statement from the Fourth International Workshop. J Clin Endocrinol Metab. 2014;99:3561–3569.
[5] Wilhelm SM, Wang TS, Ruan DT, Lee JA, Asa SL, Duh QY, et al. The American Association of Endocrine Surgeons guidelines for definitive management of primary hyperparathyroidism. JAMA Surg. 2016;151:959–968.
[6] Udelsman R. Six hundred fifty-six consecutive explorations for primary hyperparathyroidism. Ann Surg. 2002;235:665–670.
[7] Allendorf J, DiGorgi M, Spanknebel K, Inabnet W, Chabot J, LoGerfo P. 1112 consecutive bilateral neck explorations for primary hyperparathyroidism. World J Surg. 2007;31:2075–2080.
[8] Irvin GL 3rd, Carneiro DM, Solorzano CC. Progress in the operative management of sporadic primary hyperparathyroidism over 34 years. Ann Surg. 2004;239:704–708.
[9] Laird AM, Libutti SK. Minimally invasive parathyroidectomy versus bilateral neck exploration for primary hyperparathyroidism. Surg Oncol Clin N Am. 2016;25:103–118.
[10] Chapuis Y, Fulla Y, Bonnichon P, Tarla E, Abboud B, Pitre J, et al. Values of ultrasonography, sestamibi scintigraphy, and intraoperative measurement of 1–84 PTH for unilateral neck exploration of primary hyperparathyroidism. World J Surg. 1996;20:835–839.
[11] Civelek AC, Ozalp E, Donovan P, Udelsman R. Prospective evaluation of delayed technetium-99m sestamibi SPECT scintigraphy for preoperative localization of primary hyperparathyroidism. Surgery. 2002;131:149–157.
[12] Irvin GL 3rd, Solorzano CC, Carneiro DM. Quick intraoperative parathyroid hormone assay: surgical adjunct to allow limited parathyroidectomy, improve success rate, and predict outcome. World J Surg. 2004;28:1287–1292.
[13] Egan RJ, Scott-Coombes DM. The surgical management of sporadic primary hyperparathyroidism. Best Pract Res Clin Endocrinol Metab. 2018;32:847–859.
[14] Singh Ospina NM, Rodriguez-Gutierrez R, Maraka S, Espinosa de Ycaza AE, Jasim S, Castaneda-Guarderas A, et al. Outcomes of parathyroidectomy in patients with primary hyperparathyroidism: a systematic review and meta-analysis. World J Surg. 2016;40:2359–2377.
[15] Westerdahl J, Bergenfelz A. Unilateral versus bilateral neck exploration for primary hyperparathyroidism: five-year follow-up of a randomized controlled trial. Ann Surg. 2007;246:976–980.

[16] Tibblin S, Bondeson AG, Ljungberg O. Unilateral parathyroidectomy in hyperparathyroidism due to single adenoma. Ann Surg. 1982;195:245–252.
[17] Unlu MT, Aygun N, Akgun IE, Yetkin SG, Erol RS, Isgor A, et al. Parathyroidectomy results in primary hyperparathyroidism: analysis of the results from a single center. Med Bull Sisli Etfal Hosp. 2021;55:173–178.
[18] Demir B, Binnetoglu A, Sahin A, Gogas Yavuz D. Single center experience in the surgical management of primary hyperparathyroidism. Clin Exp Otorhinolaryngol. 2020;13:285–290.
[19] Mortenson MM, Evans DB, Lee JE, Hunter GJ, Shellingerhout D, Vu T, et al. Parathyroid exploration in the reoperative neck: improved preoperative localization with 4D-computed tomography. J Am Coll Surg. 2008;206:888–895.
[20] Kelly HR, Hamberg LM, Hunter GJ. 4D-CT for preoperative localization of abnormal parathyroid glands in patients with hyperparathyroidism: accuracy and ability to stratify patients by unilateral versus bilateral disease in surgery-naive and re-exploration patients. AJNR Am J Neuroradiol. 2014;35:176–181.
[21] Shen W, Düren M, Morita E, Higgins C, Duh QY, Siperstein AE, et al. Reoperation for persistent or recurrent primary hyperparathyroidism. Arch Surg. 1996;131:861–867.
[22] Caron NR, Sturgeon C, Clark OH. Persistent and recurrent hyperparathyroidism. Curr Treat Options Oncol. 2004;5:335–345.
[23] Udelsman R. Approach to the patient with persistent or recurrent primary hyperparathyroidism. J Clin Endocrinol Metab. 2011;96:2950–2958.
[24] Alhefdhi A, Schneider DF, Sippel R, Chen H. Recurrent and persistent primary hyperparathyroidism occurs more frequently in patients with double adenomas. J Surg Res. 2014;190:198–202.
[25] Tezelman S, Shen W, Siperstein AE, Duh QY, Clark OH. Persistent or recurrent hyperparathyroidism in patients with double adenomas. Surgery. 1995;118:1115–1122.

Dimensional Accuracy of Dental Models Printed with Different Resins Using a Low-Cost LCD 3D Printer



https://doi.org/10.70921/medev.v32i1.2029

Alexandru Victor Burde[1], Marius Ciprian Manole[2*], Sorana Baciu[2], Sabina Gabriela Cretu[1], Cosmin Sinescu[3,4]

[1]Faculty of Nursing and Health Sciences, "Iuliu Haţieganu" University of Medicine and Pharmacy, 8 Victor Babes Street, 400012 Cluj-Napoca, Romania;
[2]Faculty of Dental Medicine, "Iuliu Haţieganu" University of Medicine and Pharmacy, 32 Clinicilor Street, 400394 Cluj-Napoca, Romania;
[3]Faculty of Dental Medicine, "Victor Babes" University of Medicine and Pharmacy of Timisoara, 2 Eftimie Murgu Square, 300041 Timisoara, Romania;
[4]Research Center in Dental Medicine Using Conventional and Alternative Technologies, Department of Prostheses Technology and Dental Materials, Faculty of Dental Medicine, "Victor Babes" University of Medicine and Pharmacy of Timisoara, 9 Revolutiei 1989 Ave., 300070 Timisoara, Romania

Correspondence to:
Name: Marius Ciprian Manole
E-mail address: marius.manole@umfcluj.ro

Received: 28 February 2026; Accepted: 14 March 2026; Published: 31 March 2026

Abstract

This in vitro study investigated the influence of resin formulation on the dimensional accuracy of dental models fabricated using a consumer-grade LCD 3D printer. Thirty full-arch models (n = 10 per group) were printed with three resins: Water-Washable, Ortho Model, and Study Model. All specimens were produced at 50 µm layer height and analyzed using an inEos X5 scanner and Geomagic Control 2014 software. Trueness was quantified using Root Mean Square (RMS) deviation values. One-way ANOVA revealed a significant effect of resin type ($F(2,27) = 9.53$, $p = 0.0007$). The water-washable resin showed the lowest mean RMS deviation (109.0 ± 13.8 µm). All materials remained within clinically acceptable limits (<250 µm). Resin selection influences accuracy when using consumer-grade LCD printing systems.

Keywords: 3D printing, Digital dentistry, Dental resins, Dimensional accuracy, Vat polymerization, LCD 3D printer, Digital workflow

INTRODUCTION

Vat photopolymerization (VP) is extensively employed in digital dentistry for fabricating dental models and appliances [1–3]. Among VP technologies, liquid crystal display printers solidify photopolymer resins layer-by-layer through a UV light source modulated by an LCD mask [4]. Relative to stereolithography and digital light processing printers, LCD systems deliver cost-effective performance alongside high pixel resolution and satisfactory surface finish [5].

The rapid development of consumer-grade LCD printers has led to their increasing adoption in dental practices and academic settings. These devices enable affordable in-office manufacturing and streamlined digital workflows [6]. However, despite improvements in screen resolution and light uniformity, concerns remain regarding the dimensional reliability of models produced with consumer-grade systems [7].

Dimensional accuracy is critical in dentistry, as printed models frequently serve as the basis for prosthetic restorations, orthodontic appliances, and surgical guides [8]. According to ISO standards, accuracy includes trueness and precision [9]. In vat photopolymerization systems, factors such as light distribution, exposure parameters, peel forces [10], and post-curing conditions can influence accuracy [11]. Among these variables, resin composition plays a central role. Differences in polymerization kinetics and volumetric shrinkage may affect the dimensional stability of printed objects, particularly in systems where exposure conditions are optimized for general rather than material-specific performance [12].

Although previous studies have evaluated the accuracy of professional-grade systems [13], limited evidence exists regarding resin-dependent differences when using consumer-grade LCD printers. Given the expanding clinical use of these devices, understanding how resin selection influences dimensional accuracy is important for optimizing digital workflows.

The chemical composition of photopolymer resins should be regarded as an additional determinant of dimensional accuracy in vat photopolymerization systems, alongside printer architecture and exposure-related parameters [14]. Dental printing resins are generally formulated from multifunctional methacrylate monomers and oligomers, in association with photoinitiators and auxiliary additives intended to modulate viscosity, polymerization kinetics, and the final mechanical behavior of the material. Variations in resin formulation may alter the extent of polymerization shrinkage, the resulting cross-link density, and the magnitude of internal stresses generated during sequential layer curing [15]. As a consequence, even under identical hardware settings and slicing conditions, distinct resin systems may yield different levels of dimensional trueness.

From a clinical perspective, faithful reproduction of dental anatomy remains essential for the predictability of digital workflows [16]. In orthodontics, printed models are routinely employed for treatment planning and for the fabrication of thermoformed aligners, in which even limited geometric discrepancies may influence appliance fit and the pattern of force delivery [17]. In prosthodontics and implant dentistry, inaccuracies at the model level may compromise diagnostic assessment and may further propagate through subsequent digital and laboratory stages, resulting in cumulative error [18]. Accordingly, the assessment of dimensional behavior in commonly used dental resins represents a necessary step toward the optimization of additive manufacturing workflows in dental practice. Similar concerns regarding the clinical relevance of accuracy have been emphasized in previous investigations on digital scanning and additively manufactured dental models.

Despite the growing adoption of consumer-grade LCD-based printers into dental laboratories, comparative evidence specifically addressing the effect of resin formulation on dimensional accuracy remains limited. Most currently available studies have concentrated

predominantly on printer technology [19], layer thickness [20], or post-processing conditions [21], whereas the independent contribution of material chemistry has been explored to a lesser extent. Existing work from the same field has already shown that printer type and additive manufacturing method can significantly influence the dimensional outcome of dental models [22], thereby supporting the need to isolate and investigate the resin-related component more rigorously.

Therefore, the aim of this in vitro study was to evaluate the dimensional accuracy of dental models printed with three different resins using a consumer-grade LCD 3D printer. The null hypothesis was that resin type would not significantly influence root mean square (RMS) deviation values.

Aim and objectives

The aim of this in vitro study was to evaluate the dimensional accuracy of dental models fabricated with three different resin formulations using a consumer-grade LCD 3D printer. RMS deviation values were calculated to assess trueness relative to reference STL files, and differences among resin types were compared under standardized printing and post-processing conditions. Additionally, the study aimed to determine whether all printed models remained within clinically acceptable deviation thresholds (<250 μm).

MATERIAL AND METHODS

This in vitro experimental study was designed to evaluate the influence of resin formulation on the dimensional accuracy of dental models fabricated using a consumer-grade Liquid Crystal Display (LCD) vat photopolymerization system.

A standardized reference dataset consisting of one ideal full-arch dental model in Standard Tessellation Language (STL) format was selected as the control geometry. The reference digital model was designed as hollow structure with a uniform wall thickness of 2.5 mm to optimize material consumption while maintaining mechanical stability. The same digital reference file was used for all specimens to ensure methodological standardization. A total of 30 models were fabricated and allocated into three experimental groups according to resin type (n = 10 per group): Water-Washable Dental Model Resin (WW), Dental Ortho Model Resin (OM), and Dental Study Model Resin (DS) (Phrozen Tech Co., Hsinchu City, Taiwan). All resins were manufactured by the same company as the printing system to minimize variability related to hardware–material compatibility.

Additive manufacturing was performed using a Phrozen Sonic Mini 8K S (Phrozen Tech Co., Hsinchu City, Taiwan), a consumer-grade LCD-based system equipped with an 8K monochrome display (7500 × 3240-pixel resolution). The printer operates using a 405 nm ultraviolet light source and provides an approximate native XY resolution of 22 μm, enabling high-detail reproduction of dental geometries. Prior to fabrication, the printer was calibrated according to the manufacturer's recommendations to ensure consistent platform leveling and exposure conditions.

All models were printed at a standardized layer height of 50 μm and identical horizontal build orientation. STL files were prepared using Chitubox Basic version 2.3 software. Mesh integrity was verified prior to slicing, and automatic support generation was applied uniformly across all specimens. Printing parameters specific to each resin are summarized in Table 1.

Table 1. Printing parameters for each resin group

Parameter	**Water-Washable Resin (WW)**	**Ortho Model Resin (DO)**	**Study Model Resin (DS)**
Layer height	50 µm	50 µm	50 µm
Bottom layers	6	6	6
Bottom exposure time	20 s	30 s	25 s
Normal exposure time	4.7 s	6.9 s	4.2 s
Light-off delay	2 s	2 s	2 s
Lift height	3 mm	3 mm	3 mm
Lift speed	60 mm/min	60 mm/min	50 mm/min
Anti-aliasing	Level 4	Level 4	Level 4
Shrinkage compensation (X/Y)	100.028% / 100.18%	100.042% / 100.06%	100.031% / 100.12%

The printing environment was maintained under standard laboratory conditions with an ambient temperature of approximately 22–24 °C. For each type of resin a brand new resin vat and build platform were used throughout the fabrication process, and the resin was gently mixed before each printing cycle to ensure homogeneous photopolymer composition.

Post-processing was performed according to the manufacturer's recommendations for each resin. For the Water-Washable Dental Model resin, printed objects were cleaned in an ultrasonic cleaner using clean water for 5 minutes to remove uncured resin, followed by drying in a dark environment for up to 30 minutes or immediate drying using compressed air; rubbing was avoided to prevent dimensional alteration. For the Dental Ortho Model and Dental Study Model resins, printed objects were cleaned in an ultrasonic cleaner using 95% isopropyl alcohol for 120 seconds, followed by drying under identical conditions; mechanical rubbing was avoided to preserve precision tolerances. Post-curing for all specimens was performed using a Phrozen Cure V2 unit (Phrozen Tech Co., Hsinchu City, Taiwan). Water-Washable and Ortho Model specimens were cured for 30 minutes, whereas Study Model specimens were cured for 1 minute, in accordance with manufacturer instructions.

In order to evaluate the dimensional accuracy of the resulting models, all printed models were digitized using an inEos X5 laboratory scanner (Dentsply Sirona, Bensheim, Germany). Each model was scanned under standardized acquisition settings and exported in STL format for metrological analysis.

Three-dimensional metrological evaluation was conducted using Geomagic Control 2014 software (3D Systems, Rock Hill, USA). Each scanned STL dataset was superimposed onto its corresponding reference file using a staged best-fit alignment protocol, comprising an initial alignment with 300 common points, followed by refinement with 3000 points and a final high-precision alignment using 15000 points. Surface deviation analysis was subsequently performed using the "3D Compare" module to generate color-coded deviation maps and calculate Root Mean Square (RMS) deviation values.

Statistical analysis was performed using Python (SciPy and Statsmodels libraries). Data normality was assessed using the Shapiro–Wilk test, and homogeneity of variances was evaluated using Levene's test. As assumptions were satisfied, intergroup comparisons were conducted using one-way analysis of variance (ANOVA), followed by Tukey's post-hoc testing. Effect sizes were calculated using eta-squared (η^2) and omega-squared (ω^2). Statistical significance was set at $\alpha = 0.05$.

RESULTS

A total of 30 full-arch dental models (n=10 per resin type) were successfully fabricated, post-processed, digitized, and subjected to rigorous three-dimensional surface deviation analysis. Notably, zero printing failures, structural fractures, or scanning artifacts occurred, ensuring

no specimens required exclusion and confirming the reliability of the methodology across all groups. Descriptive statistics for RMS deviation values are presented in Table 2.

Table 2. Printing parameters for each resin group

Resin	Mean ± SD (µm)	Median (µm)	IQR (µm)	Min–Max (µm)	95% CI (µm)
Water-Washable Resin (WW)	109.0 ± 13.8	108.5	25.8	91-126	99.1–118.9
Study Model Resin (DS)	124 ± 8.1	125.1	10.8	110-136	118.2-129.8
Ortho Model Resin (DO)	131 ± 11.9	130.9	19.0	112-148	122.5-139.5

The WW resin demonstrated the lowest mean RMS deviation, demonstrating superior dimensional trueness under the standardized printing conditions employed in this study. In contrast, the Study Model Resin exhibited intermediate mean RMS values with the lowest dispersion, while the Ortho Model Resin produced the highest mean RMS deviation coupled with greater variability, as demonstrated in Figure 1.

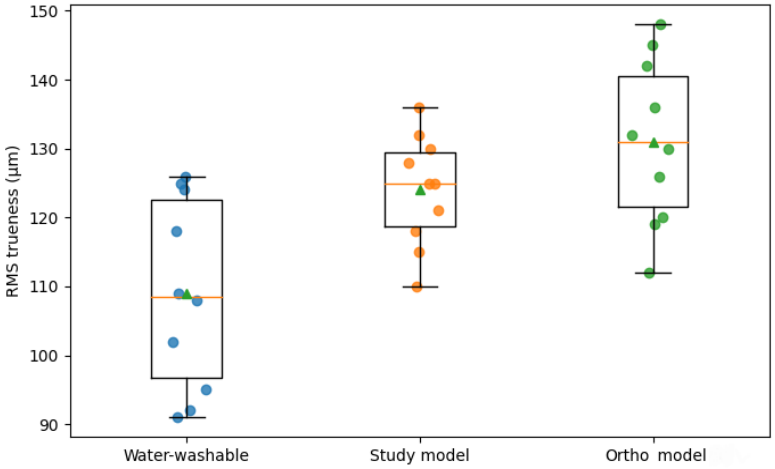


Figure 1. Comparison of RMS trueness among the three resin groups

Assessment of normality was performed using the Shapiro–Wilk test for each resin group. No statistically significant deviations from normal distribution were detected ($p > 0.05$ for all groups), indicating that the assumption of normality was satisfied. Visual inspection of the corresponding Q–Q plots (Figure 2) demonstrated that data points closely followed the theoretical reference line, with only minor deviations at the distribution tails, further supporting approximate normality of RMS values.

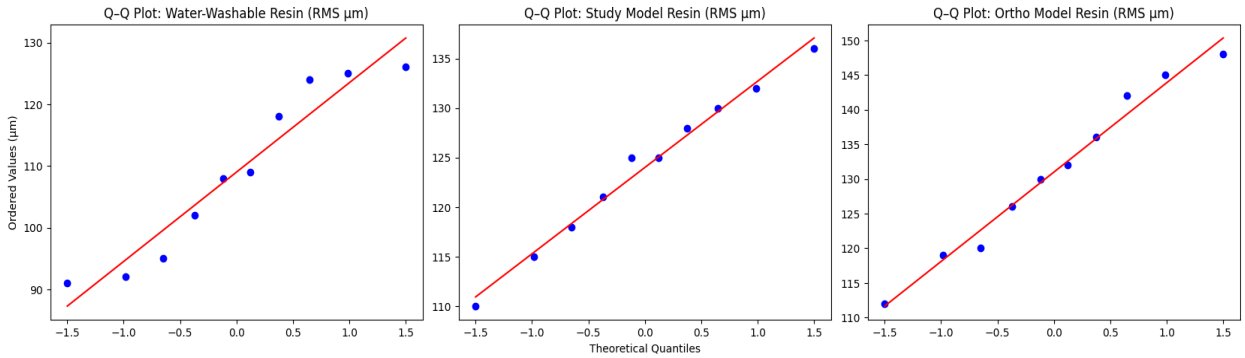


Figure 2. Q–Q plots illustrating the distribution of RMS deviation values for each resin group

Homogeneity of variances was evaluated using Levene's test, which did not reveal significant differences in variance among groups (p = 0.167). These findings confirmed that the assumptions required for parametric one-way ANOVA were met.

One-way ANOVA demonstrated a statistically significant effect of resin type on dimensional trueness (F (2,27) = 9.53, p = 0.0007), indicating that mean RMS values differed among the evaluated materials. The magnitude of this effect was substantial, as reflected by a large effect size (η^2 = 0.41; ω^2 = 0.36). These values indicate that approximately 41% of the total variability in RMS deviation measurements can be attributed to differences in resin formulation rather than random variation.

Post-hoc Tukey analysis revealed that the Water-Washable Resin exhibited significantly lower RMS values compared with the Ortho Model Resin (mean difference 22 µm; p = 0.0006) and the Study Model Resin (mean difference 15 µm; p = 0.0188). No statistically significant difference was identified between the Ortho and Study Model resins (p = 0.376).

Representative three-dimensional color-coded deviation maps were generated for each resin group to illustrate the spatial distribution of surface discrepancies relative to the reference model, as seen in Figure 3.

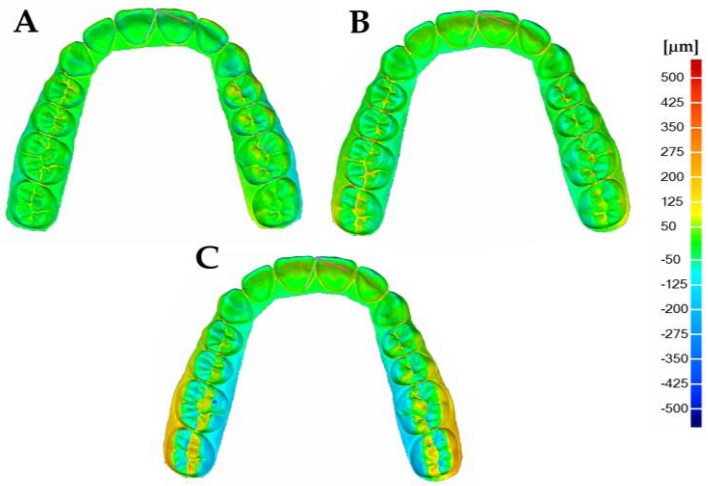


Figure 3. Representative color-coded deviation maps illustrating three-dimensional surface discrepancies relative to the reference STL model. (A) Water-Washable Dental Model Resin; (B) Study Model Resin; (C) Ortho Model Resin

All groups predominantly showed green areas within the predefined tolerance range; however, localized deviations were more evident in the Study and Ortho Model resins compared with the more homogeneous pattern observed in the Water-Washable group.

DISCUSSIONS

The present in-vitro study evaluated the influence of resin formulation on the dimensional accuracy of dental models fabricated using a consumer-grade LCD vat photopolymerization system. The results demonstrated that resin type significantly affected RMS trueness values, leading to rejection of the null hypothesis. Although all tested materials produced models within clinically acceptable limits (<250 µm) [23], statistically significant differences were observed among groups.

The Water-Washable Dental Model Resin exhibited the lowest mean RMS deviation, followed by the Study Model Resin, while the Ortho Model Resin demonstrated the highest deviations. The magnitude of the effect (η^2 = 0.41) indicates that resin formulation accounted

for a substantial proportion of the observed variability. These findings suggest that, even when using the same printer, identical build orientation, standardized layer thickness (50 μm), and manufacturer-matched materials, resin chemistry remains a decisive factor influencing dimensional trueness.

In vat photopolymerization systems, dimensional deviations are primarily influenced by polymerization shrinkage, light scattering behavior, and interlayer curing dynamics [24,25]. Differences in monomer composition, cross-link density, viscosity, and photoinitiator systems affect polymerization kinetics and volumetric contraction during curing [26]. Resins with faster polymerization rates or higher cross-link density may generate increased internal stresses, potentially contributing to distortion. Conversely, formulations optimized for dimensional stability may exhibit reduced shrinkage and more uniform curing behavior [27]. The superior performance of the water-washable resin under the present conditions may be attributed to differences in shrinkage compensation and polymer network formation during layer-by-layer curing.

It is also important to consider the interaction between exposure parameters and resin formulation. Although layer height and printer hardware were standardized, normal exposure times differed between groups according to manufacturer-recommended profiles. Longer exposure times, such as those used for the Ortho Model Resin, may increase overcuring at layer interfaces, potentially affecting dimensional fidelity. In consumer-grade LCD systems, where exposure calibration is less dynamically regulated than in medical-grade 3D printers, such material–parameter interactions may become more pronounced.

Despite statistically significant differences, all groups remained well below the commonly accepted clinical threshold of 250 μm for dental model fabrication. From a clinical perspective, the magnitude of intergroup differences (15–22 μm) may be considered modest; however, in workflows requiring high precision, such as fixed prosthodontics, small deviations can accumulate across digital steps. Therefore, resin selection may represent a relevant optimization parameter in digital dental workflows.

The present findings align with previous investigations reporting that material-dependent factors influence the accuracy of additively manufactured dental models. While many studies focus primarily on printer technology or layer thickness, the current results emphasize that material formulation alone can significantly affect trueness outcomes, within the same manufacturer ecosystem.

Several limitations must be acknowledged. First, the study evaluated only trueness (RMS deviation) and did not assess precision through repeated-print variability analysis. Second, only one printer model and one set of exposure parameters per resin were investigated. Third, environmental factors such as ambient temperature and resin aging were not systematically controlled beyond standard laboratory conditions.

In addition, it should be acknowledged that the present investigation was conducted using a single consumer-grade LCD printer platform. In vat photopolymerization systems, dimensional accuracy may also be affected by hardware-specific variables, including pixel size, light distribution across the LCD panel, peel mechanics during layer separation, and firmware-controlled exposure strategies [28]. Therefore, although the present findings emphasize the role of resin formulation, the absolute RMS values reported in this study should not be interpreted as universally transferable to all printing systems, as different printer architectures, light sources, and slicing environments may yield different outcomes.

Another factor that may influence dimensional behavior is the post-processing workflow. Cleaning procedures, solvent interaction, and post-curing protocols may alter the final degree of polymerization and, consequently, introduce additional dimensional changes [11]. In the present study, standardized cleaning and post-curing procedures were applied to all specimens in an attempt to minimize procedural variability. Nevertheless, differences in

post-processing conditions may affect the dimensional stability of photopolymer materials and should be taken into account when comparing findings across studies.

From a clinical perspective, the results of the present study support the use of consumer-grade LCD printers for the fabrication of dental models intended for diagnostic and orthodontic applications. All tested resins produced deviations well below the 250 µm threshold frequently regarded as clinically acceptable for dental models [29]. Such a level of accuracy is generally adequate for applications including study casts, orthodontic appliance planning, and thermoforming procedures. However, in workflows that demand a higher level of precision, such as the fabrication of prosthodontic restorations or implant-supported frameworks, cumulative errors arising along the digital chain may become clinically relevant. In these situations, optimization of both material selection and printing parameters becomes particularly important.

It should also be noted that the present analysis was conducted using a single model geometry and a limited number of specimens per group. Although the standardized model allows controlled comparison between materials, it may not fully reproduce the geometric complexity encountered in clinical dental arches. More complex anatomical structures may present additional challenges related to support placement, layer orientation, and localized polymerization behavior.

Future research should further investigate the interaction between resin formulation, exposure parameters, and printer architecture in order to clarify the mechanisms underlying dimensional deviations in LCD vat photopolymerization systems. Studies involving multiple printer platforms, larger sample sizes, and repeated-print precision analyses would provide a more comprehensive understanding of the reproducibility and generalizability of these findings within clinical digital dentistry workflows.

CONCLUSIONS

Within the limitations of this in vitro study, resin formulation significantly influenced the dimensional accuracy of dental models printed using a consumer-grade LCD 3D printer. Although all materials achieved clinically acceptable trueness, the water-washable resin demonstrated superior dimensional performance under standardized conditions. These findings highlight the importance of material selection when implementing consumer-grade vat photopolymerization systems in the digital dental workflow.

Conflicts of Interest

The authors declare no conflict of interest.

REFERENCES

[1] Nulty A. A comparison of trueness and precision of 12 3D printers used in dentistry. BDJ Open. 2022 May 26;8(1):14.

[2] Bud E, Bocăneț V, Muntean MH, Vlasa A, Bucur SM, Păcurar M, et al. Accuracy of Three-Dimensional (3D) Printed Dental Digital Models Generated with Three Types of Resin Polymers by Extra-Oral Optical Scanning. Journal of Clinical Medicine. 2021 Apr 28;10(9):1908.

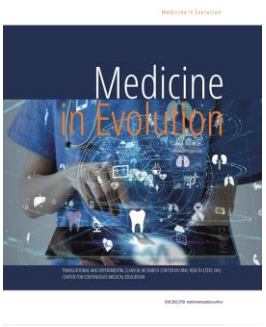
[3] Arnold C, Riß L, Hey J, Schweyen R. Dimensional Accuracy of Different Three-Dimensional Printing Models as a Function of Varying the Printing Parameters. Materials. 2024 Jul 22;17(14):3616.

[4] Caussin É, Moussally C, Goff SL, Fasham T, Troizier-Cheyne M, Tapie L, et al. Vat Photopolymerization 3D Printing in Dentistry: A Comprehensive Review of Actual Popular Technologies. Materials. 2024;17(4):950.

[5] Narongdej P, Hassanpour M, Alterman N, Rawlins-Buchanan F, Barjasteh E. Advancements in Clear Aligner Fabrication: A Comprehensive Review of Direct-3D Printing Technologies. Polymers. 2024 Jan 29;16(3):371.
[6] Oğuz F, Bor S. An Evaluation of the Performance of Low-Cost Resin Printers in Orthodontics. Biomimetics. 2025 Apr 18;10(4):249.
[7] Tsolakis IA, Papaioannou W, Papadopoulou E, Dalampira M, Tsolakis AI. Comparison in Terms of Accuracy between DLP and LCD Printing Technology for Dental Model Printing. Dentistry Journal. 2022 Sep 28;10(10):181.
[8] Arcas LPB, Tribst JPM, Baroudi K, Amaral M, Silva-Concílio LR, Vitti RP. Dimensional Accuracy Comparison of Physical Models Generated by Digital Impression/3D-Printing or Analog Impression/Plaster Methods. Int J Odontostomatol. 2021 Sep 1;15(3):562.
[9] Falih MY, Majeed MA. Trueness and Precision of Eight Intraoral Scanners with Different Finishing Line Designs: A Comparative In Vitro Study. European Journal of Dentistry. 2022 Dec 13;17(4):1056.
[10] Lipkowitz G, Saccone MA, Panzer MA, Coates IA, Hsiao K, Ilyn D, et al. Growing three-dimensional objects with light. Proceedings of the National Academy of Sciences. 2024 Jul 1;121(28):e2321231121.
[11] Morali A, Lyros I, Plakias S, Scuzzo G, Tsolakis IA. Influence of Different Post-Processing Procedures on the Accuracy of 3D Printed Dental Models Using Vat Polymerization: A Systematic Review. Applied Sciences. 2025 Oct 16;15(20):11123.
[12] Yüceer ÖM, Öztürk EK, Çiçek ES, Aktaş N, Güngör MB. Three-Dimensional-Printed Photopolymer Resin Materials: A Narrative Review on Their Production Techniques and Applications in Dentistry. Polymers. 2025 Jan 24;17(3):316.
[13] Tsolakis IA, Lyros I, Christopoulou I, Tsolakis AI, Papadopoulos MA. Comparing the accuracy of 3 different liquid crystal display printers for dental model printing. American Journal of Orthodontics and Dentofacial Orthopedics. 2024 Apr 22;166(1):7.
[14] Schittecatte L, Geertsen V, Bonamy D, Nguyen TT, Guénoun P. From resin formulation and process parameters to the final mechanical properties of 3D printed acrylate materials. MRS Communications. 2023;13(2):357–377.
[15] Hata K, Ikeda H, Nagamatsu Y, Masaki C, Hosokawa R, Shimizu H. Development of Dental Poly(methyl methacrylate)-Based Resin for Stereolithography Additive Manufacturing. Polymers. 2021; 13(24):4435.
[16] Soni M, Soni P, Soni P, Chokhandre S, Moni M, Gupta S. The Role of Digital Workflow in Customizing the Prosthetic Solutions: A Literature Review. J Pharm Bioallied Sci. 2025;17(Suppl 2):S1095-S1097.
[17] Dubey S, Prasad Dash B, Mohanty B, Jena S, Sahoo N, Singh S. 3D printing in orthodontics - Past, present and future: A systematic review and meta-analysis. Bioinformation. 2025;21(6):1766-1774.
[18] Chen HT, Feng SW, Vo TTT, Wang YL, Fan FY, Lee IT. Cumulative Error in Digital Workflows for Full-Arch Implant Rehabilitation: A Narrative Review. Bioengineering (Basel). 2026;13(2):219.
[19] Kim JH, Pinhata-Baptista OH, Ayres AP, da Silva RLB, Lima JF, Urbano GS, No-Cortes J, Vasques MT, Cortes ARG. Accuracy Comparison among 3D-Printing Technologies to Produce Dental Models. Applied Sciences. 2022; 12(17):8425.
[20] Ahn J-H, Choi J-W. The Influence of the Internal Design and Layer Thickness on the Accuracy of 3D-Printed Dental Models. Materials. 2025; 18(17):4173.
[21] Piedra-Cascón W, Krishnamurthy VR, Att W, Revilla-León M. 3D printing parameters, supporting structures, slicing, and post-processing procedures of vat-polymerization additive manufacturing technologies: A narrative review. J Dent. 2021;109:103630.
[22] Hassanpour M, Narongdej P, Alterman N, Moghtadernejad S, Barjasteh E. Effects of Post-Processing Parameters on 3D-Printed Dental Appliances: A Review. Polymers. 2024; 16(19):2795..
[23] Németh A, Vitai V, Czumbel LM, Szabó B, Varga G, Kerémi B, et al. Clear guidance to select the most accurate technologies for 3D printing dental models – A network meta-analysis. Journal of Dentistry. 2023 Apr 28;134:104532.

[24] Pruksawan S, Chong YT, Zhao Y, Sivaraja VK, Ngo ACY, Jin P, et al. Minimizing Polymer Curl Distortion and Heat Impact to Improve Digital Light Processing Printing Accuracy via Subdivision Method. Advanced Engineering Materials. 2024 Nov 8;26(24).
[25] Ahmadi M, Ehrmann K, Koch T, Liska R, Stampfl J. From Unregulated Networks to Designed Microstructures: Introducing Heterogeneity at Different Length Scales in Photopolymers for Additive Manufacturing. Chemical Reviews. 2024 Mar 28;124(7):3978.
[26] Ahn D, Stevens LM, Zhou K, Page ZA. Additives for Ambient 3D Printing with Visible Light. Advanced Materials. 2021 Sep 14;33(44).
[27] Chaudhary R, Akbari R, Antonini C. Rational Design and Characterization of Materials for Optimized Additive Manufacturing by Digital Light Processing. Polymers. 2023 Jan 6;15(2):287.
[28] Guven E, Karpat Y, Cakmakci M. Improving the dimensional accuracy of micro parts 3D printed with projection-based continuous vat photopolymerization using a model-based grayscale optimization method. Addit Manuf. 2022;57:102954.
[29] Kim SY, Shin YS, Jung HD, Hwang CJ, Baik HS, Cha JY. Precision and trueness of dental models manufactured with different 3-dimensional printing techniques. Am J Orthod Dentofacial Orthop. 2018;153(1):144-153.

The Effect of Nozzle Diameter on the Dimensional Accuracy of FDM-Printed Dental Models



https://doi.org/10.70921/medev.v32i1.2030

Marius Ciprian Manole[1], Alexandru Victor Burde[2*], Alexandru Grecu[1], Mihaela Hedeşiu[1], Cosmin Sinescu[3,4]

[1]Faculty of Dental Medicine, "Iuliu Haţieganu" University of Medicine and Pharmacy, 32 Clinicilor Street, 400394 Cluj-Napoca, Romania
[2]Faculty of Nursing and Health Sciences, "Iuliu Haţieganu" University of Medicine and Pharmacy, 8 Victor Babes Street, 400012 Cluj-Napoca, Romania;
[3]Faculty of Dental Medicine, "Victor Babes" University of Medicine and Pharmacy of Timisoara, 2 Eftimie Murgu Square, 300041 Timisoara, Romania;
4Research Center in Dental Medicine Using Conventional and Alternative Technologies, Department of Prostheses Technology and Dental Materials, Faculty of Dental Medicine, "Victor Babes" University of Medicine and Pharmacy of Timisoara, 9 Revolutiei 1989 Ave., 300070 Timisoara, Romania

Correspondence to:
Name: Alexandru Victor Burde
E-mail address: burde.alexandru@umfcluj.ro

Received: 06 March 2026; Accepted: 11 March 2026; Published: 31 March 2026

Abstract

Additive manufacturing has become an integral component of the digital workflow in dentistry. Among available technologies, fused deposition modeling (FDM) offers a cost-effective alternative for producing dental models, although concerns remain regarding dimensional accuracy. The aim of this study was to evaluate the influence of nozzle diameter and dental arch morphology on the dimensional accuracy of FDM-printed dental models. Reference STL datasets representing ideal maxillary and mandibular arches were printed using a Bambu Lab X1 Carbon printer with two nozzle diameters (0.2 mm and 0.4 mm) in a 2 × 2 factorial design (n = 40). Dimensional accuracy was assessed using Root Mean Square (RMS) deviation obtained through 3D surface comparison. Models printed with the 0.2 mm nozzle demonstrated significantly lower RMS deviations compared with those printed using the 0.4 mm nozzle. Additionally, mandibular models exhibited higher dimensional stability than maxillary models. These findings indicate that smaller nozzle diameters can improve the accuracy of FDM-printed dental models.

Keywords: Fused Deposition Modeling, Additive Manufacturing, Dental Models, Dimensional Accuracy, Nozzle Diameter, Digital Dentistry, 3D Printing

INTRODUCTION

The transition toward the concept of Dentistry 4.0 has positioned additive manufacturing (AM) as a central component of the contemporary digital workflow in dentistry and dental technology [1]. Through the conversion of conventional impressions into high-resolution digital datasets, AM enables the rapid fabrication of complex dental geometries that would be difficult or time-consuming to obtain using traditional subtractive manufacturing methods [2]. Within the clinical dental practice, vat polymerization technologies such as stereolithography (SLA) and digital light processing (DLP) have been widely adopted due to their high surface quality and micron-level resolution [3,4]. However, the relatively high cost of proprietary photopolymer resins and the requirement for post-processing using chemical solvents have stimulated interest in more accessible and cost-effective manufacturing alternatives [5].

In this context, fused deposition modelling (FDM), also referred to as fused filament fabrication (FFF), has gained increasing attention within the dental field [6]. This technology offers several advantages, including lower equipment costs, a broad range of thermoplastic materials such as PLA, PETG, or PEEK, and a production workflow that does not involve liquid resins or chemical post-processing steps [7]. Nevertheless, the use of FDM for dental restorations remains limited due to concerns related to dimensional accuracy and structural anisotropy of the printed components [8]. Common limitations include the staircase effect on inclined surfaces, volumetric shrinkage during cooling, and reduced interlayer adhesion, all of which may negatively influence the precision required in dental applications [9]. Despite these limitations, FDM technology has demonstrated promising potential for the fabrication of dental study models, orthodontic aligner templates, and diagnostic casts [10]. In such applications, dimensional accuracy of the printed arch is essential, as even minor deviations may compromise the fit of vacuum-formed appliances or affect the interpretation of occlusal relationships. Consequently, recent studies have focused on the optimization of printing parameters in order to improve the accuracy of FDM-produced dental models, with nozzle diameter emerging as a critical factor [11].

The nozzle diameter represents the primary parameter governing the extrusion width of the deposited filament and therefore determines the minimum feature size achievable during printing [12]. While the standard 0.4 mm nozzle is generally preferred due to its higher printing speed and reliable extrusion, it may lack the resolution required to accurately reproduce fine dental anatomical details such as occlusal grooves or preparation margins [13]. The use of smaller nozzle diameters, such as 0.2 mm, can theoretically improve the fidelity of printed structures by reducing extrusion width and allowing a closer approximation of the digital STL geometry [14]. In addition, the interaction between nozzle diameter and the specific morphology of dental arches remains insufficiently investigated, particularly considering that the different geometries of maxillary and mandibular arches may influence thermal behaviour and cooling dynamics during the printing process. In light of these considerations, further investigation is required to clarify the influence of nozzle diameter and anatomical morphology on the dimensional accuracy of FDM-printed dental models.

Aim and objectives

The aim of this study was to evaluate the effect of nozzle diameter and arch morphology on the dimensional accuracy of dental models fabricated using fused deposition modeling (FDM) and to determine whether smaller nozzle diameters improve the trueness of printed models when compared with the standard 0.4 mm configuration.

MATERIAL AND METHODS

An in vitro experimental protocol was designed to investigate the influence of nozzle diameter and arch morphology on the dimensional accuracy of dental models manufactured using fused deposition modeling.

In order to establish the control dataset, one ideal maxillary arch and one ideal mandibular arch in STL format were selected as reference models. These represented anatomically complete and well-aligned dentitions without restorations, missing teeth, or pathological features. The reference models were characterized by regular arch morphology, complete dentition from second molar to second molar, and anatomically defined occlusal and interproximal structures typical of a standard dental arch. Such standardized geometries were selected in order to minimize anatomical variability and to allow a controlled evaluation of the influence of printing parameters on dimensional accuracy.This approach ensured that the observed dimensional deviations were primarily attributable to the printing parameters rather than variations in patient-specific anatomical complexity.

Printable models were generated by using dental CAD software Exocad version 3.2 (Exocad GmbH, Darmstadt, Germany). These reference models were designed in a hollow-base configuration to reduce material consumption and printing time while maintaining structural stability. A uniform base was defined and the optimal insertion axis was established to facilitate digital processing and manufacturing. Wall thickness was set to 2.5 mm to ensure adequate mechanical stability. Each model was visually inspected to verify margin integrity and correct spatial orientation before export in STL format.

Preparation for fused deposition modeling (FDM) printing was carried out using Bambu Studio software (version 2.4.0.70). The STL models were imported into the slicing software, where the printing parameters were configured prior to manufacturing. All specimens were produced using a Bambu Lab X1 Carbon 3D printer (Bambu Lab, Shenzhen, China) and Bambu PLA Basic White filament. PLA was selected as the printing material due to its widespread use in fused deposition modeling and its good dimensional stability during printing. Compared with other thermoplastics such as ABS or PETG, PLA exhibits lower thermal shrinkage, reducing the risk of warping and facilitating the fabrication of accurate dental models. However, PLA has lower thermal resistance and mechanical strength than medical-grade polymers, which may limit its use in applications requiring higher mechanical performance. The layer height was set to 0.08 mm, corresponding to the highest quality setting for both nozzle configurations evaluated in this study (0.2 mm and 0.4 mm). The number of perimeters was set to three to ensure adequate wall stability, while the seam position was configured as aligned to maintain consistent layer junction positioning during printing. The internal structure of the models was defined using a 15% gyroid infill pattern, selected for its favorable balance between mechanical stability and material efficiency. All relevant printing parameters used for the fabrication of the dental models are summarized in Table 1.

Table 1. Summary of printing parameters used in the study

Parameter	Value
Nozzle diameter	0.2 mm / 0.4 mm
Material	PLA
Layer height	0.08 mm
Initial layer height	0.10 mm
Line width	0.22 mm
Extrusion temperature	210 °C
Build plate temperature	60 °C
Cooling fan speed	70%
Outer/ **Inner** wall speed	60/150 mm/s

Infill density	15%
Infill pattern	Gyroid
Number of wall loops	4
Top shell layers	7
Bottom shell layers	5
Support structures	None
Bed adhesion	5 mm brim

After finalizing the printing parameters, the models were sliced and exported as G-code files, which were subsequently transferred to the printer for fabrication (Figure 1).

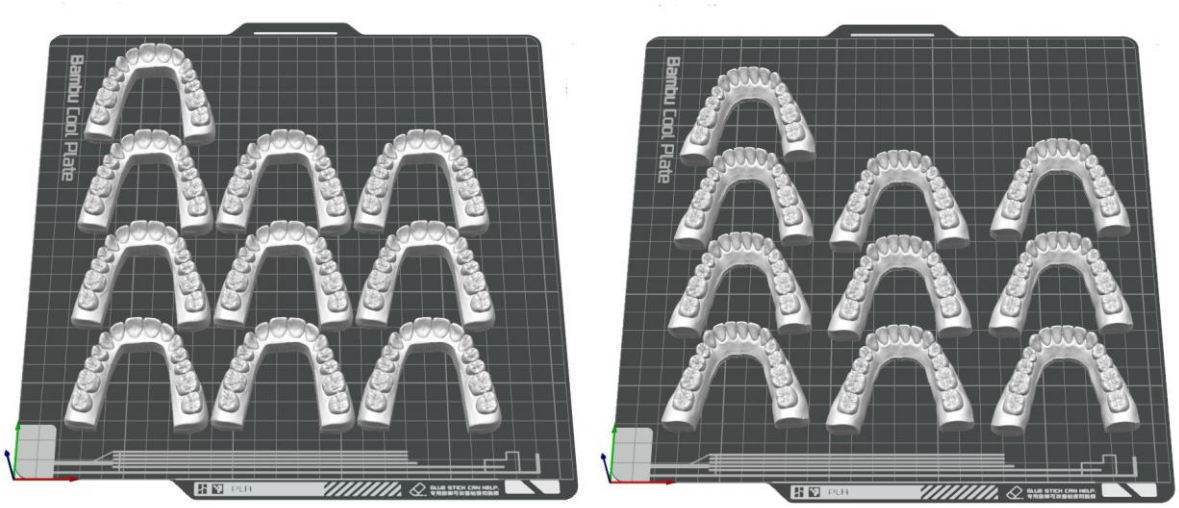


Figure 1. Build platform layout of the maxillary and mandibular models prepared for fused deposition modelling (FDM)

Before each printing session, the filament spool was mounted on the dedicated holder and the filament tip was cut at an oblique angle to facilitate insertion into the extruder. The build platform was cleaned before every printing cycle using 99.8% isopropyl alcohol (Kontakt IPA Plus, TermoPasty, Poland) applied with a non-abrasive wipe to remove dust, grease, or adhesive residues that could compromise first-layer adhesion. The printer uses a magnetic build platform with a removable flexible spring-steel plate, allowing easy removal of printed models. A smooth build plate surface was used throughout the experiment. Before each printing cycle, the printer performed an automatic calibration procedure including first-layer calibration.

The experimental design followed a 2 × 2 factorial structure, with nozzle diameter (0.2 mm and 0.4 mm) and dental arch type (maxillary and mandibular) as independent variables. Four experimental groups were generated, each group consisting of ten models (N = 40): maxilla printed with a 0.4 mm nozzle (Figure 2 A), mandible printed with a 0.4 mm nozzle (Figure 2 B), maxilla printed with a 0.2 mm nozzle, and mandible printed with a 0.2 mm nozzle. All specimens were fabricated using the same printer. Initially, the models were printed using a 0.4 mm nozzle, and after completion of the first set of specimens, the nozzle was replaced with a 0.2 mm nozzle. The nozzle replacement procedure was performed in accordance with the manufacturer's specifications.

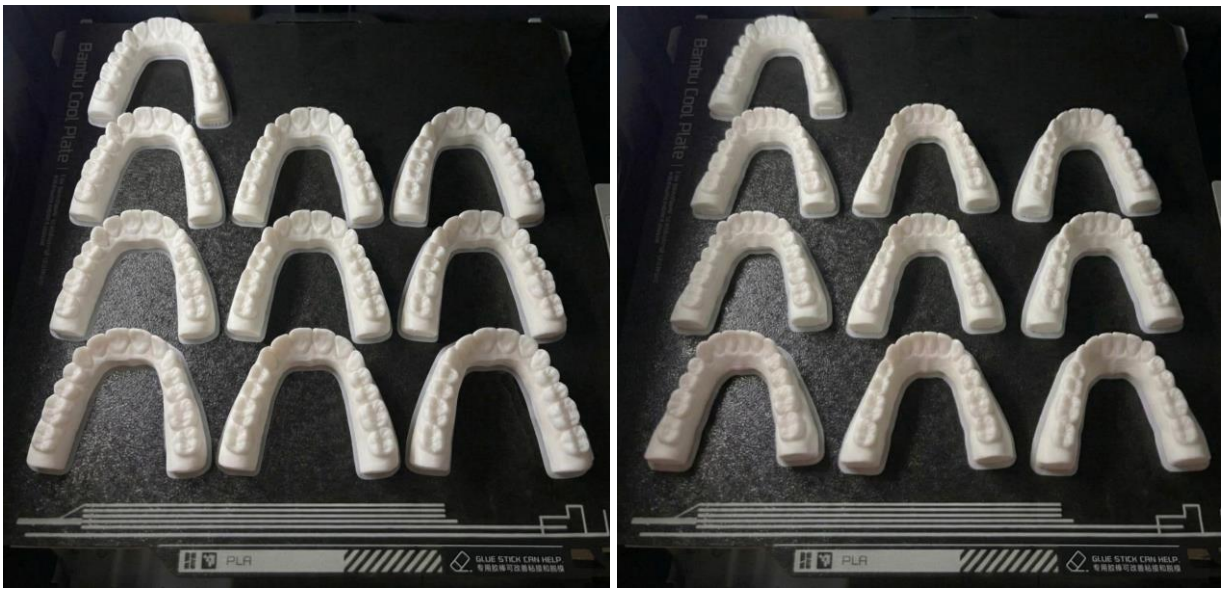


Figure 2. Printed dental models: (A-left) maxillary and (B-right) mandibular models printed with the 0.4 mm nozzle

After fabrication, all printed models were digitized using the InEos X5 laboratory scanner (Dentsply Sirona, Bensheim, Germany), a high-precision extraoral scanning system with a reported accuracy of up to 2 µm. Each model was inspected before scanning to ensure that it was complete, stable, and free of contaminants. Scanning was performed within the inLab 15 software (Dentsply Sirona, Bensheim, Germany), where a digital case was created for each specimen and assigned a unique identification number. The scanner's robotic arm captured the geometry from multiple angles, ensuring complete coverage of dental and gingival surfaces. The acquired images were automatically aligned and merged to generate the final three-dimensional digital models. Dimensional accuracy was evaluated using Geomagic Control 2014 (3D Systems, Rock Hill, USA). Reference STL models and scanned STL files were imported into the software. Initial alignment was performed using a best-fit algorithm based on 300 corresponding points. The models were then trimmed and the alignment repeated using 3000 points, followed by a final alignment using 15,000 points to ensure accurate superimposition. The models were further trimmed near the alveolar ridge while preserving the cervical margins of the teeth.

The stepwise alignment strategy was applied to progressively refine the superimposition between the reference and test models, starting with a coarse registration step and followed by higher-resolution alignments to improve the stability and convergence of the best-fit algorithm prior to deviation analysis. Trimming of the models near the alveolar ridge was performed to standardize the comparison region among all specimens and to minimize potential artifacts generated by variations in the model base geometry. Consequently, the deviation analysis focused on the dentition surfaces, which represent the clinically relevant regions for orthodontic and diagnostic applications.

Dimensional comparison was performed using the "3D Compare" function, which calculates point-to-surface deviations between the reference and test models. The deviation thresholds were defined as +1000 µm (maximum deviation), +500 µm (critical positive deviation), +50 µm (normal positive deviation), −500 µm (critical negative deviation), and −50 µm (normal negative deviation). The analysis generated color-coded deviation maps where warm colors indicate positive deviations and cool colors indicate negative deviations. Quantitative accuracy was expressed using the Root Mean Square (RMS) deviation,

representing the square root of the mean of the squared distances between corresponding points.

Statistical analysis was performed using Python (version 3.10) with the NumPy and SciPy libraries. Data normality was assessed using the Shapiro–Wilk test, while homogeneity of variances was evaluated using Levene's test. The effects of nozzle diameter and arch type on dimensional accuracy were analyzed using two-way ANOVA with RMS deviation as the dependent variable. Statistical significance was set at $p < 0.05$.

RESULTS

Quantitative analysis was performed on 40 FDM-printed dental models, comprising 20 maxillary and 20 mandibular arches. Fabrication was executed using a Bambu Lab X1 Carbon system to compare two distinct nozzle diameters (0.2 mm and 0.4 mm). Accuracy was quantified through a 3D surface comparison, where the Root Mean Square (RMS) deviation (µm) served as the primary means for assessing the trueness of the printed models relative to the corresponding reference STL dataset.

Models printed with the 0.2 mm nozzle demonstrated consistently lower RMS deviation values compared with those fabricated with the 0.4 mm nozzle, indicating improved dimensional accuracy. Descriptive statistics showed that maxillary models printed with the 0.4 mm nozzle presented the highest RMS values (mean = 128.6 ± 8.7 µm), followed by mandibular models printed with the 0.4 mm nozzle (109.3 ± 7.6 µm). In contrast, lower RMS deviations were observed for models printed with the 0.2 mm nozzle, with maxillary models presenting a mean RMS of 93.0 ± 4.1 µm and mandibular models showing the lowest values (85.7 ± 6.1 µm). The distribution of RMS values across the four experimental groups is illustrated in Figure 3.

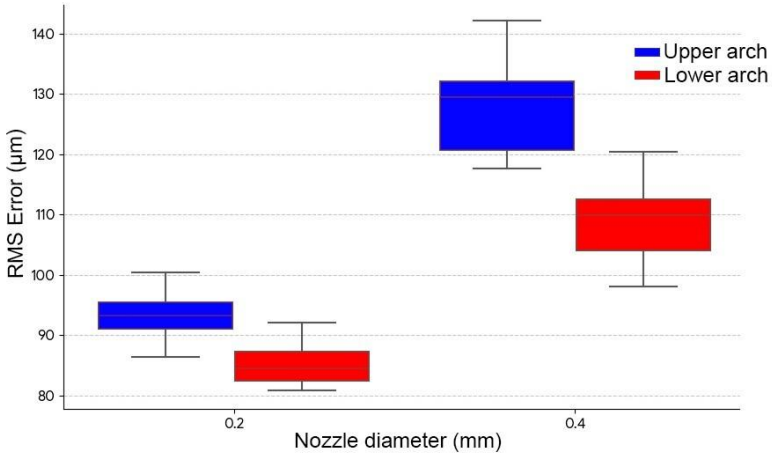


Figure 3. Comparison of Dimensional Accuracy (RMS Error) between 0.2 mm and 0.4 mm Nozzle Diameters for Maxillary and Mandibular Dental Models

The boxplot demonstrates a clear reduction in both median RMS values and dispersion for models printed with the 0.2 mm nozzle, suggesting improved geometric fidelity. Maxillary models printed with the 0.4 mm nozzle exhibited the largest variability, while mandibular models printed with the 0.2 mm nozzle showed the most consistent measurements.

Prior to inferential analysis, the assumptions required for parametric testing were evaluated. The Shapiro–Wilk test was applied to assess the normality of the RMS distributions within each group. Most datasets followed a normal distribution (Maxilla–0.4

mm: $W = 0.908$, $p = 0.265$; Mandible–0.4 mm: $W = 0.951$, $p = 0.677$; Maxilla–0.2 mm: $W = 0.965$, $p = 0.841$), while a slight deviation from normality was observed for Mandible–0.2 mm ($W = 0.801$, $p = 0.015$). Given the balanced experimental design (n = 10 per group) and the robustness of ANOVA to moderate deviations from normality, parametric analysis was considered appropriate.

Homogeneity of variances was evaluated using Levene's test, which confirmed that the assumption of equal variances across groups was satisfied ($F = 1.52$, $p = 0.226$).

In order to evaluate the influence of printing parameters and anatomical morphology on dimensional accuracy, a two-way analysis of variance (ANOVA) was performed with nozzle diameter (0.2 mm vs 0.4 mm) and dental arch (maxillary vs mandibular) as independent variables and RMS deviation as the dependent variable. The analysis revealed a statistically significant main effect of nozzle diameter (F (1,36) = 187.53, $p < 0.001$), indicating that models printed with the 0.2 mm nozzle exhibited significantly lower RMS deviations than those printed with the 0.4 mm nozzle. A significant main effect of arch type was also identified (F (1,36) = 37.88, $p < 0.001$), with mandibular models demonstrating lower RMS deviations compared with maxillary models. In addition, a statistically significant interaction between nozzle diameter and arch type was observed (F (1,36) = 7.69, $p = 0.0087$), suggesting that the magnitude of the improvement in dimensional accuracy associated with the smaller nozzle differed between the two dental arches. This interaction is illustrated in Figure 4, where the reduction in RMS deviation associated with the 0.2 mm nozzle appears more pronounced for maxillary.

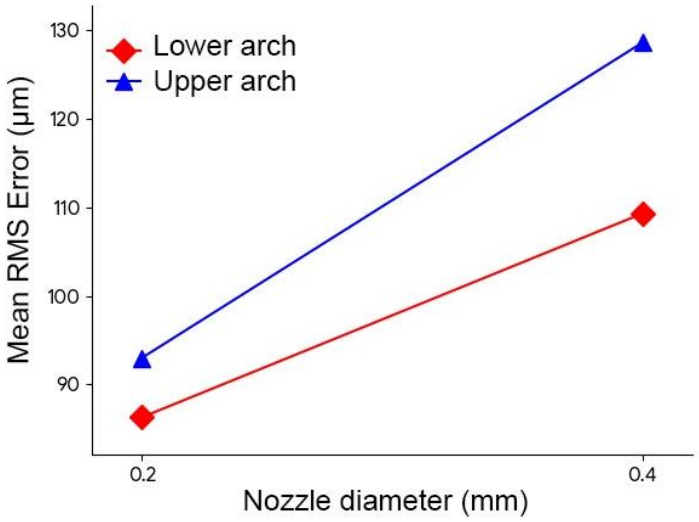


Figure 4. Interaction plot illustrating the combined effect of nozzle diameter and dental arch on RMS deviation values

To further verify the robustness of the findings, a non-parametric Kruskal–Wallis test was performed as a sensitivity analysis due to the slight deviation from normality observed in one group. The analysis confirmed a statistically significant difference in RMS deviation among the experimental groups ($p < 0.001$), supporting the results obtained from the parametric two-way ANOVA.

The color-coded deviation maps (Figure 5) illustrate the spatial distribution of dimensional differences between the printed models and the reference STL datasets. Models printed with the 0.2 mm nozzle show a more uniform deviation pattern, with larger areas within the green tolerance range (±50 µm), indicating higher trueness. In contrast, models produced with the 0.4 mm nozzle present more pronounced localized deviations, particularly on occlusal surfaces. These visual findings are consistent with the lower RMS values obtained

for the 0.2 mm nozzle and further support the statistical results indicating improved dimensional accuracy with smaller nozzle diameters.

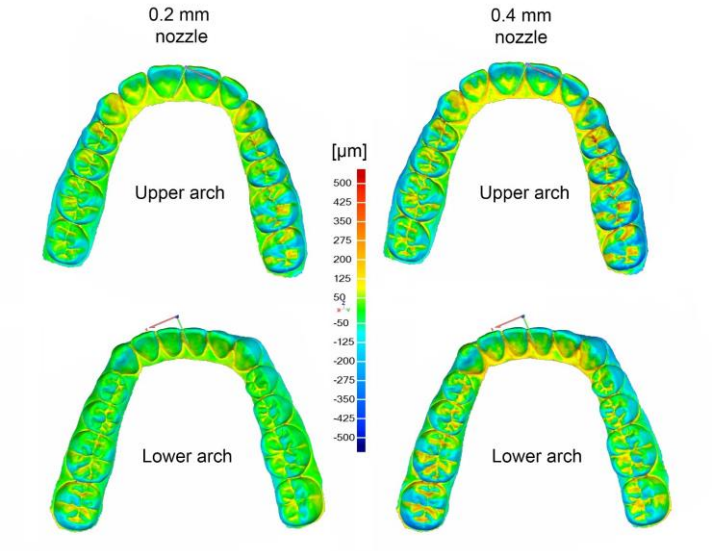


Figure 5. Color-coded deviation maps obtained from the 3D comparison analysis between the printed models and the reference STL datasets. Maxillary and mandibular arches printed with the 0.2 mm and 0.4 mm nozzles are presented. The color scale represents point-to-surface deviations in micrometers (µm), with warm colors indicating positive deviations and cool colors indicating negative deviations

Overall, the results indicate that nozzle diameter represents the primary factor influencing the dimensional accuracy of FDM-printed dental models, while the anatomical morphology of the arch also contributes to the variability observed between maxillary and mandibular models.

DISCUSSIONS

The present study evaluated the influence of nozzle diameter and arch morphology on the dimensional accuracy of dental models manufactured through fused deposition modeling (FDM) using the Bambu Lab X1 Carbon system. The results indicate that nozzle diameter represents the main determinant of printing precision, as the 0.2 mm nozzle significantly improved the trueness of printed models compared with the standard 0.4 mm configuration. In addition, mandibular models exhibited greater dimensional stability than maxillary models, an observation that may be explained by differences in anatomical volume and surface geometry between the two arch types.

The 0.2 mm nozzle produced significantly lower RMS values across all experimental groups. This finding is consistent with previous studies by Khaw et al. [2], which reported that reducing nozzle diameter decreases the staircase effect on inclined surfaces and enables a more accurate reproduction of complex dental morphologies, including occlusal anatomy and interproximal regions. Although 0.4 mm nozzles are frequently preferred in clinical workflows because of faster fabrication times and a lower risk of clogging, they resulted in a mean RMS error of 128.6 ± 8.7 µm for maxillary models in the present study. This value exceeds the clinically acceptable threshold of approximately 100 µm commonly reported for orthodontic and prosthodontic study models. In contrast, models printed with the 0.2 mm nozzle showed RMS deviations between 85.7 and 93.0 µm, placing them within the clinically acceptable range for diagnostic and treatment planning applications.

Another important finding was the significantly higher dimensional accuracy of mandibular models compared with maxillary models ($p < 0.001$). This difference may be explained by the thermal behaviour of thermoplastic filaments during the cooling phase after deposition. Maxillary models typically present a larger cross-sectional area and include a solid palatal region, which results in a greater material volume and footprint. Consequently, more thermal energy accumulates during deposition, which may influence the dimensional stability of the printed structure. As reported by Park et al. [15], larger printed volumes in FDM systems may lead to increased shrinkage and warping due to uneven cooling gradients. The statistically significant interaction between nozzle diameter and arch type ($p = 0.0087$) supports this interpretation, as the 0.2 mm nozzle produced a more pronounced improvement for maxillary models. These results suggest that higher resolution extrusion may partially compensate for the geometric complexity and volumetric shrinkage associated with larger anatomical datasets.

The use of RMS deviation as the primary accuracy metric allowed a comprehensive evaluation of trueness and precision. Boxplot analysis showed that the 0.2 mm nozzle not only improved trueness but also increased measurement consistency, as indicated by the narrowest interquartile range in the mandibular group. This higher level of reproducibility is particularly relevant in clinical workflows, where the predictability of the additive manufacturing process is considered as important as the absolute dimensional accuracy of printed models [3]. Although a slight deviation from normality was observed in one experimental group, the balanced experimental design and the homogeneity of variances confirmed by Levene's test support the robustness of the applied two-way ANOVA.

Despite the clear accuracy advantages of the 0.2 mm nozzle, this configuration presents certain practical limitations. Smaller nozzle diameters increase printing time and may also raise the likelihood of nozzle obstruction, as previously reported by Mani et al. [16]. Consequently, the choice of nozzle diameter in clinical practice must balance dimensional accuracy with manufacturing efficiency. Overall, the findings of this study provide useful guidance for optimizing FDM parameters in digital dentistry and highlight that both hardware configuration and anatomical morphology should be considered to achieve optimal manufacturing outcomes.

The frequently cited threshold of approximately 100 µm RMS for dental model accuracy should be interpreted as a practical benchmark rather than a universally established clinical cutoff. International standards such as ISO 12836 [18] define methods for evaluating trueness and precision of digital dental devices, but do not prescribe specific clinical thresholds. In prosthodontic workflows, the 100 µm value is often justified by analogy with reported marginal gap tolerances and cement film thickness values of approximately 100–120 µm [19]. However, acceptable deviations vary depending on the clinical application. For example, orthodontic digital models and aligner-related discrepancies may reach 00.30 mm without affecting treatment planning [20]. In the present study, the RMS values obtained with the 0.2 mm nozzle (85.7–93.0 µm) fall within commonly cited accuracy targets for dental models, whereas the values observed with the 0.4 mm nozzle approach the upper range of these benchmarks.

It should be noted that the present investigation was conducted using a single FDM platform, namely the Bambu Lab X1 Carbon, operating within the proprietary Bambu Studio slicing environment. As a consequence, the dimensional accuracy values obtained in this study may be influenced by several machine-specific variables, including firmware-regulated extrusion dynamics, automated calibration procedures, motion control algorithms, and the proprietary slicing strategies implemented by the manufacturer. These factors can directly affect the stability of layer deposition, the control of extrusion width, and the thermal conditions governing material solidification during the printing process.

Therefore, although the observed relationship between nozzle diameter and the dimensional accuracy of the fabricated models is likely representative of general trends within FDM technology, the absolute root mean square (RMS) deviation values reported herein should be interpreted with caution, as they may differ when alternative printers, firmware architectures, or slicing software are employed. Future investigations incorporating multiple FDM systems and a broader range of printable materials would be beneficial in order to further validate the reproducibility and generalizability of these findings within digital dental manufacturing workflows.

The present study has several other limitations, as the experiments were performed using a single a single thermoplastic material, which may restrict the generalizability of the findings to other materials commonly used in FDM printing. In addition, dimensional accuracy was evaluated through surface-based deviation analysis using RMS values derived from digital model comparison. Although this approach reflects geometric trueness, it does not directly assess the clinical fit of fabricated appliances. Potential sources of manufacturing error related to toolpath generation and G-code execution, previously reported in additive manufacturing research such as the work of Beyer et al. [17], were also not investigated. Finally, only two nozzle diameters were included, and future studies should examine a wider range of extrusion parameters and printing platforms to further optimize FDM workflows for dental model fabrication.

CONCLUSIONS

Within the limitations of this study, nozzle diameter significantly influenced the dimensional accuracy of dental models produced through fused deposition modelling. Models printed with the 0.2 mm nozzle exhibited significantly lower RMS deviations and improved trueness compared with those fabricated using the 0.4 mm nozzle. In addition, mandibular models demonstrated greater dimensional stability than maxillary models, likely due to differences in anatomical geometry and material distribution during the printing and cooling process. These findings indicate that the use of smaller nozzle diameters may improve the curacy of FDM printed dental models, particularly in situations where high precision is required for diagnostic or orthodontic applications.

Funding

This research was funded by the National Recovery and Resilience Plan (PNRR), project PNRRIII-C9-2023-I8 “Technologically Enabled Advancements in Dental Medicine (TEAM)”, Contract No. CF 80/31.07.2023, Project No. 760235/28.12.2023.

Acknowledgments

This study was supported by project PNRRIII-C9-2023-I8, "Technologically Enabled Advancements in Dental Medicine (TEAM)", CF. 80/31.07.2023, number 760235/28.12.2023. The authors used ChatGPT, an AI language model developed by OpenAI, exclusively to improve the manuscript’s language and readability. All the scientific content, interpretations, and conclusions are the original work of the authors.

Conflicts of Interest

The authors declare no conflict of interest.

Author Contributions

Conceptualization, M.C.M. and A.V.B.; Methodology, M.C.M., A.V.B. and A.G.; Software, M.C.M.; Validation, M.C.M., A.V.B. and M.H.; Formal analysis, M.C.M. and A.V.B.;

Investigation, M.C.M. and A.G.; Resources, M.H. and C.S.; Data curation, M.C.M. and A.V.B.; Writing—original draft preparation, M.C.M. and A.V.B.; Writing—review and editing, A.V.B., M.H. and C.S.; Visualization, M.C.M.; Supervision, A.V.B. and C.S.; Project administration, A.V.B. All authors have read and agreed to the published version of the manuscript.

Ethics Statement

This study was conducted in vitro and did not involve human participants, human-derived materials, or animal subjects. Therefore, ethical approval was not required.

REFERENCES

[1] Etemad-Shahidi Y, Qallandar OB, Evenden J, Alifui-Segbaya F, Ahmed KE. Accuracy of 3-dimensionally printed full-arch dental models: a systematic review. J Clin Med. 2020;9(10):3357.

[2] Khaw S, Liu X, Cameron A, Aarts J, Choi JJE. Factors influencing the dimensional accuracy of additively manufactured dental models: A systematic review of in vitro studies. J Mech Behav Biomed Mater. 2023;146:106057.

[3] Kim SY, Shin YS, Jung HD, Hwang CJ, Baik HS, Cha JY. Precision and trueness of dental models manufactured with different 3-dimensional printing techniques. Am J Orthod Dentofacial Orthop. 2018 Jan;153(1):144–53.

[4] Beyer M, Scheller L, Burde AV, Abazi S, Sommacal A, Seifert L, Sharma N, Thieringer FM. Comparative evaluation of sla and dlp 3d printing in dental implant guides: impact on fabrication accuracy, speed, and resin usage. Dent J. 2025;13(10):471.

[5] Alharbi N, Wismeijer D, Osman R. Additive manufacturing techniques in prosthodontics: where do we currently stand? A critical review. Int J Prosthodont. 2017;30(5):474–84.

[6] Jeong M, Radomski K, Lopez D, Liu JT, Lee JD, Lee SJ. Materials and applications of 3d printing technology in dentistry: an overview. Dent J. 2023;12(1):1.

[7] Borthakur PP, Sahariah JJ, Sarma M, Das A, Pathak K, Ahmad MZ, et al. Advances in 3D printing for dentistry: clinical applications and future perspectives. Explor Med. 2025;6:1001374.

[8] Ben Said L, Ayadi B, Alharbi S, Dammak F. Recent advances in additive manufacturing: a review of current developments and future directions. Machines. 2025; 13(9):813.

[9] Batu T, Lemu HG, Shimels HG, Zebenay M. Process parameter modelling and optimization techniques applied to fused deposition modelling: A review. IOP Conf Ser Mater Sci Eng. 2023;1294(1):012047.

[10] Chen Y, Wei J. Application of 3D Printing Technology in Dentistry: A Review. Polymers. 2025;17(7):886.

[11] Birgani PT, Hardani H. Effect of nozzle diameter on mechanical properties and microstructure of fused deposition modeling 3D printed polylactic acid parts. ResearchSquare [Preprint]. 2025.

[12] Ferretti P, Leon-Cardenas C, Santi GM, Sali M, Ciotti E, Frizziero L, et al. Relationship between FDM 3D printing parameters study: parameter optimization for lower defects. Polymers. 2021;13(13):2190.

[13] Tayyab M, Tanveer MQ, Singari RM, Sathikh PM. Effect of nozzle diameter on the physical behavior of fdm-printed part: an experimental study. In: Yadav S, Shrivastava Y, Rab S, editors. Recent Advances in mechanical engineering. Singapore: Springer Nature Singapore; 2024. p. 489–500.

[14] Czyżewski P, Marciniak D, Nowinka B, Borowiak M, Bieliński M. Influence of extruder's nozzle diameter on the improvement of functional properties of 3d-printed pla products. Polymers. 2022;14(2):356.

[15] Park ME, Shin SY. Three-dimensional comparative study on the accuracy and reproducibility of dental casts fabricated by 3D printers. J Prosthet Dent. 2018;119(5):861.e1-e7.

[16] Mani M, Karthikeyan AG, Kalaiselvan K, Muthusamy P, Muruganandhan P. Optimization of FDM 3-D printer process parameters for surface roughness and mechanical properties using PLA material. Mater Today Proc. 2022;66:1926–31.

[17] Beyer M, Burde A, Roser AE, Beyer M, Abazi S, Thieringer FM. A Slicer-Independent Framework for Measuring G-Code Accuracy in Medical 3D Printing. J Imaging. 2026;12(1):25.
[18] ISO 20896-1:2019. Dentistry — Digital impression devices — Part 1: Methods for assessing accuracy. Geneva: International Organization for Standardization; 2019.
[19] Son K, Lee KB. Effect of Tooth Types on the Accuracy of Dental 3D Scanners: An In Vitro Study. Materials (Basel). 2020;13(7):1744.
[20] Hiroki Y, Sohmura T, Satoh H, Takahashi J, Takada K. Complete 3-D reconstruction of dental cast shape using perceptual grouping. IEEE Trans. Med. Imaging. 2001;20(10): 1093–1101.