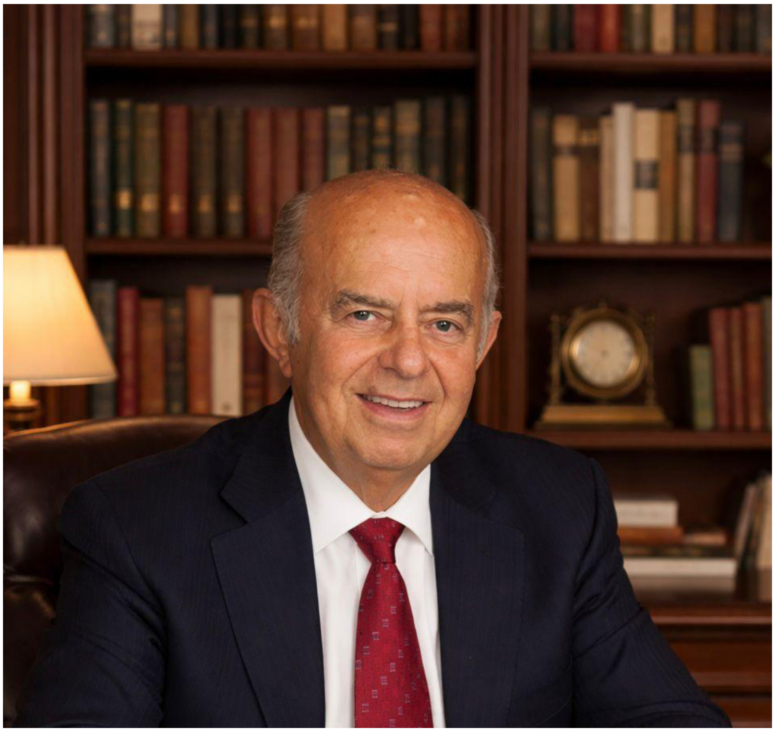
VOLUME: 11 ISSUE: 1 YEAR: 2026

TEJ TURKISH ENDODONTIC JOURNAL

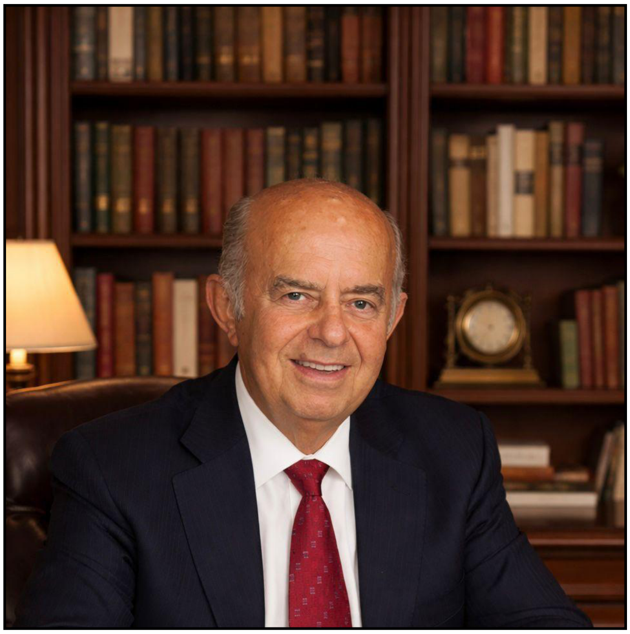
E-ISSN 2459-1726



TÜRK ENDODONTİ DERNEĞİ 1990 TURKISH ENDODONTIC SOCIETY

The official Journal of Turkish Endodontic Society

In Loving Memory of Prof. Gündüz Bayırlı



January 2026 marked not only the beginning of a new year for us, but also a time of profound sorrow and a great sense of loss following the sudden passing of our esteemed and beloved mentor, Prof. Gündüz Bayırlı, one of the most prominent figures of Endodontics in our country. After a period of health struggle, we sadly lost Professor Bayırlı on Saturday, January 3, 2026.

Words truly fall short when attempting to describe Prof. Gündüz Bayırlı. With his diligence, disciplined character, dedication to education, and paternal compassion, he was not only an academic but also a true guide in our lives. At a time when preventive dentistry was not yet widespread and the prevailing belief was that “a painful tooth should be extracted,” he introduced and established the philosophy of Endodontics which prioritizes preserving the natural tooth in our country. Through the books he authored, his lectures and conferences, and the countless students he trained, he laid the foundations for the growth and establishment of this discipline in Türkiye. In the field of endodontics, and even in the broader dentistry community, defining Prof. Gündüz Bayırlı as the “Father of Endodontics” carries great significance.

During our student years, we were first introduced to Endodontics through his books and lectures. His teaching philosophy, works, written in clear, simple, and pure Turkish, along with the numerous clinical cases he patiently followed and shared, not only inspired us to love Endodontics but also formed the basis of our desire to pursue academic careers in this field. Thanks to him, we learned the true meaning of being clinicians who preserve natural teeth rather than extract them.

At a time when there were not yet any textbooks published in Turkish in our country, the works our professor authored with great effort, written in clear, simple, and pure Turkish, became our bedside references throughout our academic journey.

Prof. Gündüz Bayırlı’s contribution to dental education was not limited to Endodontics; in addition to numerous books he wrote on the fundamental principles and clinical practices of Endodontics, he also made significant contributions to the development of Conservative Dentistry, Oral Diagnosis, and Dental Radiology through his publications in these fields.

As our professor had been a member of well-known international endodontic journals since their very first issues, he closely followed current publications and scientific advancements, and by sharing this knowledge with his students, assistants, and colleagues, he continuously kept our development dynamic.

Our Professor was not only a role model through his scientific and academic identity, but also through his perspective on life and the profession. He consistently emphasized the importance of supporting hardworking and productive individuals, the value of research grounded in scientific principles, participation in national and international scientific meetings, the significance of global academic collaboration, and the indispensable role of proper language use in scientific expression.

His often-quoted statement, “Rather than doing nothing and criticizing, I prefer to do something and be criticized,” reflects the essence of his life philosophy, a principle that many of us have adopted as a guiding rule in our professional lives.

The memorable phrases he shared with his students best reflect his educational philosophy. His words, “The pulp is like a young girl’s heart; it must be treated gently,” are not merely clinical advice, but also a symbol of the respect and delicacy required in our profession.

With his visionary leadership, Prof. Bayırlı served as the founding president of the Turkish Endodontic Society in 1990, an important scientific milestone for our country. Established under more limited conditions yet far ahead of its time, the Turkish Endodontic Society has evolved into one of the most respected Endodontic organizations worldwide. Through its congresses and international invited speakers, it continues to operate with great success. The Turkish Endodontic Association, which our professor chaired for many years, has undertaken the mission of disseminating new knowledge not only to endodontists but also to dentists interested in Endodontics, through the free monthly scientific meetings it has organized since its establishment. At the core of all these achievements lies the innovative and scientific vision of our esteemed mentor.

Our professor also played a leading role in the Turkish Endodontic Association gaining an international identity. By attending the Executive Board meeting at the 6th Congress of the European Society of Endodontology (ESE), held in London on November 11–13, 1993, he ensured that the Turkish Endodontic Association became a member of the ESE.

The 13th Congress of the ESE, for which Prof. Gündüz Bayırlı served as Congress President, was jointly organized with the Turkish Endodontic Association and held in Istanbul on September 5–8, 2007. It achieved outstanding success in terms of participation, as well as scientific and social aspects, ranking among the most successful ESE congresses organized up to that time.

Beyond his scientific identity, our Professor was also an exemplary figure in his personal life and family values. He always expressed his deep appreciation for his beloved wife, İnci Bayırlı, and his children, Burcu and Burak. The dedication pages to his family at the beginning of all his books are the most tangible reflection of the importance he placed on family. He frequently emphasized that success is built upon a healthy and happy family life, and he always treated us as his own children, offering unwavering support in every challenge we faced.

It is truly difficult to describe Prof. Gündüz Bayırlı within these lines. For more than forty years, since our student days, he has been an integral part of our lives and has played a fundamental role in shaping our professional identity and values. The clinical patient case slides he meticulously followed over the years are not only educational materials for us today, but also invaluable legacies he has left behind. One undeniable truth remains: His place can never be filled, and we will always miss him deeply. As his students, our duty is to carry forward his principles grounded in science and to pass them on to future generations.

We will always remember him with gratitude, respect, and longing. The legacy of a life devoted to science, education, and humanity will continue to live on through the students he trained and the values he instilled.

We extend our deepest condolences to our professor's family and to the entire community of Dentistry and Endodontics. May his path be illuminated, and may he rest in peace.

On behalf of the endodontic community,

PhD students of Prof. Gündüz Bayırlı,

Prof. Işıl Küçükay

Prof. Jale Tanalp

e-ISSN 2459-1726

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INFORMATION FOR THE AUTHORS

1. Aims and Scope

Turkish Endodontic Journal (TEJ) is the official scientific publication of Turkish Endodontic Society and open access, peer-reviewed international journal. TEJ is published three times per year (May, August, December). The authors are invited to submit original scientific articles, case reports, review articles regarding endodontology and dental traumatology. Letter to the Editor section is also available for authors to write a comment letter on a previously published article in the journal.

TEJ does not charge authors or authors' institutions to submit, process or publish articles. There is no fee for extra pages or color images.

2. Editorial Policies and Ethical Considerations

The acceptance criteria for all articles are the article's quality, originality and its significance to our readership. Except where otherwise stated, manuscripts are peer-reviewed by two anonymous reviewers and the Editor. The final decision is given by the Editorial Board, which reserves the right to refuse any material for publication.

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Authorship

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(1) Substantial contributions to the conception or design of the work; or the acquisition, analysis, or interpretation of data for the work;

(2) Drafting the work or revising it critically for important intellectual content;

(3) Final approval of the version to be published;

(4) Agreement to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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Authors should take collective responsibility for their work and the content of their publications. Corresponding author should submit Authors Contribution Form before proceeding with further submission and evaluation processes.

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Standards

All submissions should comply with the ICMJE Uniform requirements. Submission of checklists and flow charts of Preferred Reporting Items for Study Designs in Endodontics (PRIDE) requirements are mandatory before proceeding the article processing for case reports (PRICE), animal studies (PRIASE), randomised clinical trials (PRIRATE), laboratory studies (PRILE). Systematic reviews and meta analysis should comply with Transparent reporting of systematic reviews and meta-analysis (PRISMA). Observational studies should comply with Strengthening the reporting of observational studies in epidemiology (STROBE). Diagnostic accuracy studies should comply with Essential Items for Reporting Diagnostic Accuracy Studies (STARD). All relevant and required checklists and flow charts can be found at: https://turkishendodonticjournal.com/Forms

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Ethical Approvals

Experimentation involving human subjects should be conducted in full accordance with the Helsinki Declaration of World Medical Association (http://www.wma.net/en/30publications/10policies/b3/index.html) and legal requirements of the country where the research had been carried out. The manuscript must include a statement indicating that informed consent was obtained from all participants. A statement confirming that the study has been reviewed and approved by an ethical or advisory board with the approval number and board name should also be included. The patient's privacy should not be violated. Identifying information such as names, initials, hospital numbers, unnecessary details in photographs should be omitted from the submission. When detailed descriptions, photographs and/or videos of faces or identifiable body parts that might permit a patient to be identified must be included in the submission, authors must obtain written informed consent for its publication from the patient or his/her parent/guardian.

Experiments on laboratory animals must comply with the Guidelines of the European Communities Council Directive 2010/63/EU and with local laws and regulations. A statement confirming that the study has been reviewed and approved by an ethical or advisory board should also be included (http://www.eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32010L0063).

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3. Submissions

Note that submission implies that the content has not been published or submitted for publication elsewhere except as a brief abstract in the proceedings of a scientific meeting or symposium. Once you have prepared your submission following the Guidelines, manuscripts should be submitted online at https://jag.journalagent.com/tej/?plng=eng.

Authors must declare any financial support or relationships that may pose a conflict of interest (see 'Disclosure Statement' above).

Two mandatory word-files prepared using Microsoft Word need to be included upon submission: A title page, the main text file that includes all parts of the text in the sequence indicated in the section 'Parts of the manuscript', including figure legends but the tables and figures should be supplied separately. The main text file should be prepared using Microsoft Word, double-spaced and should not contain author name(s), affiliation(s) or information(s) regarding their identity to ensure blind review.

Each figure should be supplied as a separate file, with the figure number incorporated in the file name. For submission, figures with 300 d.p.i. saved as .jpg or .bmp files should be uploaded.

The submission system will prompt you to use an ORCiD (a unique author identifier) to help distinguish your work from that of other researchers.

An optional cover letter may be included; the text can be entered directly into the field "Message to the Editor" or uploaded as a separate file.

Submission Forms

Authors who are willing to submit their manuscripts to TEJ are required to complete and sign the Copyright Transfer Form. Please send these forms electronically when submitting your manuscript. Article evaluation process cannot be started until all documents are received.

4. Manuscript Categories and Requirements

Original Research - reports of new research findings or conceptual analyses that make a significant contribution to the current knowledge (3500 word limit). The relevant checklist must be provided in the submission documents.

Literature Reviews - critical reviews of the literature, including systematic reviews and meta-analyses (5000 word limit).

Case Reports / Series – reports of the diagnosis and/or the management of patient(s) with unusual observations of novel cases, diseases, therapeutic approaches with significant contribution to knowledge (3000 word limit). Case reports / series should be reported in full accordance with the guidelines of PRIDE. The PRICE checklist must be provided in the submission documents.

Letters to the Editor - are welcomed (1000 word limit).

Clinical Trials

Randomized controlled clinical trials should be reported in full accordance with the guidelines of PRIDE. The PRIRATE checklist must be provided in the submission documents. Following free public clinical registries can be used to register clinical trials. Registration number and project name will be published in the article.

Systematic reviews & meta analysis – should comply with Transparent reporting of systematic reviews and meta-analysis (PRISMA) (6000 word limit). The PRISMA checklist must be provided in the submission documents.

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Manuscripts reporting protein or DNA sequences and crystallographic structure should provide Genbank or Brookhaven Protein Data Bank accession numbers, respectively.

5. Manuscript preparation

Language

Authors should write their manuscripts in US English. Spelling and phrasing should conform to standard usage and be consistent throughout the paper. Authors whose native language is not English are encouraged to consult with a native speaker or to collaborate with a colleague whose English skills are more advanced. Authors may also use professional translation services at their own expense. Please note that using language editing services does not imply that the article will be selected for peer-review or be accepted by TEJ.

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Use A4 page format in Microsoft Word software, normal margins (top & bottom & left & right 2.5 cm), Times New Roman Font, Font size 12, double line spacing for main text and single line spacing for "References" section. US English grammar check option should be enabled. Words and abbreviations in Latin should be written in italics: "et al., in vivo, in vitro, in utero, in situ, ad libitum, clostridium perfringens, Staphylococcus aureus".

Units

Abbreviations used for units, prefixes, and symbols should comply with the International System of Units (SI) (http://physics.nist.gov/Pubs/SP330/sp330.pdf). If this is not possible, SI equivalents must be presented between parentheses. The complete names of individual teeth must be given in the main text (e.g., maxillary right central incisor). FDI 2-digit system should be used in table and figure legends (e.g., 11 for maxillary right central incisor).

Abbreviations

Abbreviations should be used sparingly – only where they ease the reader's task by reducing repetition of long, technical terms. Initially, use the word in full, followed by the abbreviation in parentheses. After that, use the abbreviation only.

Trade Names

Chemical substances should be referred to by the generic name only. Trade names should not be used. Drugs should be referred to by their generic names. If proprietary drugs have been used in the study, refer to these by their generic name, mentioning the proprietary name, and the manufacturer's name and location in parentheses.

Parts of the Manuscript

The manuscript should be submitted in separate files: (A) Title page; (B) Main text file; (C) Figures.

A. Title Page

Main title of the manuscript should be written in Times New Roman font, in bold capital letters of 12 font size. A running title with no more than 50 characters (including spaces) written in lower case letters must also be provided below the main title. Names, surnames and affiliations of all authors should appear below the running title. Use superscript numbers "1,2,3" for authors from different institutions, do not use any numbers if all authors are from the same department.

Name, surname, postal address, phone, fax and email of the corresponding author should be mentioned separately. If the paper has been previously presented in a scientific meeting either as an oral presentation or as a poster presentation, the title of the manuscript should be followed by an asterisk (*), which refers to a footnote indicating the name of the organization, location and date of its presentation.

The present address of any author, if different from that where the work was carried out, should be supplied in a footnote.

Please upload the title page as separate under the files section during submission.

Authors should disclose whether they used artificial intelligence (AI)– assisted technologies (such as Large Language Models [LLMs], chatbots, or image creators) in the production of submitted work. Authors should assert that there is no plagiarism in their paper, including in text and images produced by the AI -if any- and must ensure there is appropriate attribution of all quoted material, including full citations.

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Manuscripts should be presented in the following order: (I) title, abstract and keywords, (II) text, (III) disclosure, ethical approval, funding and acknowledgments statements and (IV) references, (V) figure legends (VI) tables.

I. Abstract & Keywords Page

This page should start with the main title of your manuscript. It should not contain author names, affiliations or any citations. This section must describe the main objective(s) of the study, and explain how the study was conducted without giving too much methodological detail and summarize the most important results and their significance. It should be as clear and concise as possible. Start numbering from this page and place it at the lower right-hand corner of the page footer. Abstracts should not exceed 200 words for original research papers and should be structured to include Purpose, Methods, Results, Conclusion headings written in bold letters.

Abstracts of case reports and review articles are limited to 200 words and should be unstructured.

A maximum of five keywords should follow the abstract, preferably chosen from the Medical Subject Headings (MESH) terms (http://www.ncbi.nlm.nih.gov/mesh). Keywords should be listed alphabetically and separated with a comma.

II. Text

Original research articles

Authors should use the following subheadings to divide the sections of their original research manuscript: Introduction, Materials and Methods, Results and Discussion.

Introduction should provide a concise account of the research problem and introduce the reader to the pertinent literature. The gap in the literature and study objective(s) and/or hypothesis should be clearly stated in the last paragraph.

Materials and Methods section should describe the study population/sample or specimens, the variables, and the study procedures with sufficient detail to ensure reproducibility. Include ethical approvals for clinical trials and animal studies in the first paragraph of this section. Provide the name of the responsible organization, year of approval and project number. Authors may use sub-headings to increase the readability such as "specimen collection", "micro-ct analysis" or "statistical analysis". These sub-headings should be written in italic letters. Statistical methods, and analysis should be mentioned.

Results should be written clearly without subjective interpretation and be supported with tables and figures when necessary. Text should complement any figures or tables but it should not repeat the same information. When reporting your findings, follow the same order you have used in "Materials and Methods" section.

Use a maximum of two digits after the decimal point.

Provide the relation of p values with the selected threshold between parentheses at the end of the sentence before the period. Such as; $p > .05$ or $p < .0001$.

Discussion section state major findings, their meanings and clinical relevance, present any contrasts with the results of similar studies, describe unavoidable limitations in the study design and make suggestions for further research within the limits of their data.

Conclusion should be supported by results and must be consistent with the objectives of the research.

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The main text is divided into these subheadings: introduction, case report (or series), and discussion.

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The manuscripts should summarize the current state of understanding on a particularly important topic in dentistry based on previously published data, preferably written by authoritative figures of that field. A minimum of 50 references must be cited. Authors may use their selected headings between Introduction and Conclusion sections.

Systematic review or a meta-analysis include the same manuscript design as for the original research articles.

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In-text Citations

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If cited in tables or figure legends, number according to the first identification of the table or figure in the text.

III. Disclosure, Ethical Approval, Funding and Acknowledgments Statements

Acknowledgments

This section is optional. Authors must acknowledge all individuals who do not fulfill the requirements for authorship but who had contributed to the preparation of the manuscript by assisting in writing, literature search, data analysis and/or supply of materials.

Source of Funding

This section is mandatory. Financial support from any institutional, private or corporate sources must be disclosed. Clearly state the name of the funding organization, year and the project number. If there is no source of funding declaration to make, please declare.

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This section is mandatory. Any financial or personal activities (royalties, grants, consultancy fee, patent registration, ownership, employment) that could be perceived as potential conflicts of interests must also be disclosed. If the author has no declaration to make, please declare "Authors declare any conflict of interest" or "None declared".

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Manuscripts must contain a statement that all human/animal studies have been reviewed by the appropriate ethics committee providing approval number, year and committee name. If there is no human/animal subject involve, please write "Not applicable".

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All investigations on human subjects must include a statement that the subject gave informed consent. If there is no human subject involve, please write "Not applicable".

IV. References

Authors are responsible for the accuracy of the references.

Cite all authors' names when there are six or fewer; when seven or more, list the first three followed by et al.

All citations mentioned in the text, tables or figures must be listed in the reference list.

Names of journals should be abbreviated in the style used in Index Medicus.

References should be listed in the following form:

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1. Keskin KO, Parker P. Microbiota of deep caries in permanent dentition. J Endod 2022; 124: 980–3.

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Book:

3. Keskin KO, Parker P. Endodontic microbiology. 2nd ed. Albany, NY: Wiley; 1996.

Chapter in a Book:

4. Keskin C. Root canal irrigants. In: Keleş A, eds. Endodontology: pathophysiology, diagnosis, and management. 2nd ed. New York: Raven Press; 1995. pp. 465–78.

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5. National Health and Medical Research Council. Clinical practice guidelines for the management of early breast cancer. 2nd ed. [PDF on Internet]. Canberra: Commonwealth of Australia, [updated 6 September 2003; cited 3 March 2004]. Available from: www.nhmrc.gov.au/publiactions/pdfcp74.pdf

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Please set table format to custom borders, no vertical lines, no shades, no background colors. Tables should be numbered consecutively with Arabic numerals in the order mentioned in the text.

All tables must be included in the main text of the article followed by figure legends in separate pages. All tables should be self-explanatory. Please provide full explanation for abbreviations even if they are presented in the main text. Legends should be written in Times New Roman and be positioned right above the table.

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Figures (photographs, graphs, charts, drawings, pictures, etc.) should be numbered consecutively with Arabic numerals in the order of mention in the text. High-quality pictures with 300 dpi resolution in JPEG JPG, BMP, TIFF, PNG or PSD file formats are generally acceptable for publication. Drawings and shapes should be in vector format.

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Turkish Endodontic Journal

Volume 11, Number 1, Year 2026

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Turk Endod J 2026;11(1):1–10
doi: 10.14744/TEJ.2025.94695

Effect of different canal shaping and obturation techniques on retreatment efficacy: An in vitro study

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Purpose: This study aimed to evaluate the effect of different canal shaping and obturation techniques on retreatment efficacy by analyzing the weight of removed filling material, retreatment time, and surface area reduction.

Methods: Eighty standardized acrylic resin blocks were shaped using four endodontic file systems [ProTaper Next (PTN), ProTaper Ultimate (PTU), VDW Rotate (VR), and XP-endo Shaper (XPS)] and obturated with either single-cone (SC) or continuous wave compaction (CWC), forming eight experimental groups (n=10). All samples were retreated using a single-file system. The amount of removed material was measured with a precision balance, time was recorded in seconds, and surface cleanliness was assessed using ImageJ software. Data were analyzed using the Kruskal–Wallis test followed by Bonferroni-adjusted pairwise comparisons.

Results: Statistically significant differences were found among groups for all parameters. XPS/SC and PTN/SC removed significantly more filling material than PTU/CWC and XPS/CWC. Retreatment times were significantly longer in XPS/SC and PTN/SC, and significantly shorter in PTU/CWC and XPS/CWC. For surface area reduction, PTU/CWC and XPS/CWC achieved the highest values, with CWC groups generally outperforming SC groups in cleanliness. Weight reduction correlated positively with time, while time correlated negatively with surface area reduction.

Conclusion: Retreatment efficacy is significantly influenced by the initial shaping and obturation technique. CWC generally resulted in shorter retreatment times and greater surface cleanliness, whereas SC groups tended to have greater filling removal by weight.

Keywords: Obturation; retreatment; root canal treatment; shaping.

Introduction

Root canal treatment (RCT) aims to restore and maintain oral health by eliminating infection and preserving the tooth's function, aesthetics, and patient comfort in individuals affected by pulp or periapical disease due to trauma or carious lesions (1). One of the principal causes of RCT failure is the continued presence of intraradicular infection (2). Thus, achieving complete removal of previously placed

Cite this article as: Cakmak YE, Erkal D, Akbulut M, Eroğlu D, Er K. Effect of different canal shaping and obturation techniques on retreatment efficacy: An in vitro study. Turk Endod J 2026;10:1-10.
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Submitted: June 08, 2025 Revised: August 14, 2025 Accepted: August 19, 2025 Published: April 27, 2026

fillings is fundamental to the retreatment process. Nonsurgical endodontic retreatment is often required when primary RCT fails, with reported failure rates ranging from 14% to 22% depending on case complexity, presence of missed canals, and operator skill (3). During endodontic retreatment, apical extrusion of obturation residues and debris may lead to postoperative discomfort and delayed healing. Thus, using a shaping technique that minimizes extrusion can help reduce such complications (4).

Recent advancements in metallurgy and file design (e.g., heat-treated NiTi alloys and reciprocating motion) have enhanced the flexibility and cyclic fatigue resistance of retreatment files, thereby improving their ability to negotiate complex canal anatomies (5). Nickel-titanium (NiTi) alloy-based motor-driven files, available in a variety of designs and taper configurations, have been widely adopted for effective cleaning and shaping of the root canal system. These files are engineered to facilitate coronal transportation of dentinal debris, which contributes to minimizing the apical extrusion of fillings during canal shaping (6).

The type of obturation technique and sealer used in the primary RCT significantly influences the ease of removal during retreatment and the amount of residual material left on the canal walls. Athkuri et al. (7) reported that root canals initially obturated using thermoplasticized techniques exhibited a significantly greater percentage of residual filling following retreatment procedures. In a recent systematic review and meta-analysis, Olivieri et al. (8) concluded that the obturation technique and sealer employed during primary RCT may significantly influence retreatment outcomes, particularly regarding the efficiency of filling removal and the amount of residual material remaining on canal walls.

Recently introduced as part of a contemporary instrumentation approach, the Perfect Super System Retreat ONE (Shenzhen Perfect Medical Instruments Co., Ltd., Shanwei, China) been specifically designed for non-surgical root canal retreatment procedures. This system represents a novel advancement in endodontic retreatment by offering enhanced cutting efficiency and flexibility, particularly in curved and previously filled canals. According to manufacturer documentation, the Retreat ONE file enables effective removal of gutta-percha and root canal sealers with minimal stress on the instrument, supporting safer and faster retreatment workflows. Its design aligns with the principles of minimally invasive endodontics, aiming to preserve dentin while ensuring thorough debridement of the root canal system (9).

To explore the impact of shaping and obturation techniques on retreatment efficacy, four widely used file systems were selected in this study: ProTaper Next (Maillefer Ins., Ballaigues, Switzerland) and ProTaper Ultimate (Dentsply Sirona, Ballaigues, Switzerland), which are multi-file rotary systems with progressive tapers; VDW Rotate (VDW GmbH, Munich, Germany), a heat-treated NiTi system optimized for minimally invasive shaping; and XP-Endo Shaper (FKG Dentaire Sàrl, Le Crêt-du-Locle, Switzerland), a single-file system designed to adapt to canal morphology due to its shape-memory properties (10). For obturation, the Single-Cone (SC) technique and Continuous Wave Compaction (CWC) method were used to represent two common yet distinct approaches. These combinations were chosen to reflect a range of contemporary clinical practices and to evaluate how different initial protocols affect retreatment outcomes

Therefore, this study aimed to compare the impact of different shaping and obturation techniques on retreatment efficacy by evaluating material removal, surface cleanliness, and procedural time in a standardized in vitro model. The findings of this study are expected to contribute to evidence-based decision-making by guiding clinicians toward more effective and predictable retreatment protocols in nonsurgical endodontics. The null hypothesis tested was that the type of root canal shaping system and obturation technique would not significantly influence the amount of removed filling material, retreatment time, or canal surface cleanliness during retreatment procedures.

Materials and Methods

The manuscript of this laboratory study has been written according to Preferred Reporting Items for Laboratory studies in Endodontology (PRILE) 2021 guidelines (11) (Fig. 1).

Sample Selection and Standardization

Since this study was conducted entirely in vitro using standardized training acrylic blocks (TABs), with no involvement of human or animal subjects, ethical approval was not required. No human or animal tissues or biological samples were used.

The sample size was determined using GPower 3.1 software (Heinrich Heine University, Düsseldorf, Germany), based on a significance level of $\alpha=0.05$, a statistical power of 80% ($1-\beta$), and an assumed effect size of $f=0.50$, which corresponds to a large effect according to Cohen's conventions. This value was selected based on previous studies that reported substantial intergroup differences in retreatment efficacy using standardized models. (7) The analysis indicated that a minimum of 9 samples per group would be sufficient to achieve adequate power; therefore, 10 samples were included in each group, totaling 80 TABs (Dentsply Maillefer, Ballaigues, Switzerland). Experimental groups

Fig. 1. Preferred reporting ıtems for laboratory studies in endodontology (PRILE 2021) flow chart.

were categorized based on 2 variables: The type of shaping system (PTN, PTU, VR, and XPS) and the obturation technique used (SC or CWC).

The TABs were approximately 17 mm in length, with a 2% taper and a curvature of 30°, simulating single-rooted canal morphology. All the TABs were examined under a stereomicroscope (Stemi 508, Zeiss, Oberkochen, Germany) to identify manufacturing defects or deformations, and only defect-free TABs were included in the study. Working length (WL) was established by inserting a #10 K-file until it was visible at the apical foramen and subtracting 0.5 mm. Glide path preparation was performed using a #15 K-file in all canals.

Since standardized TABs were used, sterilization was not applicable; all specimens were handled using clean gloves and stored in dry conditions prior to use.

Shaping Procedure

The TABs were randomly assigned to 4 main groups according to the shaping system used: PTN, PTU, VR, and XPS. All procedures were performed by two endodontists with at least 5 years of clinical experience, strictly following the manufacturers' instructions. For stabilization, the TABs were embedded in modeling wax (Polywax, Bilkim, Istanbul, Türkiye).

PTN group: The glide path was prepared using the ProGlider file, followed by sequential use of X1 (17/.04), X2 (25/.06), and X3 (30/.07) files at 300 rpm with 2 Ncm torque.

PTU group: The glide path was created with the Slider file (16/.02), followed by Shaper (20/.04), Finisher F1 (20/.07), F2 (25/.06), and F3 (30/.09) files in sequence, operated at 400 rpm and 4 Ncm torque.

VR group: The glide path was prepared using VR 15/.04, followed by VR 20/.05, 25/.04, and 30/.04 files, operated at 350 rpm and 2 Ncm torque.

XPS group: The glide path was verified using a K-file, and then a single XPS file (30/.01) was used at 800 rpm and 1 Ncm torque. This group was shaped in a 35 °C warm water bath to simulate body temperature conditions.

Each canal was irrigated with 10 mL of distilled water during shaping, followed by a final rinse with 5 mL of distilled water. The canals were then dried using sterile paper points.

Obturation Procedure

Twenty TABs prepared with each shaping system were further divided into 2 subgroups based on the used obturation technique (n=10) (SC and CWC):

SC group: The canals were obturated using the conventional SC technique. Master cones with appropriate tapers were selected for each system: X3 for PTN, F3 for PTU, and 30/.04 cones for both VR and XPS groups. The cones were severed at the canal orifice using the Fast Pack Pro device (200 °C), and then vertically condensed using a #70 hand plugger.

CWC group: All samples were obturated using the Fast Fill device (Eighteeth, Changzhou, China) with the thermoplastic injection technique. The obturation was performed in 3 segments, progressing from the apical to the coronal third. After each segment, vertical compaction was applied using appropriately sized hand pluggers to ensure homogenous filling.

The SC technique was chosen instead of cold lateral condensation (CLC) to reduce technique sensitivity and operator-dependent variability. Unlike CLC, which involves multiple accessory cones and lateral compaction, SC provides a more reproducible approach in in vitro models, allowing for more standardized comparisons across groups.

Retreatment Procedure

During retreatment, each canal was irrigated with a total of 10 mL of distilled water using Endo-Eze Tips (Ultradent Products Inc., South Jordan, UT, USA) attached to a 30-gauge side-vented needle. Irrigation was performed after each file use and also after completing the entire instrumentation sequence. For standardization, all retreatment procedures were performed using a single file system: The Perfect Super System Retreat ONE file. The file was operated at 500-600 rpm in the coronal third, 400 rpm in the middle third, and 250 rpm in the apical third, with a constant torque of 2.5 Ncm. Retreatment in each canal was completed using only this file, and the same protocol was consistently applied to all samples. The endpoint for retreatment was defined as the absence of visible filling material on the canal walls and on the instruments, confirmed by visual inspection under ×10 magnification using a stereomicroscope (Zeiss Stemi 508, Carl Zeiss, Germany).

Blinding Statement

To minimize bias, the operator performing the retreatment procedures was blinded to the group allocation. The retreatment files were presented in a randomized manner, and no identifying marks were present on the samples. However, the individual recording the retreatment time was not blinded to the group assignments.

Weight Measurement

The weight of each TAB was measured before and after the procedures using a precision balance (XB 220A; Kunz Precisa, Switzerland), and the differences were recorded in grams. The percentage of material loss was calculated using the following formula:

Material Loss (%)=(Initial Weight – Final Weight) / Initial Weight × 100

Time Measurement

The retreatment time was measured by an independent observer using a digital stopwatch (Neval Digital Stopwatch, Istanbul, Türkiye), considering only the active shaping time of the file within the canal. The durations of irrigation, patency checks, and drying procedures were excluded from the measurement.

Surface Area Analysis

High-resolution images (2560 × 1920 pixels, 300 dpi) were captured and exported in TIF format using a stereomicroscope (Zeiss Stemi 508) at ×10 magnification, no staining was applied. The same settings were used for all pre- and post-retreatment images. No image enhancement or labeling was applied. The "initial area" referred to the portion of the canal surface covered by filling material prior to retreatment. The "post-RT area" represented the remaining filled surface after retreatment. The surface areas (mm^2) were calculated using ImageJ software (National Institutes of Health, Bethesda, MD, USA). Each image was binarized using a thresholding function in ImageJ, and manual segmentation was performed by outlining the filled areas. Measurements were taken by a single calibrated examiner blinded to group allocation. The filled area before and after retreatment was calculated in pixels, and the percentage of reduction was determined. The difference in area was evaluated as a percentage using the following formula:

Area Reduction (%)=(Initial Area – Post-RT Area) / Initial Area × 100

Statistical Analysis

Data was analyzed using SPSS version 27.0 (IBM Co., Armonk, NY, USA). The normality of distribution was assessed using the Shapiro-Wilk test, and since the data were not normally distributed, the Kruskal-Wallis test was applied. Although standardized acrylic blocks and a single operator were used, normal distribution was not achieved. This may be due to subtle procedural differences such as variations in gutta-percha condensation, material adaptation to canal walls, or manual segmentation in ImageJ, all of which can introduce micro-level variability despite standardization. For variables showing significant differences, Bonferroni-adjusted post hoc analyses and Mann-Whitney U tests were conducted for pairwise group comparisons. Spearman's rho correlation analysis was used to evaluate the relationships between variables. A p-value of <0.05 was considered statistically significant. None of the outcome variables passed the Shapiro–Wilk normality test (P<0.05). Although data transformation techniques (logarithmic and square root) were considered, they did not sufficiently normalize the distribution. Therefore, non-parametric tests (Kruskal–Wallis and Mann–Whitney U) were chosen instead of two-way ANOVA to ensure valid statistical interpretation without violating underlying assumptions.

The selection of the shaping and obturation systems was based on their distinct design philosophies and widespread clinical relevance, as previously described (10). These combinations allowed for a comparative evaluation of commonly used strategies and their potential impact on retreatment outcomes.

Results

In this study, a total of 80 TABs were used, each shaped with one of 4 different file systems and obturated using 2 distinct techniques. Three primary variables were evaluated: Weight difference of the removed filling, retreatment duration, and reduction in surface area based on gutta-percha area reference, calculated via ImageJ. Eight experimental groups were established (n=10); VR/SC, VR/CWC, PTN/SC, PTN/CWC, PTU/SC, PTU/CWC, XPS/SC, and XPS/CWC.

The initial analysis of the removed filling weight revealed a statistically significant difference among the groups (Kruskal-Wallis H=33.969; df=7; P<0.001). Post hoc comparisons showed that both XPS/SC and PTN/SC groups exhibited significantly greater weight difference compared to PTU/CWC and XPS/CWC groups (p_adj<0.05), with the XPS/SC group showing the highest mean value (3.5±0.3).

Retreatment time exhibited statistically significant differences among the groups, as confirmed by the Kruskal–Wallis test (H=51.150; df=7; P<0.001). The Bonferroni-adjusted Mann–Whitney U test revealed that the XPS/SC and PTN/SC groups required significantly more time than PTU/CWC and XPS/CWC groups (p_adj<0.05). Conversely, the shortest retreatment durations were observed in PTU/CWC (70±7) and XPS/CWC (80±6) groups.

Surface area reduction, calculated using ImageJ, also showed significant differences among the groups (Kruskal–Wallis H=34.654; df=7; P<0.001). After Bonferroni adjustment, only the comparison between the PTN/SC and XPS/CWC groups showed a statistically significant difference in surface area reduction (p_adj=0.0277) (Fig. 2). Although the XPS/SC group had the lowest mean

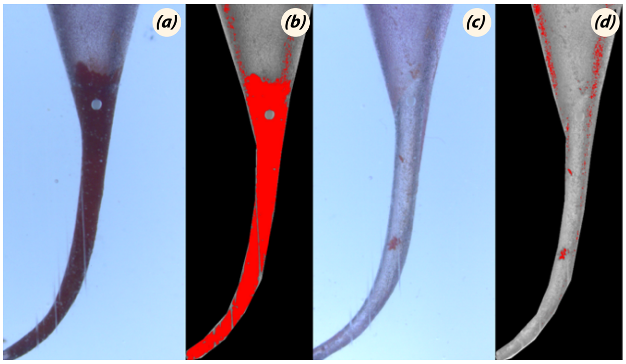

Fig. 2. Representative images of a sample from the PTN CWC group before and after retreatment. **(a)** Pre-retreatment stereomicroscopic image, **(b)** ImageJ segmentation of the pre-retreatment image (red overlay indicates gutta-percha-filled area). **(c)** Post-retreatment stereomicroscopic image of the same sample, **(d)** ImageJ segmentation of the post-retreatment image, with residual gutta-percha areas highlighted in red.

Table 1. Mean ± standard deviation values of the weight (mg), time (sec), and area reduction (%) differences among the groups.

Group	Weight	Time	Area Reduction
VR/SC	2.3±0.4^{b}	120±10^{B}	55±5^{c}
VR/CWC	1.8±0.5^{bc}	95±8C	60±6b^{c}
PTN/SC	3.1±0.3^{a}	135±12^{A}	50±4^{c}
PTN/CWC	2.2±0.6^{b}	100±9^{C}	65±5^{b}
PTU/SC	1.7±0.5^{c}	90±10^{C}	70±6^{ab}
PTU/CWC	0.9±0.4^{d}	70±7^{D}	80±7^{a}
XPS/SC	3.5±0.3^{a}	140±11^{A}	45±3^{c}
XPS/CWC	1.1±0.2^{d}	80±6^{D}	75±4^{a}

Different letters indicate statistically significant differences (P<0.05).

Table 2. Pairwise comparisons between groups showing statistically significant differences based on Bonferroni-adjusted Mann-Whitney U test results (P<0.05). Group names indicate the root canal shaping system and the type of obturation technique used.

Variable	Group 1	Group 2	p-value	Adjusted p-value
Weight difference	PTN/SC	PTU/CWC	0.00018	0.01534
Time	VR/CWC	PTN/SC	0.00018	0.01534
Time	VR/CWC	XPS/SC	0.00018	0.01534
Time	PTN/SC	PTN/CWC	0.00018	0.01534
Time	PTN/SC	PTU/CWC	0.00018	0.01534
Time	PTN/CWC	XPS/SC	0.00018	0.01534
Time	PTU/CWC	XPS/SC	0.00018	0.01534
Time	PTN/SC	XPS/CWC	0.00024	0.02056
Time	XPS/SC	XPS/CWC	0.00033	0.02756
Surface area reduction	PTN/SC	XPS/CWC	0.00033	0.02771

value, no statistically significant differences were detected between this group and others after correction. In general, groups obturated with the continuous wave compaction technique exhibited greater surface area reduction than those filled using the single-cone technique, with the highest reduction observed in the PTU/CWC group (80±7), followed by the XPS/CWC group (75±4). The descriptive statistics, including mean and standard deviation values for weight (mg), time (sec), and area reduction (%) across all groups, are summarized in Table 1. Post hoc comparisons indicated that groups sharing the same superscript letter in Table 1 were not significantly different from each other, whereas groups with different letters showed statistically significant differences ($p < 0.05$). Specifically, for weight difference, the XPS/SC and PTN/SC groups exhibited the highest mean values and were significantly different from PTU/CWC and XPS/CWC, which had the lowest values. For retreatment time, PTN/SC and XPS/SC groups had the longest durations, significantly differing from PTU/CWC and XPS/CWC groups, which had the shortest durations. Regarding surface area reduction, PTU/CWC showed the highest mean value, followed by XPS/CWC; both were significantly different from the lowest group, XPS/SC.

Spearman's correlation analysis demonstrated several key relationships among the study variables. A moderate, positive, and statistically significant correlation was observed between weight difference and retreatment time ($\rho=0.557$; $P<0.001$) and a significant negative correlation was identified between retreatment time and surface area reduction ($\rho=-0.370$; $p=0.001$). No significant correlation was found between weight difference and surface area reduction ($\rho=-0.061$; $p=0.593$). The results of the correlation analysis between the variables are shown in Table 2.

Discussion

This study aimed to investigate how different root canal shaping and obturation techniques used during the primary RCT influence the efficacy of subsequent nonsurgical endodontic retreatment, by assessing parameters such as filling removal, canal wall cleanliness, and procedural time. The findings revealed notable differences among the groups regarding retreatment time, residual filling, and cleanliness of the canal walls. These outcomes underscore the critical role of both shaping kinematics and obturation techniques in influencing the efficiency and safety of retreatment procedures. Based on the statistically significant differences observed among the groups for all primary outcome measures, the null hypothesis of the study was rejected. A prominent outcome of the present study was the influence of the initial obturation technique on the effectiveness and efficiency of filling material removal.

Although various irrigants such as sodium hypochlorite, EDTA, and chlorhexidine are routinely employed in clinical endodontics for their antimicrobial and tissue-dissolving properties, distilled water was selected as the irrigant in the present study to eliminate the potential confounding effects of these chemically active agents on the tested artificial blocks. Previous studies (12,13) have demonstrated that these irrigants can alter the physical characteristics of synthetic canal models, potentially compromising the structural integrity of the simulated canals and resulting in inaccurate assessments of instrumentation efficacy. Therefore, the use of distilled water ensured a controlled environment and preserved the standardization required for valid comparisons among the different instrumentation systems.

Samples obturated with the continuous wave compaction technique generally demonstrated shorter retreatment durations compared to those filled using the single-cone technique. While certain SC groups, such as XPS/SC and PTN/SC, exhibited higher weight difference values, CWC groups achieved greater surface area reduction, with PTU/CWC and XPS/CWC showing the highest values. Samples obturated with the continuous wave compaction technique generally demonstrated shorter retreatment durations compared to those filled using the single-cone technique. While certain SC groups, such as XPS/SC and PTN/SC, exhibited higher weight difference values, CWC groups achieved greater surface area reduction, with PTU/CWC and XPS/CWC showing the highest values. These results support the conclusions drawn by Athkuri et al. (7), who found a greater percentage of residual material in canals initially obturated with thermoplasticized techniques. Olivieri et al. (8) similarly reported that warm vertical compaction techniques are more challenging to perform retreatment due to increased adaptation of filling into canal irregularities. The present findings are in agreement with a study by Rödig et al. (14) reporting no significant difference between carrier-based and warm vertical compaction techniques regarding residual filling and dentin removal.

Furthermore, among the shaping systems used prior to obturation, PTN and XPS showed superior performance in terms of residual material removal and canal wall cleanliness. The progressive taper of PTN and the adaptive design of the XPS allow for efficient shaping and debris removal, even in complex canal morphologies. These properties likely facilitated not only better primary canal preparation but also more accessible retreatment, as demonstrated in previous studies (15,16). In contrast, shaping with less flexible systems may result in irregular filling patterns and compromised retreatability.

The correlation analysis revealed two important trends: A moderate positive correlation between the amount of filling removed and retreatment time, and a negative correlation between retreatment time and canal wall cleanliness. In alignment with the findings of Çapar et al. (17) our study similarly demonstrated that root canals initially obturated with thermoplasticized techniques retain a significantly greater amount of residual material following retreatment procedures compared to SC obturated canals, emphasizing the impact of initial obturation modality on retreatment efficacy. These findings suggest that although longer instrumentation time may increase the volume of material removed. Most recent in vitro studies (18-21) have demonstrated that, regardless of the obturation technique used, complete removal of filling material is rarely achieved after retreatment, and some residual material remains in all specimens. However, some studies (19,22) reports inconsistent findings regarding the amount of residual filling material between the SC and CWC techniques. Some studies have indicated that canals obturated with the CWC method tend to be cleaner after retreatment, with significantly less remaining gutta-percha or sealer compared to the SC technique. It was reported (22) that canals obturated with the SC technique allowed faster achievement of working length and apical patency; however, a greater amount of residual filling material remained in these canals. In contrast, the same study found that retreatment of canals filled with the CWC technique required a slightly longer time, but resulted in less residual material. This difference has been attributed to the greater amount of sealer used in the SC technique, which may adhere more strongly to the dentinal walls and make complete removal more challenging. On the other hand, in a study (23) conducted on curved root canals using the same bioceramic sealer, no statistically significant difference was found between the SC and CWC techniques in terms of the amount of residual filling material after retreatment. In another study (24), it was observed that the CWC technique not only resulted in less residual filling material but also required a shorter retreatment time. In comparisons of apical debris extrusion during retreatment (25), it has been reported that roots obturated with the warm vertical compaction technique exhibit significantly greater debris extrusion and require longer retreatment times compared to those filled with the cold lateral compaction technique. Despite these conflicting findings, it has been emphasized that when the type of sealer is kept constant, the choice of obturation technique is not a critical factor in retreatment success, as complete removal of filling material cannot be achieved in canals obturated with either technique—this is especially evident in cases with complex canal anatomy, where even extended mechanical action may fail to achieve optimal cleanliness (23).

Notably, the findings indicated no statistically significant association between the quantity of filling removed and the proportion of canal wall cleanliness. This observation highlights that extensive material removal does not inherently translate to effective debridement. Consistent with other studies (26,27) residual smear layers or sealer remnants may remain adherent to the canal walls even after substantial gutta-percha elimination.

The selection of standardized simulated canals contributed to enhanced experimental reproducibility; however, this approach inherently limited the anatomical diversity typically encountered in clinical settings. Although extracted human teeth offer more authentic root canal morphologies, their natural variability can hinder methodological standardization, making synthetic models a pragmatic alternative for controlled comparative studies (28-30).

To represent a broad range of modern endodontic instrumentation philosophies, four distinct file systems were intentionally selected for this study. PTN was included due to its extensive clinical validation and frequent use in practice. As a multi-file system utilizing M-Wire alloy and an off-centered design, PTN provides improved flexibility and shaping performance (31), making it suitable as a benchmark. PTU and VR were selected as newer generation multi-file systems that incorporate advanced heat-treated metallurgy and emphasize minimally invasive canal shaping (32,33).

These systems were evaluated specifically for their potential to enhance dentin preservation through such design attributes. In contrast, the XPS was chosen for its unique thermomechanical characteristics and single-file capability, which allowed for direct comparison with multi-file systems under standardized conditions (34).

In the present study, only gutta-percha was employed for obturating the root canals in the test TABs, and no root canal sealer was applied. This methodological choice represents a limitation of the study. The exclusion of sealer was primarily due to practical challenges, including difficulty in standardizing the sealer volume, achieving a uniform distribution within the canal, and controlling coronal or apical extrusion during the procedure. Similar experimental protocols without the use of sealer have been reported in prior studies (35–38). Nevertheless, we acknowledge the need for further investigations and recommend that future laboratory-based research be complemented with clinical studies to enhance the validity and applicability of the findings.

This study has several limitations. The in vitro setting does not fully represent clinical complexities. Only one retreatment system was used across all samples, which may not reflect variable retreatment approaches in practice. Additionally, the study did not assess post-operative pain, healing, or long-term outcomes. Despite these limitations, the results provide meaningful insights into how prior shaping and obturation techniques impact retreatment efficiency and can guide future research and clinical decision-making.

Conclusion

This in vitro study demonstrated that retreatment efficiency is influenced by both the initial canal shaping and obturation techniques. While some single-cone (SC) groups, such as XPS/SC, showed favorable outcomes in terms of material removal and surface cleanliness, they also exhibited longer retreatment durations compared to their thermoplasticized counterparts. Conversely, certain CWC groups demonstrated shorter retreatment times but lower efficiency in material removal. These findings highlight that neither obturation technique consistently outperformed the other across all parameters. Given the limitations of the standardized in vitro model, these results should be interpreted with caution. Further clinical investigations are warranted to validate the influence of primary root canal treatment protocols on retreatment efficacy under real-world conditions.

Authorship Contributions: Concept: K.E.; Design: K.E.; Supervision: K.E.; Materials: M.A., Di.E.; Data: Y.E.Ç., M.A., Di.E.; Analysis: Da.E.; Writing: Y.E.Ç., Da.E.; Critical Revision: K.E.

Use of AI for Writing Assistance: No artificial intelligence (AI)-assisted technologies were used in the writing, image generation, or data analysis of this manuscript. All content is original and free from plagiarism.

Source of Funding: This study received no financial support from any funding agency.

Conflict of Interest: The authors declare no conflict of interest.

Ethical Approval: Since this study was conducted entirely in vitro using standardized training acrylic blocks (TABs), with no involvement of human or animal subjects, ethical approval was not required.

Informed consent: No human or animal tissues or biological samples were used.

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ORIGINAL ARTICLE

Turk Endod J 2026;11(1):11–18
doi: 10.14744/TEJ.2025.44153

The technical quality of root canal filling performed by undergraduate students in pre-clinical education: Instructor versus ChatGPT-4o assessment

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Purpose: The present study aims to compare the radiographic technical quality of root canal fillings performed on 3D-printed resin and extracted natural teeth, and to examine the agreement between endodontist educator assessment and analysis performed by an artificial intelligence-based chatbot (ChatGPT-4o).

Methods: After theoretical training and practical demonstration, 3rd-year undergraduate students performed root canal treatment on 108 printed resin teeth and 108 extracted natural teeth. In the radiographic examination, parameters such as root canal filling length, filling continuity, apical transport, perforation, and instrument fracture were evaluated by both an experienced instructor and ChatGPT-4o. The technical quality of root canal filling and all procedural errors were compared between the printed teeth and extracted teeth groups using the chi-square test. Interexaminer reliability was measured between the instructor and ChatGPT-4o.

Results: Regarding overall root canal quality, 34% of extracted teeth were acceptable and 66% were unacceptable, while 45% of printed teeth were acceptable and 55% were unacceptable. There is no statistically significant difference between the acceptability rates of extracted teeth vs printed teeth ($p>0.05$). It was observed that the extracted teeth had more under-filled canals and fewer adequately filled canals than expected, whereas printed teeth were more likely to be adequately filled ($p<0.05$). There was no difference between sample types having adequate or inadequate filling continuity ($p>0.05$). Apical transportation, perforation, and instrument fracture rates did not differ significantly between extracted and printed teeth. Cohen's kappa value is 0.210, and the inter-observer agreement was 62%. These results indicated low agreement between the instructor and ChtaGPT-4o significantly ($p<0.05$).

Conclusion: The overall quality of the canal filling applied by undergraduate students on 3D-printed resin and extracted teeth was similar. ChatGPT-4o evaluation did not demonstrate a high level of agreement with the endodontist instructor.

Keywords: 3D printed teeth; artificial intelligence; preclinical education.

Cite this article as: Oncu A, Comert H, Alacam T. The technical quality of root canal filling performed by undergraduate students in pre-clinical education: Instructor versus ChatGPT-4o assessment. Turk Endod J 2026;11:11-18.

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Submitted: May 26, 2025 Revised: September 01, 2025 Accepted: September 19, 2025 Published: April 27, 2026

Introduction

The target of dental education is to train individuals to perform their profession in a reliable, skillful, and effective manner (1). The educational journey of dental students includes both theoretical and practical training throughout their studies (2). Pre-clinical training contributes to the development of motor skills and the acquisition of relevant experience in a safe environment. It also allows students to develop the skills necessary to practically apply their theoretical knowledge (3). In preclinical years, endodontic and restorative procedures are traditionally performed on extracted teeth or artificial models using various instruments (4).

With the rapid advances in technology and the increased availability of 3D printers, the overall potential for using printed models in dental education has attracted considerable interest, particularly for training dental students and enhancing dentists' practical skills (5). Three-dimensional printing enables the production of new models that reflect the anatomy of the root canal in endodontics (6).

The success of root canal treatment (RCT) depends on the proper cleaning, shaping, and consequently root canal filling. The methods used to determine the outcome of endodontic treatment are usually based on radiographic evaluation (7). Unfavourable treatment outcomes have often been associated with technically unacceptable root canal fillings (8). Examining the radiographic quality of their own root canal fillings and understanding their adequacy may help undergraduate students achieve better results (9).

While observational studies are an effective tool for clinical management, clinical audits can also help dental educators to identify curricular deficiencies, methodological problems, and issues with instruments or materials (10). Therefore, it is essential to continuously review the clinical training outcomes for undergraduate dentistry.

In recent years, artificial intelligence (AI)-assisted systems have become increasingly embedded in dental education (11). In particular, large language models (LLMs) and chatbots such as ChatGPT have the potential to be used in clinical decision support systems and student training (12). Previous studies have found that ChatGPT provides students with fast and accessible information and that ChatGPT requires students to learn how to ask the right questions to get the best answers (13,14)

Various studies have shown that ChatGPT's medical image analysis and clinical evaluation capabilities are limited (12,15). However, new versions can be expected to improve in assessing the quality of pre-clinical applications in dental undergraduate education. The present study aims to compare the radiographic technical quality of root canal fillings performed on 3D-printed resin and extracted natural teeth and to examine the agreement between endodontist educator assessment and analysis performed by an artificial intelligence-based chatbot (ChatGPT-4o).

Materials and Methods

This observational study has been written in accordance with the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) 2007 guidelines and was approved by the Scientific Research Ethics Committee of the University of Lokman Hekim (No: 2025/098, Date: 28/04/2025).

and conducted according to the Declaration of Helsinki. Figure 1 shows the STROBE flowchart illustrating the study protocol of the present. The total number of samples required for our study was determined as at least 159 in the G*Power software by using the effect size of a previously conducted study (16). This study was conducted by examining the radiological records of resin (simulated) or extracted (human) teeth that underwent root canal treatment in the preclinical courses of 3rd-year undergraduate students at Lokman Hekim University Faculty of Dentistry. The students had no previous practical experience in root canal preparation and filling. The students were given theoretical instruction and a demonstration of the RCT protocol before each application. A total of thirty-six students participated in the study. Each student was required to provide one incisor, one premolar, and one molar tooth, either maxillary or mandibular. This ensured that each participant performed procedures on three distinct tooth types, allowing for standardization across specific tooth groups rather than random allocation. Consequently, each student carried out endodontic procedures on a total of six teeth, consisting of three 3D-printed teeth and three extracted human teeth, each representing a different tooth group. Table 1 shows the numerical distribution of samples used by students according to tooth groups. The practical training sessions were organized in two phases: Initially,

Table 1. Numerical distribution of samples used by students according to tooth groups

	Printed teeth	Extracted Teeth
Maxillary incisor	18	20
Mandibular incisor	18	16
Maxillary premolar	23	19
Mandibular premolar	13	17
Maxillary molar	10	12
Mandibular molar	26	24
Total	108	108

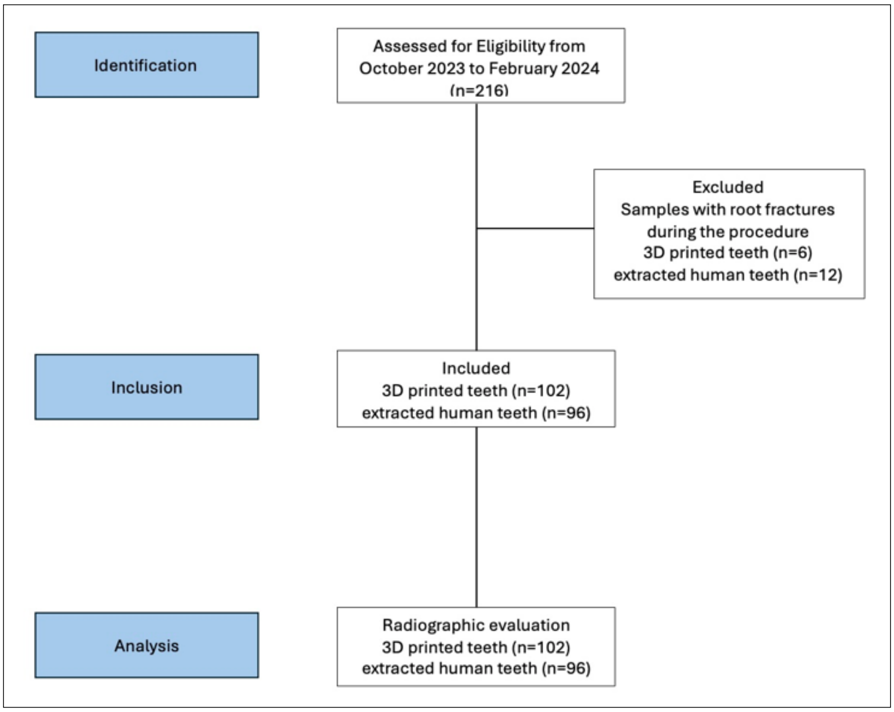

Fig. 1. STROBE flow chart of the present study protocol.

students performed RCT on 3D-printed teeth, followed by treatments on extracted natural teeth. Extracted teeth without any curvature or calcification were used. During these sessions, students worked sequentially on incisors, premolars, and molars. For each tooth sample, students were allocated 2 hours to complete the RCT procedure. In total, each student treated six teeth—three extracted natural teeth and three 3D-printed teeth covering the different tooth types mentioned. Endodontic access cavity preparation, root canal detection, instrumentation, master cone control, and canal-filling steps were checked by the instructor during the students' application. A total of 108 printed resin teeth and 108 extracted natural teeth were treated. The printed teeth (Dental Education Models, Ancorax Technology, Ankara, Türkiye) used by all students were models produced from the same resin-based material.

RCT procedure

Initially, an endodontic access cavity was created in all samples. For the determination of working length, a K-type hand file no. #10 or #15 was advanced until it was seen from the apex of the root. Then, the working length was determined by subtracting 1 mm from the length. Canals were prepared using K and H-type hand files up to #40 apical tip size with standard preparation technique. Irrigation was performed with sodium hypochlorite during shaping procedures. Canals were dried with paper points. The lateral condensation technique was used for root canal filling using gutta-percha and sealer.

Inclusion criteria

• Single or multi-rooted 3D printed resin and an extracted permanent tooth

• RCTs were conducted by a third-year undergraduate student under the supervision of a senior endodontist instructor between October 2023 and February 2024.

Exclusion criteria

• Samples where root fractures occurred during the procedure

Radiographic examination

Finally, 94 extracted and 102 printed teeth were included for examination. Then, 2D digital radiography was taken of all samples using the parallel technique. All radiographs were taken with the same X-ray device (RX DC NewTom, Bologna, Italy) with the same dose, and parameters (0.180 mAs, 60 kvp/8mA). All radiographs were scanned with the Carestream CS 7200 phosphor plate scanning system and transferred to Tropy DICOM. All images were evaluated in a dark room by a single examiner who had 7 years of experience in endodontics. Each root canal filling was evaluated radiographically for continuity, and the apical extension of filling materials, apical transportation, perforation, and instrument fracture. For the technical quality of root canal fillings, the quality guidelines for endodontic treatment (European Society of Endodontology, 2006) were adopted as the gold standard. According to these guidelines, the prepared root canal should be filled; the prepared and filled canal should maintain the original canal shape, there should be no visible gaps between the filling material and the canal walls, and no visible canal space should be present beyond the end point of the root filling. A root filling was defined as satisfactory when both the continuity and the apical extension of the filling materials were rated as acceptable.

The radiographic images obtained in this study were standardized (maximum resolution: 1920x1080 pixels, file format: TIFF) and digitally archived after being numbered sequentially.

Evaluation of the images was conducted by another researcher using the ChatGPT-4 model, accessed through Google. To eliminate any potential effects from cookies and cache, a previously unused email address was employed for each evaluation. Additionally, the browser's search history and cookies were cleared before each case evaluation, and a new chat window was opened for each case to minimize the influence of previous responses.

For assessment, radiographic images were uploaded to the chat interface, and the following standardized evaluation text was provided to the ChatGPT-4 model:

"Could you please evaluate the root canal treatment shown in the photograph based on the following parameters?

Radiological parameters:

Root canal filling length: The root canal filling should extend up to 2 mm short of the radiographic apex. Obturation should neither be overfilled nor underfilled. (overfilled, acceptable, short)

Continuity of the root canal filling: The root canal filling should appear continuous and uniform throughout the canal length, without gaps, voids, or separations. (adequate, inadequate)

Apical transportation (Present/Absent)

Perforation (Present/Absent)

Instrument fracture (Present/Absent)"

Responses from the model were recorded in an Excel spreadsheet (Microsoft), transferred to the database, and analyzed as part of the study.

The radiographic assessments conducted by the human examiner and ChatGPT-4o were performed independently. The AI model and the examiner did not have access to each other's evaluations.

Assessing the technical quality of root fillings and detecting iatrogenic errors were noticed in the following factors.

Canal filling length: The root canal filling should extend to within 2 mm of the radiographic apex. The obturation should not be overfilled or underfilled.

Continuous filling: The root canal filling should appear continuous and uniform without voids, gaps, or separations along the length of the canal.

Iatrogenic errors: Presence or absence of any apical transportation, perforation, and instrument fracture.

Statistical analysis

All statistical analyses were performed using the JAMOVI software (ver.2.6.44, Sydney, Australia). The technical quality of root canal filling and all procedural errors were compared, using the chi-square test, for the results of the printed teeth and extracted teeth groups. Cohen's Kappa was used to measure the agreement between the observer and ChatGPT 4.0.

Results

Table 2 and Table 3 show percentage values and the number of examination results. Regarding overall root canal quality, 34% of extracted teeth were acceptable and 66% were unacceptable, while 45% of printed teeth were ac-

Table 2. Descriptive results of endodontist examiner assessment

	Frequency %	
	Printed teeth (n=102)	Extracted teeth (n=94)
Canal filling length		
Over-filled	2% (n=3)	3% (n=4)
Adequate	77% (n=79)	79% (n=57)
Under-filled	19% (n=20)	18% (n=33)
χ^2 Tests	p=0.037	
Continuity of filling		
Adequate	47% (n=48)	47.8% (n=45)
Inadequate	52.9% (n=54)	52.1% (n=49)
χ^2 Tests	p=0.909	
Apical transportation		
Absence	97% (n=99)	95.7% (n=90)
Presence	2.9% (n=3)	4.2% (n=4)
χ^2 Tests	p=0.620	
Perforation		
Absence	100% (n=102)	97.8% (n=92)
Presence	0 (n=0)	2.1% (n=2)
χ^2 Tests	p=139	
Instrument fracture		
Absence	96% (n=98)	92.5% (n=87)
Presence	3.9% (n=4)	7.4% (n=7)
χ^2 Tests	p=0.284	

Table 3. Overall quality of root canal filling in extracted or printed teeth

Tooth type	Examiner: Acceptable	Examiner: Unacceptable	Total
Extracted teeth	32 (34%)	62 (66%)	94
Printed teeth	46 (45%)	56 (55%)	102
Total	78	118	196

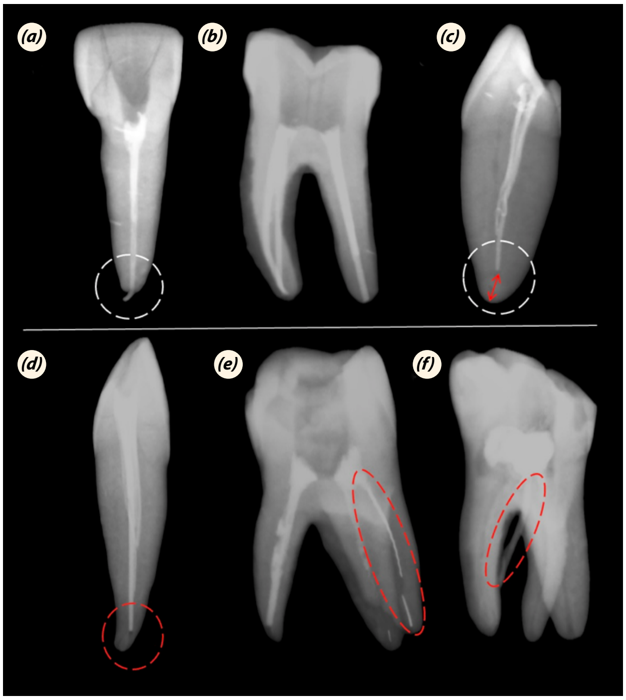

Fig. 2. The radiographic images demonstrated **(a)** over-filled root; **(b)** acceptable canal filling; **(c)** under-filled and inadequate filling; **(d)** apical transportation; **(e)** instrument fracture; and **(f)** perforation.

ceptable and 55% were unacceptable. There is no statistically significant difference between the acceptability rates of extracted teeth vs printed teeth ($p>0.05$). The chi-square test results showed a significant relationship between sample type and canal length ($p<0.05$). It was observed that the extracted teeth had more under-filled canals and fewer adequately filled canals than expected, whereas printed teeth were more likely to be adequately filled. There was no difference between sample types having adequate or inadequate filling continuity ($p>0.05$). Apical transportation and perforation rates did not show any significant difference between extracted and printed teeth. There is no statistically significant difference between instrument fracture rates in extracted and printed teeth ($p>0.05$). The occurrence of instrument fracture remains at very low levels for both groups (3.9% and 7.4%).

Table 4. Intra-examiner reliability between the examiner and ChatGPT-4o

Method	Cohen's Kappa for 2 Raters
Subjects	196
Raters	2
Agreement %	62
Kappa	0.210
z	2.94
p-value	0.003

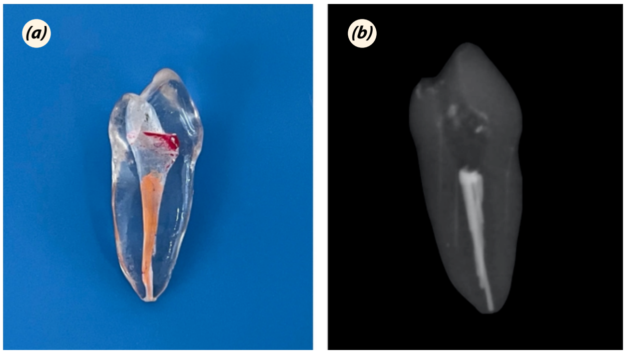

Fig. 3. The figure represents the 3D printed mandibular premolar tooth model **(a)** and its radiographic image **(b)**.

Figure 2 shows radiographic images of root canal-filled extracted teeth. Figure 3 shows a printed tooth model with a canal filling and its radiographic image.

Interobserver agreement was assessed for the examiner and ChatGPT-4o in Table 4. Cohen's Kappa value is 0.210, indicating a weak agreement between the examiner and ChatGPT-4o. The directly observed agreement rate between observers was 62%. Since the p-value is 0.003, this low agreement is not random but is statistically significant.

Discussion

In this study, the quality of root canal treatments performed by undergraduate students on extracted and 3D-printed teeth was evaluated using radiographic analysis. There are still limitations to using extracted human teeth in dental courses, such as ethical concerns, collecting sufficient numbers of samples, and the risk of infection transmission (17). The 3D printing method allows samples to be designed in various sizes and inclination levels with advantages such as reproducibility (5,18).

Our finding showed that the type of tooth used does not significantly affect the overall quality of the filling. In terms of overall root canal quality, only 34% of the treatments on extracted teeth, and 45% on printed teeth, were found to be acceptable. When analyzing canal length, extracted teeth were found to have a higher number of under-filled canals and fewer adequately filled canals than expected. In contrast, printed teeth were more likely to have adequately filled canals. It is difficult to reach the apex due to calcifications and complex canal anatomy in extracted teeth (19,20), and these factors may contribute to this difficulty.

In two previous evidence-based studies, no significant difference was found between training with artificial teeth and extracted teeth regarding the technical results of root canal filling (21,22). It has been reported that procedures performed on artificial teeth did not always indicate students' performance on natural teeth (4).

No significant differences were found in parameters such as filling continuity, apical transportation, perforation, and instrument fracture between extracted and printed teeth. This indicates that these complications occurred at similar rates in both types of specimens and supports the reliability of the instrumentation and obturation techniques used.

Gancedo-Caravia et al. (23) highlighted that micro-computed tomography data-based printed dental models were considered anatomically similar to natural teeth by evaluators. However, they also reported that students' treatment performance decreased as the anatomical difficulty of the artificial teeth increased. Moreover, the special endodontic training models developed by Yekta-Michael et al. (24) using 3D printing technology, were positively evaluated by both students and instructors; the modified versions, in particular, were reported to offer more realistic experiences in procedures such as canal shaping.

Models like ChatGPT are expected to be used in clinical treatment simulations. The concept of a "clinical ward assistant" suggests that future chatbots could be customized and trained to use evidence-based content taught in didactic courses to help educate students and residents both in the clinic and in preparation for clinical work (25). For this reason, the present study utilized the ChatGPT-4o model as a representative example of an AI-based chatbot to explore its potential contributions to endodontic education.

The significant finding of this study was the weak agreement between the ChatGPT-based evaluations and those of a human examiner (κ=0.210), indicating fair but limited consistency. This suggests that current AI models are not yet reliable enough to act as autonomous evaluators in preclinical dental education. Nevertheless, they may still serve as useful supplementary tools to enhance student feedback—particularly under instructor supervision—provided that their outputs are critically reviewed due to potential issues with accuracy and reliability. This aligns with previous reports indicating that AI models often struggle to match expert judgment in complex, high-skill domains (15,26).

Although AI-based chatbots such as ChatGPT are considered to have significant potential in medical image analysis and clinical decision-making, it should be noted that ChatGPT-4o is not specifically trained for radiographic image interpretation and was not provided with any clinical context in this study. Its performance, therefore, reflects general-purpose visual reasoning. This may explain why a previous study using visual prompts found that ChatGPT-4o performs worse in image-based questions (e.g., radiological images) than in text-based ones (27). Another study showed that the accuracy of ChatGPT in image-based questions improved when clinical context was provided and decreased when context was absent (14). Since this study used only visual prompts, this limitation may help explain the low interobserver agreement observed. Previous studies also highlighted that although ChatGPT has potential in clinical decision-making, there is a risk of generating inaccurate or fabricated information such as hallucinations (28-30).

Due to concerns about the accuracy, originality, and ethical aspects of information generated by ChatGPT, its use in clinical and academic settings should be approached with caution, and all outputs must be reviewed by experts. Garg et al. (31) emphasized that while ChatGPT can be supportive in patient education, clinical documentation, and research processes, its accuracy and ethical dimensions must be carefully evaluated.

The "zero-shot" method used in this study refers to the model performing a task without prior training on that specific task or examples. Instead, it relies solely on general training data and a given prompt. This approach allows direct evaluation without the need for task-specific training or examples. Its advantages include rapid applicability and low cost, while its disadvantages include lower accuracy, reliability, and consistency in complex tasks. Zero-shot methodology is important because it allows models like ChatGPT to be adapted across various fields with ease. The approach used in this study yielded results consistent with previous zero-shot research (14,28,29). However, in the context of this study, the absence of any clinical background or descriptive text beyond the radiographic image likely contributed to the limited diagnostic accuracy of ChatGPT-4o. Future studies should compare zero-shot performance with context-enhanced prompts.

Within the limitations of this study, the samples were the students' first experience with RCT application. Also, according to our preclinical training program, students practice directly on printed and extracted teeth to increase their manual skills, and reinforce the treatment protocol before practicing on phantom models. The canal filling quality was assessed on 2D radiographs due to their ease of use during the educational process, and their accessibility by students. Future studies can examine applications across different educational models to evaluate student performance and measure the development of ChatGPT or another AI tool.

Conclusion

According to the findings of this study, while the type of sample significantly affects the adequacy of root canal filling length, it does not considerably influence the overall quality of the treatment. Printed teeth appear to be an effective alternative in preclinical education, particularly in terms of standardization and reproducibility. However, the educational value of natural teeth should not be overlooked.

AI-assisted evaluation methods, especially when used with visual content, currently show limited accuracy. ChatGPT offers promise in medical image interpretation and clinical decision support, but its performance in image-based tasks remains limited, particularly in the absence of clinical context. Therefore, these systems should only be used under expert supervision and supported by ethical and methodological standards. Future studies are needed to improve the accuracy and reliability of AI-based systems.

Authorship Contributions: Concept: A.O., T.A.; Design: A.O., H.C.; Supervision: A.O.; Fundings: H.C.; Materials: A.O., H.C.; Data: H.C.; Analysis: A.O.; Literature Search: T.A..; Writing: A.O., H.C.; Critical Revision: T.A.

Use of AI for Writing Assistance: Not declared.

Source of Funding: There was no external financial support.

Conflict of Interest: None declared.

Ethical Approval: The study was approved by the Scientific Research Ethics Committee of the University of Lokman Hekim (No: 2025/098, Date: 28.04.2025).

Informed consent: Not applicable.

Data availability statement: The data can be provided by the corresponding author upon request of the readers.

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ORIGINAL ARTICLE

Turk Endod J 2026;11(1):19–25
doi: 10.14744/TEJ.2025.09821

Prevalence of apical periodontitis in postmenopausal women with osteoporosis: A retrospective study

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Purpose: The aim of this study was to compare the prevalence of apical periodontitis (AP) between postmenopausal women diagnosed with osteoporosis (OP) and systemically healthy postmenopausal women, representing a Mediterranean subpopulation.

Methods: The study included 71 postmenopausal women aged between 50 and 70 years. Based on dual-energy X-ray absorptiometry (DEXA) results, participants were classified into two groups: osteoporotic and healthy. Panoramic radiographs of each subject were evaluated for the presence of AP and scored using the periapical index (PAI). Additionally, the decayed, missing, and filled teeth (DMFT) index, the number of root canal-treated (RCT) teeth, and smoking status were recorded. Statistical analysis was performed using the independent samples t-test, Mann–Whitney U test, and Chi-square tests ($p<0.05$). Interobserver agreement was found to be high ($\kappa=0.86$).

Results: No statistically significant differences were observed between osteoporotic and systemically healthy postmenopausal women in terms of AP prevalence, PAI scores, DMFT index, or the number of RCT teeth ($p>0.05$).

Conclusion: The findings suggest that OP may not be an independent risk factor for the development of apical inflammation in postmenopausal women. From a clinical perspective, pharmacologically managed OP does not appear to negatively affect endodontic prognosis. Further comprehensive, multicenter studies are warranted to better understand the impact of systemic bone diseases on periapical inflammation.

Keywords: Apical periodontitis; DMF index; dual-energy X-ray absorptiometry; osteoporosis; panoramic radiography; postmenopausal woman.

Introduction

Apical periodontitis (AP) is an inflammatory disease characterized by the formation of an osteolytic lesion at the root apex, triggered by polymicrobial colonization of the root canal system (1). These lesions arise as a result of cellular and humoral responses generated by the host defense system to eliminate microorganisms. Infectious stimuli activate various immune cells, particularly neutrophils and macrophages, leading to the production of numerous cytokines and chemokines that orchestrate the inflammatory

Cite this article as: Cankaya TD, Yoldas GP, Filiz M, Kuloglu B. Prevalence of apical periodontitis in postmenopausal women with osteoporosis: A retrospective study. Turk Endod J 2026;11:19-25.
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Submitted: July 29, 2025 Revised: August 28, 2025 Accepted: August 31, 2025 Published: April 27, 2026

process. In this context, mediators such as interleukin-1β (IL-1β), interleukin-6 (IL-6), tumor necrosis factor-α (TNF-α), and receptor activator of nuclear factor kappa-B ligand (RANKL) are among the key molecular mediators involved in periapical tissue destruction (2). The clinical course of AP may vary depending on the host's immune response capacity; the duration of infection and the balance of immune regulatory mechanisms play a decisive role in whether the lesion develops in an acute or chronic form (3).

Numerous studies in the literature have explored the bidirectional relationship between AP and systemic health (4,5). It has been demonstrated that AP is not confined to a local inflammatory response but also contributes to elevated levels of systemic inflammatory cytokines and induces molecular damage at the cellular level through oxidative stress (6). These biological mechanisms have the potential to contribute to the pathogenesis of systemic diseases, thereby necessitating the consideration of AP not merely as an oral infection but as an inflammatory focus with potential systemic implications. Current evidence suggests that AP may be associated with metabolic disorders such as diabetes mellitus and osteoporosis (OP) (7,8), autoimmune diseases including hepatitis, rheumatoid arthritis, and nephritis (9,10), cardiovascular diseases (4), hepatic dysfunction (11) and even adverse pregnancy outcomes (12).

OP is an age-related systemic skeletal disorder characterized by low bone mass and microarchitectural deterioration of bone tissue, leading to increased bone fragility (13). Depending on the factors affecting bone metabolism, OP is classified as primary—comprising postmenopausal (type I) and senile (type II) forms—and secondary, which develops because of systemic diseases, medications, or lifestyle-related factors (14). In the general population, the lifetime risk of osteoporotic fractures is reported to be approximately 40–50% in women and 13–22% in men (15). Postmenopausal women represent the highest risk group due to a marked decrease in estrogen levels accompanied by an increase in follicle-stimulating hormone (FSH); these hormonal changes trigger osteoclast-mediated bone resorption, thereby accelerating bone loss (16-18). AP and OP are bone-related diseases that share similar characteristics in terms of their inflammation-associated pathogenesis and their interaction with the aging process. Low bone mineral density has been proposed as a predisposing factor in the progression of periapical lesions. The presence of common mediators, risk factors, and biological pathways in the pathophysiological mechanisms of these two conditions renders the investigation of a potential relationship between OP and AP scientifically meaningful (19).

Although some evidence in the current literature suggests that OP may increase the risk or severity of AP, particularly in female patient populations, data supporting a strong and consistent association between these two conditions remain limited (20-23). Heterogeneity among findings, methodological variations, and sample diversity limit the generalizability of the results. Therefore, the aim of this retrospective study was to compare the prevalence of AP between postmenopausal women diagnosed with OP and systemically healthy postmenopausal women representing a Mediterranean subpopulation. The null hypothesis of the study was that there would be no statistically significant differences between osteoporotic and healthy postmenopausal women in terms of the number of AP cases, periapical index (PAI) scores, DMFT index (number of decayed, missing, and filled permanent teeth), or the number of root canal-treated (RCT) teeth.

Materials and Methods

Study Design and Ethical Approval

This retrospective observational study was approved by the Non-Interventional Clinical and Observational Research Ethics Committee of the Faculty of Dentistry, Alanya Alaaddin Keykubat University (No: 4-5, Date: 12/02/2025). The study was conducted in accordance with the ethical principles outlined in the Declaration of Helsinki. Anamnesis records, panoramic radiographs, and dual-energy X-ray absorptiometry (DEXA) bone mineral density measurements of all participants were retrospectively retrieved from the institution's digital archive system. All patients were adequately informed about the purpose of the study during the diagnostic and treatment process, and their written informed consent was documented in their medical files.

The sample size was determined using G*Power software (Version 3.1.9.7; Düsseldorf, Germany), based on a previously published study with a similar methodology (24). According to the power analysis, a minimum of 56 participants was required to achieve a statistical power (1–β) of 0.95 with an effect size of 0.90 and a significance level (α) of 0.05. Considering potential data loss, exclusion criteria, and observational variability, the sample size was expanded. Ultimately, a total of 71 participants were included in the study, consisting of 31 postmenopausal women diagnosed with OP and 40 systemically healthy postmenopausal women.

Sample Selection and Inclusion Criteria

Within the scope of this study, medical records of postmenopausal female patients aged between 50 and 70 years, registered in the hospital information management system of Alanya Alaaddin Keykubat University Faculty of Dentistry, were retrospectively reviewed. All included individuals had comprehensive medical anamnesis records, panoramic radiographic ima-ges, and DEXA measurements for the assessment of bone mineral density available in their digital files. During the diagnostic and treatment process, patients were informed about the procedures, and written informed consent was obtained from each participant.

Participants were divided into two groups based on their systemic status: The study group consisted of individuals diagnosed with primary OP (25), while the control group included systemically healthy individuals without a diagnosis of OP. The groups were selected to have a similar distribution in terms of age, menopausal status, socioeconomic level, and smoking habits. The inclusion criteria for both groups are summarized in Table 1.

Radiographic Evaluation and Diagnostic Criteria for Apical Peridontitis

Medical history, diagnostic, and treatment data of all patients were retrieved from the hospital information system and transferred to a standardized Excel database. Panoramic radiographic evaluations were performed using images obtained with a single device (Planmeca ProMax® 2D S3, Planmeca Oy, Helsinki, Finland). Radiographs were selected based on sufficient image quality and inclusion of the entire dentition. Third molars were excluded from the analysis. For each patient, the number of AP cases observed in both RCT and untreated teeth, PAI scores, DMFT index, and the number of RCT teeth were recorded. In addition, smoking status was classified as a binary variable (yes/no).

PAI scoring was performed based on the five-point system developed by Ørstavik et al. (26), which evaluates the radiographic characteristics of periapical tissues. Score 1 indicates normal periapical structures; score 2 corresponds to a slight widening of the periodontal ligament space; score 3 represents a radiolucency with some changes in bone structure but with poorly defined borders; score 4 denotes a well-defined, round or oval radiolucency at the root apex; and score 5 reflects a large, clearly defined radiolucency. All panoramic radiographs were independently assessed by two observers (G.P.Y. and M.F.) with clinical experience in endodontics. Prior to evaluation, the observers underwent standardization training, and all assessments were performed according to pre-defined criteria. To assess interobserver reliability, statistical analysis was conducted. Agreement between the two observers regarding PAI scores was found to be high, with a Cohen's kappa coefficient of 0.86, indicating excellent interobserver agreement.

Statistical Analysis

Statistical analyses were performed using IBM SPSS Statistics software (version 26; IBM Corp., Armonk, NY, USA). The Kolmogorov–Smirnov and Shapiro–Wilk tests were used to assess the normality of data distribution. Since the variables for the number of AP cases, PAI scores, and RCT counts did not follow a normal distribution, intergroup comparisons for these variables were conducted using the Mann–Whitney U test. For the DMFT index, which was normally distributed, the independent samples t-test was applied. The Chi-square test and Fisher's exact test were used for categorical variables. A significance level of $p<0.05$ was considered statistically significant for all tests.

Results

No statistically significant differences were found between postmenopausal women diagnosed with OP and systemically healthy postmenopausal women in terms of the number of AP cases, PAI scores, DMFT index, or the number of RCT teeth ($p>0.05$). Similarly, the distribution of smoking status did not differ significantly between the groups. Interobserver agreement was high, with a Cohen's kappa coefficient calculated at 0.86. Detailed data regarding these findings are presented in Table 2.

Table 1. Inclusion criteria for the OP and control groups

Criteria	OP group	Control group
Age range	50–70 years old	50–70 years old
Menopausal status	Postmenopause	Postmenopause
Systemic disease status	No systemic disease other than OP	Systemically healthy
OP diagnosis	DEXA T score ≤–2.5 and primary OP diagnosis is present	No OP detected with DEXA (T score ≥–1)
OP treatment duration	Have been treated with any OP medication for ≥1 year	Not received OP treatment
Radiographic recording	Panoramic radiography available	Panoramic radiography available
Socioeconomic status and smoking	Similar to the control group	Similar to the study group

*DEXA: Dual-energy X-ray absorptiometry; OP: Osteoporosis.

Table 2. Radiographic parameters compared between osteoporotic and systemically healthy postmenopausal women

Variable	OP Group	Control Group	p value
AP Number (Mean ± SD)	1.29±1.24	1.95±2.05	0.178
PAI Score (Mean ± SD)	2.80±1.32	2.89±1.38	0.796
DMFT Score (Mean ± SD)	22.58±9.58	21.60±7.21	0.624
RCT Number (Mean ± SD)	1.87±1.88	1.53±1.65	0.414
Smoking (n, %)	3 (9.7)	3 (7.5)	0.744

*AP: Apical periodontitis; DMFT: Number of decayed, missing, and filled permanent teeth; OP: Osteoporosis; PAI: Periapical index; RCT: Root canal-treated; SD: Standard deviation, Smoking was considered as a "yes" category. p<0.05 was considered statistically significant.

Discussion

In this retrospective study, the prevalence of AP and various radiographic parameters were compared between postmenopausal women diagnosed with OP and systemically healthy counterparts. The results supported the null hypothesis proposed prior to the study, as no statistically significant differences were found between the groups for any of the evaluated parameters. This finding suggests that OP may not be an independent determinant in the development or severity of periapical inflammation. However, the literature includes studies reporting conflicting results. Some have proposed that alterations in bone metabolism may influence the host response in the periapical region, potentially resulting in larger or more persistent lesions in osteoporotic patients. Nonetheless, it is important to recognize that such outcomes can be influenced by various factors, including patient selection criteria, systemic variability of OP, imaging modalities used, and the presence of comorbid systemic conditions. In the present study, a clearly defined age range and a systemically homogeneous population consisting exclusively of female subjects were evaluated, thereby providing data that help reduce the methodological heterogeneity observed in the existing literature.

The inclusion of postmenopausal women aged 50 to 70 years in the present study was planned with consideration of the potential diagnostic implications of the pathophysiological differences among OP subtypes. This age range represents a period during which postmenopausal OP is characterized by a marked decline in bone mineral density and increased fracture risk, yet precedes the stage at which senile OP typically becomes predominant. In senile OP, which develops with advancing age, bone formation slows more noticeably, and mineral accumulation may lead to calcification foci within the bone. These calcifications can obscure the typical radiographic features of postmenopausal OP—especially in trabecular bones such as the vertebrae—thus causing diagnostic uncertainty. Moreover, the generalized and balanced cortical bone loss seen in senile OP follows a different pattern from the trabecular bone degradation typically observed in postmenopausal OP (27). Therefore, to isolate the specific effects of postmenopausal OP and ensure the consistent application of diagnostic criteria, individuals in older age groups were excluded from the study. This approach aimed to assess the potential impact of OP on AP within a more homogeneous sample.

Several studies (21,28,29) have reported that AP progresses more rapidly and presents with greater severity in osteoporotic individuals, a finding that may be associated with increased bone resorption and altered inflammatory response profiles. López-López et al. (30) observed a marginal correlation between OP and radiolucent periapical lesions in postmenopausal patients, while Katz et al. (31) reported a higher prevalence of AP in osteoporotic individuals. Experimental studies conducted on animal models have also shown that OP may adversely affect periapical healing and significantly impair bone regeneration under osteoporotic conditions (32). In contrast, Cadoni et al. (24) concluded that OP does not play a significant role in the development of AP, emphasizing instead a potential relationship between altered healing dynamics in RCT teeth and the pharmacological treatments used by OP patients. Similarly, a cohort study conducted in Austria by Grun et al. (21) found no statistically significant difference in the prevalence of AP, either in endodontically treated or untreated teeth, associated with the presence of OP. Additionally, Alam et al. (33) reported no significant difference in PAI scores between postmenopausal women with OP and healthy controls. These findings are consistent with the results of the present study and suggest that OP may not be a directly influential factor in the development of apical lesions. This similarity supports the notion that, even when similar methodologies are applied across different geographic regions and patient populations, OP alone may not play a determinative role in the occurrence of AP.

In the present study, the DMFT index values of postmenopausal women diagnosed with OP did not differ significantly from those of systemically healthy individuals. This finding suggests that OP may not be a direct determinant of dental morbidity. Similarly, Grgic et al. (34) reported comparable DMFT values between postmenopausal women with OP undergoing bisphosphonate therapy and healthy postmenopausal controls. However, the same study emphasized that periodontal parameters were negatively affected, indicating that the impact of OP may be more pronounced on the periodontium (34). This suggests that systemic alterations in bone metabolism may not always be reflected in DMFT components, such as dental caries or restorations, but may elicit more sensitive biological responses at the level of periodontal tissues. Therefore, preventive oral health strategies become particularly important in the postmenopausal period.

The findings of the present study revealed that the number of RCT teeth in postmenopausal women diagnosed with OP did not differ significantly from that of systemically healthy individuals. To date, the existing literature lacks direct and conclusive evidence indicating a difference in the number of RCT teeth between postmenopausal women with OP and healthy controls. However, some studies have reported a higher frequency of invasive dental procedures among women diagnosed with OP (35). Root canal treatment is a commonly performed procedure in the general population, and its prevalence is influenced more by factors such as dental history, oral hygiene status, and access to care rather than systemic health alone (36). Therefore, more comprehensive and comparative studies are needed to clarify the potential impact of OP on the indication for root canal treatment.

In the treatment of OP, various pharmacological agents are available that aim to increase bone mineral density and reduce fracture risk. Among the most commonly used medications in Europe for this purpose are bisphosphonates, the RANKL inhibitor denosumab, estrogen, and selective estrogen receptor modulators (37,38). Considering their effects on bone metabolism, differences observed in the apical inflammatory response among osteoporotic patients may, in part, be attributed to biological variations induced by these pharmacological interventions. Specifically, bisphosphonates reduce bone resorption by suppressing osteoclast activity, and denosumab inhibits the RANKL pathway—both of which have the potential to influence the progression of periapical inflammation and the resolution of apical lesions (24,29). However, the findings related to these medications remain inconsistent in the literature, and their roles in the pathogenesis of AP have not yet been clearly defined. In the present study, all individuals diagnosed with OP had been under pharmacological treatment for at least one year, which may have contributed to the limited impact of OP on periapical tissues. This factor could partially explain the absence of a statistically significant difference in AP prevalence between osteoporotic and healthy individuals. Therefore, future studies should consider the type, duration, and biological effects of OP medications as independent variables when evaluating their potential influence on periapical inflammation.

This study provides a valuable contribution to the literature by focusing exclusively on postmenopausal women with a clearly defined age range, well-characterized systemic health status, and a documented duration of pharmacological treatment. However, several methodological limitations should be acknowledged. These include the inherent constraints of the retrospective study design, radiographic method represents an inherent limitation. While panoramic radiographs were useful for standardized retrospective data collection, their two-dimensional nature limits the sensitivity of detecting apical lesions compared with periapical radiographs or cone-beam computed tomography (CBCT). In addition, although all patients with OP had been under pharmacological treatment for at least one year, detailed individual data regarding the specific type and duration of medication could not be obtained. Since agents such as bisphosphonates and denosumab directly affect bone resorption, the lack of detailed medication analysis limited our ability to assess correlations with bone resorption rates. Moreover, periodontal health data were not available in the present study, which further restricts interpretation of the results. These limitations have been highlighted to guide future research. Furthermore, the relatively limited sample size must be acknowledged, even though it was determined by power analysis. Larger, multicenter studies with broader populations are still necessary to reach more generalizable conclusions. In this context, future research should include prospective, multicenter studies that integrate clinical, radiographic, and biochemical data to more comprehensively elucidate the relationship between OP and AP.

Conclusion

In this retrospective study, no statistically significant differences were found in the prevalence of AP or radiographic parameters between postmenopausal women diagnosed with OP and systemically healthy individuals. The findings suggest that OP may not be an independent risk factor for apical inflammation. However, considering the limited sample size, the retrospective design, and the absence of detailed medication and periodontal health data, this conclusion should be interpreted with caution. To better understand the nature of this relationship, larger-scale, prospective, multicenter studies incorporating clinical, radiographic, pharmacological and periodontal data warranted.

Acknowledgement: The authors would like to thank Dr. Özgür Toy, Specialist in Physical Medicine and Rehabilitation, for his scientific contributions regarding the systemic effects and pharmacological management of osteoporosis; and Associate Professor Duygu Koçak for her professional support and guidance during the statistical analysis process.

Authorship Contributions: Concept: T.D.C.; Design: T.D.C.; Supervision: T.D.C.; Materials: G.P.Y., M.F.; Data: G.P.Y., M.F.; Analysis: T.D.C.; Literature Search: T.D.C., G.P.Y., M.F.; Writing: T.D.C., G.P.Y., M.F., B.K.; Critical Revision: T.D.C., G.P.Y., M.F., B.K.

Use of AI for Writing Assistance: Not declared.

Source of Funding: None declared.

Conflict of Interest: None declared.

Ethical Approval: This retrospective observational study was approved by the Non-Interventional Clinical and Observational Research Ethics Committee of Alanya Alaaddin Keykubat University Faculty of Dentistry (No: 4-5, Date: 12/02/2025).

Informed consent: Written informed consent.

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ORIGINAL ARTICLE

Turk Endod J 2026;11(1):26–37
doi: 10.14744/TEJ.2025.44366

Patient satisfaction following root canal treatment by undergraduate and postgraduate dental students: A comparative questionnaire study

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Purpose: This study aimed to evaluate patient satisfaction following root canal treatment performed by undergraduate and postgraduate dental students.

Methods: A total of 120 patients were included (n=60 per group). A validated questionnaire was used, consisting of socio-demographic questions and eight satisfaction items scored on a 5-point Likert scale. Statistical analyses were performed using non-parametric tests, with significance set at $p<0.05$.

Results: No significant differences were found between the groups regarding socio-demographic variables ($p>0.05$). However, overall satisfaction scores were significantly higher among patients treated by postgraduate students ($p=0.001$). In the undergraduate group, differences were observed according to age and marital status, with some results only marginally significant ($p\approx0.04$). Patients with lower income reported greater satisfaction with treatment plan explanations ($p=0.027$).

Conclusion: Both groups received generally favorable satisfaction ratings; however, postgraduate students obtained significantly higher scores. In the undergraduate group, socio-demographic factors, particularly age and marital status, appeared to influence satisfaction levels. Overall, these findings suggest potential areas for improvement in dental education and clinical supervision, including strategies to enhance patient-centered care.

Keywords: Dental education; patient satisfaction; root canal therapy; students.

Introduction

Globally, the increasing demand for healthcare services and the efforts of healthcare providers to meet these demands in a competitive environment are undeniable realities. In recent years, the rise in public and private healthcare institutions has focused on addressing patients' needs and expectations. Ensuring patient satisfaction is crucial for the preference of healthcare institutions (1). Particularly in dentistry, patient satisfaction surveys are frequently used to evaluate service quality and suggest improvements. Data related to patient satisfaction are collected and evaluated using both quantitative and qualitative approaches (2).

In addition to satisfaction, factors such as ease of access to treatment and the proximity of dental clinics to patients' residences significantly influenced their choice of dentist.

Cite this article as: Ocak MS, Konus F, Oztekin F. Patient satisfaction following root canal treatment by undergraduate and postgraduate dental students: A comparative questionnaire study. Turk Endod J 2026;11:26-37.
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Submitted: July 08, 2025 Revised: August 25, 2025 Accepted: August 29, 2025 Published: April 27, 2026

However, patients' primary concern has consistently been the skills and techniques of the dentist (3). One study reported that the technique/skill of the dentist had the most significant impact on patient satisfaction (4). Consequently, patients often seek treatment from centers or universities with specialist dentists because of the perceived professional competence, skill, and status of the practitioners (5).

Academic dental institutions fulfill a dual mission—delivering patient care while training future professionals—where both undergraduate and postgraduate students perform procedures under supervision (3,6). This context raises an important question: Does the provider's level of training affect patient satisfaction, particularly in technically demanding procedures such as root canal treatment?

Root canal treatment is one of the most common procedures in dental training, but it often provokes patient anxiety and discomfort due to procedural complexity and multiple visits (7,8). While advancements in endodontic instrumentation and anesthesia have improved the experience, patients still report concerns related to intraoperative pain, treatment duration, postoperative clarity, and communication (9,10). These psychosocial and clinical factors together shape satisfaction scores (11).

Patient satisfaction is an important indicator reflecting both the quality of clinical education and the effectiveness of treatment services (12). For this purpose, the Dental Satisfaction Questionnaire (DSQ) is frequently used, as it allows multidimensional evaluation of the patient experience. Luo et al. (2) summarized the DSQ into six domains: Attitude, quality, convenience, cost, pain management, and patients' perceived needs for oral disease. In the present study, three domains were excluded. The cost domain was not relevant because patients did not directly pay treatment fees, as these were covered by social insurance. The pain management domain was excluded since it can be influenced by individual and psychological differences, potentially biasing results (13). The domain of perceived needs for oral disease prevention was also excluded, as it is more closely related to preventive and community dentistry rather than endodontic treatment. Therefore, only the domains of attitude, quality, and convenience were assessed in this study.

This study aimed to evaluate the satisfaction of patients receiving healthcare services in the field of endodontics from undergraduate and postgraduate students. The null hypothesis of the study was that there would be no difference in patient satisfaction levels between treatments performed by undergraduate and postgraduate students.

Materials and Methods

Ethical Approval and Sample Size Calculation

The study protocol was approved by the Firat University Non-Interventional Research Ethics Board (Date: 18.07.2024, No: 2024/10-14), and conducted in compliance with the principles of the Helsinki Declaration. Sample size calculation was performed using the G-Power 3.1.9.7 program (Universitat Kiel, Kiel, Germany), with a significance level (α\alphaα) of 0.05, power of 0.95, and effect size of 0.65. The minimum total sample size required was determined to be n=104. Consequently, in this study, the total sample size was set at n=120, with n=60 participants in each group (3,11).

Survey Form and Implementation

The survey was conducted between 29.07.2024 - 29.08.2024, coinciding with the duration of an endodontic internship for undergraduate students at the Department of Endodontics, Faculty of Dentistry, Firat University. Surveys were distributed in clinics where postgraduate students treated patients and in undergraduate clinics under the supervision of faculty members.

The inclusion criteria for the study were patients aged 18 and older who provided informed consent and were capable of understanding and answering the survey questions. The exclusion criteria were as follows: Patients who did not undergo root canal treatment during their appointment, emergency cases (e.g., trauma), patients who completed the survey incorrectly or incompletely, and patients with illiteracy. These criteria were determined in accordance with previous study evaluating patient satisfaction in endodontic clinics (11).

The survey used to evaluate patient satisfaction was adapted from a previous study in the literature (11). It consisted of two sections: "Socio-demographic" questions and "satisfaction" questions. The second section, which assessed patient satisfaction, included eight questions. Patients were asked to answer based on their experiences during treatment. In the original study, the questionnaire consisted of three sections (socio-demographic, importance, and satisfaction). In the present study, the 'importance' section was excluded, and only two sections were used: Socio-demographic information and satisfaction items. During the adaptation process, the content validity of the questions was reviewed by two endodontic specialists. Responses were scored on a Likert scale, with possible scores ranging from 1 to 5, and higher scores indicating more positive outcomes (1=very poor, 2=poor, 3=fair, 4=good, 5=very good). The internal consistency of the questionnaire was analyzed using Cronbach's alpha and found to be reliable (α=0.889).

Furthermore, when each item was deleted in turn, the alpha coefficient showed no substantial increase (ranging between 0.863 and 0.882), confirming the robustness of the scale. No separate pilot testing or pre-validation of the questionnaire was performed prior to the study.

For study design, informed consent was obtained from patients to participate in the survey after their root canal treatment. The survey was explained in detail, and patients were given the form to complete in the waiting room. To ensure objectivity and comfort, no identifying information was requested, and patients were left alone while completing the survey. The questionnaire was administered only once, immediately after treatment completion. Pre-treatment expectations were not assessed to minimize potential response bias, as patients might have perceived that their answers could affect the care to be provided. Physicians were not informed whether their patients participated in the survey.

Survey Form:

Section 1: Socio-Demographic Information

Gender? Female ( ) Male ( )

Date of Birth? ………/………/…………….

Marital Status? Married ( ) Single ( )

Education Level? Literate ( ) Primary School ( ) Middle School ( )

High School ( ) University and Above ( )

Household Income? Minimum Wage or Below ( ) Above Minimum Wage ( )

Have you previously completed this survey? Yes ( ) No ( )

Section 2: Satisfaction Form

(For the following items, please select the option that best represents your experience)

1. Satisfaction with the technical competence of the dentist

Very Poor/ Poor/ Fair/ Good/ Very Good

2. Satisfaction with the attitude of the dentist

Very Poor/ Poor/ Fair/ Good/ Very Good

3. Satisfaction with the continuity of care by the same dentist

Very Poor/ Poor/ Fair/ Good/ Very Good

4. Satisfaction with the length of waiting time

Very Poor/ Poor/ Fair/ Good/ Very Good

5. Satisfaction with the duration of the treatment

Very Poor/ Poor/ Fair/ Good/ Very Good

6. Satisfaction with the suitability of clinic hours

Very Poor/ Poor/ Fair/ Good/ Very Good

7. Satisfaction with the scheduling of the next appointment

Very Poor/ Poor/ Fair/ Good/ Very Good

8. Satisfaction with the detailed explanation of the treatment plan

Very Poor/ Poor/ Fair/ Good/ Very Good

Statistical Analysis

Statistical analyses were performed using IBM SPSS Statistics 22 software. The normal distribution of parameters was evaluated using the Kolmogorov-Smirnov test, which revealed that the parameters did not follow a normal distribution. While evaluating the study data, descriptive statistical methods (minimum, maximum, mean, standard deviation, median, frequency) were used, along with the Kruskal-Wallis test to compare quantitative data across different levels of education. The Mann-Whitney U test was used for two-group comparisons. For qualitative data comparisons, Chi-square and Continuity (Yates) Correction tests were applied. A significance level of $p<0.05$ was considered statistically significant.

Results

A total of 120 patients were included in the study, with 60 treated by undergraduate students and 60 by postgraduate students. The mean age of participants was 34.77±14.04 years, and the sample consisted of 62 males (51.7%) and 58 females (48.3%). There were no statistically significant differences between the two groups in terms of baseline socio-demographic variables, including age, gender, marital status, education level, and income ($p>0.05$).

Comparison of Overall Satisfaction Between Groups

Patients treated by postgraduate students reported significantly higher overall satisfaction scores compared to those treated by undergraduate students ($p=0.001$, $r=0.38$, large effect). The median scores across all eight satisfaction items were consistently higher in the postgraduate group, particularly for aspects related to technical competence, continuity of care, and clarity of communication (Table 1).

Gender-Based Subgroup Analysis

In the undergraduate group, male patients reported significantly higher satisfaction than females in two domains: Treatment duration ($p=0.019$) and suitability of clinic hours ($p=0.029$). However, no statistically significant gender-based differences were observed in the postgraduate group ($p > 0.05$) (Table 2).

Age-Based Subgroup Analysis

Among patients treated by undergraduate students, those aged ≤35 years reported higher satisfaction levels than

Table 1. Satisfaction scores of undergraduate and postgraduate groups

	Undergraduate Students (n=60)	Postgraduate Students (n=60)	Total (n=120)			
	Mean±SD (Median) (min-max)	Mean±SD (Median) (min-max)	Mean±SD (Median) (min-max)	p	Mean diff (95% CI)	Effect size (r)
Satisfaction with the technical competence of the dentist	4.38±0.72 (4.5) (2-5)	4.78±0.49 (5) (3-5)	4.58±0.64 (5) (2-5)	0.001*	0.40 (0.18-0.62)	0.275
Satisfaction with the attitude of the dentist	4.55±0.65 (5) (3-5)	4.85±0.36 (5) (4-5)	4.7±0.54 (5) (3-5)	0.005*	0.30 (0.12-0.50)	0.198
Satisfaction with the continuity of care by the same dentist	4.58±0.7 (5) (2-5)	4.8±0.48 (5) (3-5)	4.69±0.61 (5) (2-5)	0.048*	0.22 (0.00-0.43)	0.133
Satisfaction with the length of waiting time	3.78±1.08 (4) (1-5)	4.43±0.83 (5) (2-5)	4.11±1.01 (4) (1-5)	0.001*	0.65 (0.30-0.98)	0.309
Satisfaction with the duration of the treatment	3.77±0.98 (4) (1-5)	4.65±0.61 (5) (2-5)	4.21±0.92 (4) (1-5)	0.001*	0.88 (0.60-1.17)	0.463
Satisfaction with the suitability of clinic hours	4.17±1.03 (4) (1-5)	4.62±0.61 (5) (3-5)	4.39±0.87 (5) (1-5)	0.012*	0.45 (0.13-0.75)	0.203
Satisfaction with the scheduling of the next appointment	4.22±0.8 (4) (2-5)	4.58±0.65 (5) (3-5)	4.4±0.75 (5) (2-5)	0.006*	0.37 (0.10-0.63)	0.224
Satisfaction with the explanation of the detailed treatment plan	4.25±0.97 (5) (1-5)	4.63±0.71 (5) (2-5)	4.44±0.87 (5) (1-5)	0.010*	0.38 (0.08-0.70)	0.202
Total score	33.7±5.25 (34) (22-40)	37.35±3.57 (39) (24-40)	35.53±4.84 (37) (22-40)	0.001*	3.65 (2.05-5.23)	0.381

Mann Whitney U Test *p<0.05.

those aged ≥36 years, with statistically significant differences in treatment duration (p = 0.024, r=0.28, small-to-medium effect), clinic hours (p=0.042, r=0.24, small effect), and appointment scheduling (p=0.002, r=0.38, medium effect) and total satisfaction scores, with some of these differences reaching only marginal significance (p=0.019, r=0.30, medium effect). In contrast, age did not significantly influence satisfaction in the postgraduate group (Table 3).

Effect of Marital Status

In the undergraduate group, single patients expressed higher satisfaction than married patients regarding treatment duration (p=0.045, r=0.25, small effect) and clinic hours (p=0.002, r=0.36, medium effect), with total satisfaction scores, although the differences in treatment duration and overall satisfaction were only marginally significant (p=0.044, r=0.26, small effect). Interestingly, in the postgraduate group, married patients reported higher satisfaction in the continuity of care by the same dentist (p=0.030) (Table 4).

Education and Income Levels

No statistically significant associations were observed between education level and satisfaction scores in either group (p>0.05) (Table 5). However, in the undergraduate group, patients with income at or below the minimum wage reported higher satisfaction regarding explanation of the treatment plan compared to those with higher income levels (p=0.027, r=0.26, small effect). No such differences were observed in the postgraduate group (Table 6).

Discussion

With the rise in living standards, the demand for high-quality healthcare services has also increased. Medical centers and university hospitals have become focal points for improving healthcare providers' professional skills and training specialists. Patients seeking care in medical centers must accept that services will be provided not only by specialists but also by undergraduate and postgraduate students. Therefore, the quality of treatment provided by these students is of paramount importance (3). Therefore, this study evaluated the satisfaction of patients treated by undergraduate and postgraduate students, who play an important role in healthcare delivery. The hypothesis that satisfaction levels of patients treated by postgraduate students would be higher than those treated by undergraduate students was supported.

The findings revealed that satisfaction in the undergraduate group was mostly rated as "good"(4) and "very good"(5), although for certain questions like "Satisfaction

Table 2. Satisfaction scores by gender in both groups

	Undergraduate Students					Postgraduate Students				
	Male (n=27)	Women (n=33)				Male (n=35)	Female (n=25)			
	Mean±SD (Median) (min-max)	Mean±SD (Median) (min-max)	p	Mean diff (95% CI)	Effect size (r)	Mean±SD (Median) (min-max)	Mean±SD (Median) (min-max)	p	Mean diff	Effect size (r)
Satisfaction with the technical	4.26±0.86	4.48±0.57	0.423	0.23	-0.09	4.83±0.38	4.76±0.53	0.783	-0.07	0.02
competence of the dentist	(4) (2-5)	(5) (3-5)		(-0.12-0.60)		(5) (4-5)	(5) (3-5)		(-0.30-0.17)	
Satisfaction with the attitude	4.56±0.7	4.55±0.62		0.773	-0.01	4.83±0.38	4.86±0.35	0.825	0.02	
of the dentist	(5) (3-5)	(5) (3-5)		(-0.33-0.33)	0.03	(5) (4-5)	(5) (4-5)		(-0.17-0.24)	-0.02
Satisfaction with the continuity	4.59±0.8	4.58±0.61		0.531	-0.02	4.78±0.55	4.81±0.45	0.970	0.03	
of care by the same dentist	(5) (2-5)	(5) (3-5)		(-0.36-0.36)	0.07	(5) (3-5)	(5) (3-5)		(-0.24-0.33)	-0.00
Satisfaction with the length	4.07±0.96	3.55±1.12		0.062	-0.53	4.33±0.84	4.48±0.83	0.377	0.14	
of waiting time	(4) (2-5)	(4) (1-5)		(-1.04-0.02)	0.23	(5) (2-5)	(5) (2-5)		(-0.26-0.62)	-0.10
Satisfaction with the duration	4.11±0.8	3.48±1.03	0.019*	-0.63	0.287	4.78±0.43	4.60±0.66	0.358	-0.18	
of the treatment	(4) (3-5)	(4) (1-5)		(-1.11-0.16)		(5) (4-5)	(5) (2-5)		(-0.46-0.10)	0.10
Satisfaction with the suitability	4.48±0.8	3.91±1.13	0.029*	-0.57	0.260	4.50±0.71	4.67±0.57	0.390	0.17	
of clinic hours	(5) (2-5)	(4) (1-5)		(-1.03-0.08)		(5) (3-5)	(5) (3-5)		(-0.18-0.56)	-0.09
Satisfaction with the scheduling	4.33±0.88	4.12±0.74		0.172	-0.21	4.56±0.62	4.60±0.66		0.04	
of the next appointment	(5) (2-5)	(4) (2-5)		(-0.60-0.22)	0.16	(5) (3-5)	(5) (3-5)	0.669	(-0.29-0.40)	-0.05
Satisfaction with the explanation	4.41±1.01	4.12±0.93		0.097	-0.29	4.72±0.57	4.60±0.77		-0.13	
of the detailed treatment plan	(5) (1-5)	(4) (1-5)		(-0.76-0.25)	0.20	(5) (3-5)	(5) (2-5)	0.609	(-0.45-0.23)	0.05
Total score	34.81±5.34	32.79±5.08	0.110	-2.03	37.33±3.33	37.36±3.71	0.574		0.02	
	(37) (23-40)	(34) (22-40)	(-4.56-072)	0.21	(39) (28-40)	(40) (24-40)			(-1.76-2.01)	-0.07

Mann Whitney U Test *p<0.05.

Table 3. Age-based (≤35 vs ≥36) satisfaction comparison in both groups

	Undergraduate Students					Postgraduate Students				
	35 and under (n=41)	36 and over (n=19)				35 and under (n=28)	36 and over (n=32)			
	Mean±SD (Median) (min-max)	Mean±SD (Median) (min-max)	p	Mean diff (95% CI)	Effect size (r)	Mean±SD (Median) (min-max)	Mean±SD (Median) (min-max)	p	Mean diff (95% CI)	Effect size (r)
Satisfaction with the technical	4.49±0.71	4.16±0.69	0.054	-0.33	0.22	4.71±0.53	4.84±0.45	0.234	0.13	-0.10
competence of the dentist	(5) (2-5)	(4) (3-5)		(-0.69-0.03)		(5) (3-5)	(5) (3-5)		(-0.11-0.38)	
Satisfaction with the attitude	4.59±0.63	4.47±0.70	0.544	-0.11	0.07	4.79±0.42	4.91±0.30	0.200	0.12	-0.10
of the dentist	(5) (3-5)	(5) (3-5)		(-0.48-0.22)	0.03	(5) (4-5)	(5) (4-5)		(-0.05-0.29)	-0.02
Satisfaction with the continuity	4.61±0.70	4.53±0.70	0.566	-0.08	0.06	4.68±0.61	4.91±0.30	0.097	0.23	-0.14
of care by the same dentist	(5) (2-5)	(5) (3-5)		(-0.46-0.29)	0.07	(5) (3-5)	(5) (4-5)		(0.00-0.47)	-0.00
Satisfaction with the length	3.88±1.05	3.58±1.12	0.282	-0.30	0.13	4.25±0.89	4.59±0.76	0.081	0.34	-0.20
of waiting time	(4) (1-5)	(3) (1-5)		(-0.93-0.28)	0.23	(4) (2-5)	(5) (2-5)		(-0.05-0.76)	-0.10
Satisfaction with the duration	3.95±0.95	3.37±0.96	0.024*	-0.58	0.278	4.57±0.74	4.72±0.46	0.623	0.15	-0.05
of the treatment	(4) (1-5)	(3) (1-5)		(-1.11-0.11)		(5) (2-5)	(5) (4-5)		(-0.16-0.49)	0.10
Satisfaction with the suitability	4.34±0.94	3.79±1.13	0.042*	-0.55	0.244	4.61±0.63	4.62±0.61	0.935	0.02	-0.01
of clinic hours	(5) (2-5)	(4) (1-5)		(-1.17-0.01)		(5) (3-5)	(5) (3-5)		(-0.29-0.32)	-0.09
Satisfaction with the scheduling	4.46±0.60	3.68±0.95	0.002*	-0.78	0.379	4.64±0.56	4.53±0.72	0.694	-0.11	0.04
of the next appointment	(5) (3-5)	(4) (2-5)		(-1.24-0.31)	0.16	(5) (3-5)	(5) (3-5)	0.669	(-0.44-0.21)	-0.05
Satisfaction with the explanation	4.39±0.92	3.95±1.03	0.057	-0.44	0.23	4.61±0.74	4.66±0.70	0.766	0.05	-0.03
of the detailed treatment plan	(5) (1-5)	(4) (1-5)		(-1.00-0.08)	0.20	(5) (2-5)	(5) (2-5)	0.609	(-0.32-0.39)	0.05
Total score	34.71±5.05	31.53±5.15	0.019*	-3.18	0.303	36.86±4.17	37.78±2.96	0.277	0.92)	-0.13
	(35) (23-40)	(32) (22-39)		(-5.96-0.53)		(39) (24-40)	(40) (31-40)		(-0.83-2.77)	

Mann Whitney U Test *p<0.05.

Table 4. Marital status–based satisfaction comparison in both groups

	Undergraduate Students					Postgraduate Students				
	Married (n=28)	Single (n=32)				Married (n=36)	Single (n=24)			
	Mean±SD (Median) (min-max)	Mean±SD (Median) (min-max)	p	Mean diff (95% CI)	Effect size (r)	Mean±SD (Median) (min-max)	Mean±SD (Median) (min-max)	p	Mean diff (95% CI)	Effect size (r)
Satisfaction with the technical	4.32±0.67	4.44±0.76	0.361	0.12	-0.11	4.86±0.42	4.67±0.56	0.086	-0.19	0.15
competence of the dentist	(4) (3-5)	(5) (2-5)		(-0.25-0.47)		(5) (3-5)	(5) (3-5)		(-0.47-0.08)	
Satisfaction with the attitude	4.46±0.69	4.63±0.61	0.338	0.16	-0.11	4.92±0.28	4.75±0.44	0.079	-0.17	0.14
of the dentist	(5) (3-5)	(5) (3-5)		(-0.17-0.50)	0.03	(5) (4-5)	(5) (4-5)		(-0.36-0.03)	-0.02
Satisfaction with the continuity	4.5±0.69	4.66±0.7	0.250	0.16	-0.12	4.92±0.28	4.63±0.65	0.030*	-0.29	0.18
of care by the same dentist	(5) (3-5)	(5) (2-5)		(-0.19-0.49)	0.07	(5) (4-5)	(5) (3-5)		(-0.58-0.04)	-0.00
Satisfaction with the length	3.57±1.17	3.97±0.97	0.187	0.40	-0.16	4.5±0.81	4.33±0.87	0.375	-0.17	0.10
of waiting time	(4) (1-5)	(4) (2-5)		(-0.10-0.92)	0.23	(5) (2-5)	(5) (2-5)		(-0.61-0.25)	-0.10
Satisfaction with the duration	3.46±1.1	4.03±0.78	0.045*	0.57	-0.25	4.78±0.42	4.46±0.78	0.082	-0.32	0.18
of the treatment	(3.5) (1-5)	(4) (3-5)		(0.11-1.04)		(5) (4-5)	(5) (2-5)		(-0.68-0.01)	0.10
Satisfaction with the suitability	3.71±1.18	4.56±0.67	0.002*	0.85	-0.36	4.69±0.58	4.5±0.66	0.189	-0.19	0.14
of clinic hours	(4) (1-5)	(5) (2-5)		(0.37-1.32)		(5) (3-5)	(5) (3-5)		(-0.54-0.11)	-0.09
Satisfaction with the scheduling	4±0.94	4.41±0.61	0.102	0.41	-0.20	4.56±0.69	4.63±0.58	0.856	0.07	-0.02
of the next appointment	(4) (2-5)	(4) (3-5)		(0.02-0.82)	0.16	(5) (3-5)	(5) (3-5)	0.669	(-0.25-0.42)	-0.05
Satisfaction with the explanation	4.11±0.99	4.38±0.94	0.203	0.27	-0.15	4.67±0.68	4.58±0.78	0.696	-0.08	0.04
of the detailed treatment plan	(4) (1-5)	(5) (1-5)		(-0.20-0.75)	0.20	(5) (2-5)	(5) (2-5)	0.609	(-0.47-0.29)	0.05
Total score	32.14±5.69	35.06±4.49	0.044*	2.92	-0.26	37.89±2.92	36.54±4.32	0.158	-1.35	0.17
	(32) (22-40)	(35.5) (23-40)		(0.46-5.46)		(40) (31-40)	(38.5) (24-40)		(-3.40-0.62)	

Mann Whitney U Test *p<0.05.

Table 5. Education level–based satisfaction comparison in both groups

	Undergraduate Students				Postgraduate Students			
	Primary School (n=15)	High School (n=32)	University and above (n=13)		Primary School (n=14)	High School (n=27)	University and above (n=19)	
	Mean±SD (Median) (min-max)	Mean±SD (Median) (min-max)	Mean±SD (Median) (min-max)	p	Mean±SD (Median) (min-max)	Mean±SD (Median) (min-max)	Mean±SD (Median) (min-max)	p
Satisfaction with the technical competence of the dentist	4.27±0.70 (4) (3-5)	4.44±0.76 (5) (2-5)	4.46±0.52 (4) (4-5)	0.492	4.86±0.36 (5) (4-5)	4.70±0.61 (5) (3-5)	4.84±0.37 (5) (4-5)	0.718
Satisfaction with the attitude of the dentist	4.53±0.64 (5) (3-5)	4.56±0.67 (5) (3-5)	4.62±0.51 (5) (4-5)	0.907	4.86±0.36 (5) (4-5)	4.85±0.36 (5) (4-5)	4.84±0.37 (5) (4-5)	0.992
Satisfaction with the continuity of care by the same dentist	4.47±0.83 (5) (2-5)	4.62±0.61 (5) (3-5)	4.69±0.63 (5) (3-5)	0.603	4.86±0.36 (5) (4-5)	4.74±0.59 (5) (3-5)	4.84±0.37 (5) (4-5)	0.895
Satisfaction with the length of waiting time	4.00±0.76 (4) (3-5)	3.72±0.92 (4) (2-5)	4.08±1.32 (5) (1-5)	0.299	4.29±0.73 (4) (3-5)	4.33±1.04 (5) (2-5)	4.68±0.48 (5) (4-5)	0.323
Satisfaction with the duration of the treatment	3.73±0.70 (4) (3-5)	3.69±0.97 (4) (1-5)	4.08±1.19 (4) (1-5)	0.241	4.71±0.47 (5) (4-5)	4.52±0.75 (5) (2-5)	4.79±0.42 (5) (4-5)	0.436
Satisfaction with the suitability of clinic hours	4.40±0.74 (5) (3-5)	4.12±1.10 (4) (1-5)	4.38±0.87 (5) (2-5)	0.715	4.57±0.65 (5) (3-5)	4.56±0.64 (5) (3-5)	4.74±0.56 (5) (3-5)	0.515
Satisfaction with the scheduling of the next appointment	4.20±0.77 (4) (3-5)	4.25±0.76 (4) (2-5)	4.46±0.66 (5) (3-5)	0.277	4.36±0.63 (4) (3-5)	4.59±0.69 (5) (3-5)	4.74±0.56 (5) (3-5)	0.131
Satisfaction with the explanation of the detailed treatment plan	4.20±0.77 (4) (3-5)	4.34±0.94 (5) (1-5)	4.54±0.66 (5) (3-5)	0.404	4.57±0.51 (5) (4-5)	4.48±0.94 (5) (2-5)	4.89±0.32 (5) (4-5)	0.122
Total score	33.80±4.35 (34) (26-40)	33.75±4.94 (34) (23-40)	35.31±4.56 (36) (25-40)	0.374	37.07±3.1 (37.5) (31-40)	36.78±4.26 (39) (24-40)	38.37±2.65 (40) (32-40)	0.436

Kruskal Wallis Test *p<0.05

with the length of waiting time" and "Satisfaction with the duration of the treatment," responses were rated as "fair"(3) and "good" (4). In contrast, patient satisfaction scores for postgraduate students were consistently higher across all survey questions, ranging from "good"(4) and "very good" (5). These findings are consistent with those of Aydın et al.(11), who reported that patient satisfaction in postgraduate clinics was higher than that in undergraduate clinics in various endodontic departments. Specifically, satisfaction scores in postgraduate clinics were generally at the "good"(4) and "very good"(5) levels, and a similar trend was observed in our study. In clinics operated by undergraduate students, patients' satisfaction regarding "long waiting times" and "long treatment durations" aligns with the findings in the literature. The literature identifies waiting and treatment times as significant factors leading to patient dissatisfaction (14,15). However, the higher satisfaction scores observed among patients treated in postgraduate clinics suggest that the service provided was perceived as "very good"(5) by most patients. This could be attributed to postgraduate students' greater clinical experience and expertise, as well as the relatively more structured and organized clinical environment in which they work (16).

Alshali et al.(17) evaluated patient satisfaction with treatments performed by undergraduate dental students and reported that overall satisfaction was high, with respectful attitudes rated most positively, while pain management and treatment access were relatively lower. These findings highlight that satisfaction depends not only on technical skills but also on interpersonal and organizational factors. Similarly, our results showed that while undergraduate students achieved favorable scores in technical competence and continuity of care, their patients reported lower overall satisfaction than those treated by postgraduates, mainly due to longer treatment and waiting times (p=0.001).

The analysis of demographic variables (gender, age, marital status, educational level, and income level) showed that patient satisfaction regarding the clinician's technical competence, attitude, and continuity of care by the same clinician was high in both types of clinics, independent of these factors (p>0.05).

Many studies evaluating patient satisfaction have reported varying results concerning age and satisfaction levels (11,18,19). For example, ArRejaie et al.(18) found that in satisfaction surveys conducted in undergraduate clinics,

Table 6. Income level–based satisfaction comparison in both groups

	Undergraduate Students					Postgraduate Students				
	Minimum Wage and Below (n=25)	Above Minimum Wage (n=35)				Minimum Wage and Below (n=18)	Above Minimum Wage (n=42)			
	Mean±SD (Median) (min-max)	Mean±SD (Median) (min-max)	p	Mean diff (95% CI)	Effect size (r)	Mean±SD (Median) (min-max)	Mean±SD (Median) (min-max)	p	Mean diff (95% CI)	Effect size (r)
Satisfaction with the technical	4.48±0.65	4.31±0.76	0.414	-0.17	0.09	4.76±0.53	4.83±0.38	0.783	0.07	-0.02
competence of the dentist	(5) (3-5)	(4) (2-5)		(-0.53-0.21)		(5) (3-5)	(5) (4-5)		(-0.17-0.30)	
Satisfaction with the attitude	4.68±0.63	4.46±0.66	0.121	-0.22	0.17	4.86±0.35	4.83±0.38	0.825	-0.02	0.02
of the dentist	(5) (3-5)	(5) (3-5)		(-0.54-0.13)	0.03	(5) (4-5)	(5) (4-5)		(-0.24-0.16)	
Satisfaction with the continuity	4.6±0.82	4.57±0.61	0.430	-0.03	0.08	4.81±0.45	4.78±0.55	0.970	-0.03	0.00
of care by the same dentist	(5) (2-5)	(5) (3-5)		(-0.38-0.38)	0.07	(5) (3-5)	(5) (3-5)		(-0.33-0.21)	
Satisfaction with the length	4±1	3.63±1.11	0.211	-0.37	0.15	4.48±0.83	4.33±0.84	0.377	-0.14	0.10
of waiting time	(4) (2-5)	(4) (1-5)		(-0.83-0.15)	0.23	(5) (2-5)	(4.5) (2-5)		(-0.60-0.29)	
Satisfaction with the duration	3.96±0.98	3.63±0.97	0.147	-0.33	0.18	4.60±0.66	4.78±0.43	0.358	0.18	-0.10
of the treatment	(4) (1-5)	(4) (1-5)		(0.83-0.15)		(5) (2-5)	(5) (4-5)		(-0.09-0.44)	
Satisfaction with the suitability	4.36±1.08	4.03±0.98	0.081	-0.33	0.21	4.67±0.57	4.50±0.71	0.390	-0.17	0.09
of clinic hours	(5) (1-5)	(4) (2-5)		(0.86-0.18)		(5) (3-5)	(5) (3-5)		(-0.53-0.14)	
Satisfaction with the scheduling	4.32±0.75	4.14±0.85	0.450	-0.18	0.09	4.60±0.66	4.56±0.62	0.669	-0.04	0.05
of the next appointment	(4) (3-5)	(4) (2-5)		(-0.57-0.20)	0.16	(5) (3-5)	(5) (3-5)	0.669	(-0.39-0.29)	
Satisfaction with the explanation	4.48±1	4.09±0.92	0.027*	-0.39	0.26	4.60±0.77	4.72±0.57	0.609	0.13	-0.05
of the detailed treatment plan	(5) (1-5)	(4) (1-5)		(-0.88-0.11)	0.20	(5) (2-5)	(5) (3-5)	0.609	(-0.21-0.46)	
Total score	34.88±5.2 (36)	32.86±5.2	0.117	-2.02	0.20	37.36±3.71	37.33±3.33	0.574	-0.02	0.07
	(23-40)	(32) (22-40)		(-4.61-0.64)		(40) (24-40)	(38.5) (28-40)		(-1.95-1.79)	

Mann Whitney U Test *p<0.05.

younger patients aged ≤35 years had a more positive treatment experience. In their comprehensive study evaluating patient satisfaction at the dental clinic of Mulago Hospital in Kampala, Uganda, Mwebesa et al.(20) indicated that patients' marital status affected their satisfaction levels, with widowed patients reporting 1.34 times higher satisfaction than single patients. However, other studies have indicated no significant relationship between age and satisfaction " and "marital status and satisfaction" (11,19). This is notable as it underscores the need to consider a patient's age and marital status during treatment (3). These inconsistencies may be related to differences in study design, cultural context, and patient populations. For example, while some studies report higher satisfaction among younger or single patients, others found no association, possibly due to variations in expectations, communication preferences, and socioeconomic backgrounds. In the current study, the lower satisfaction observed among married and older patients may stem from extended treatment durations, waiting times, or the inconvenience of scheduling follow-up appointments, possibly causing disruptions in their parental or professional obligations.

Regarding education, it is generally accepted that patient satisfaction levels decrease as educational attainment increases (11,19,21). However, in the current study, as in the surveys by ArRejaie et al.(18) and Habib et al.(22) evaluating undergraduate clinics, no significant effect of education on satisfaction scores was observed ($p>0.05$). Although there was no statistically significant difference in understanding, information, and response to treatment among patients with different educational levels, numerically higher satisfaction was observed with increasing education levels (12).

Previous studies have highlighted that gender-satisfaction (11,18,19,22) and income level-satisfaction (11,18) relationships do not have significant effects. However, Hamasha et al.(6) reported that patients with higher incomes were more satisfied with their treatment than those with lower incomes. In this study, although no statistical difference was observed in household income ($p>0.05$), patients with higher income in the undergraduate group reported relatively lower satisfaction scores. Notably, the question regarding "satisfaction with the detailed explanation of the treatment plan" showed a statistical difference ($p=0.027$). Lee et al.(3) noted in their study evaluating the quality and satisfaction of dental treatments performed by undergraduates that these students may be less adept at thoroughly explaining treatment plans. Additionally, it is possible that patients with higher socioeconomic status expected more detailed explanations, similar to those in private practice settings, which may partly explain the relatively lower satisfaction in this subgroup (23).

The clinical education level of dental providers plays a pivotal role in shaping patient satisfaction outcomes. In this study, patients treated by postgraduate students reported significantly higher satisfaction, likely due to their greater clinical exposure, advanced theoretical training, and refined procedural skills. Postgraduate students may demonstrate greater competence in time management, communication, and patient education, which could contribute to more positive patient perceptions. Moreover, postgraduate clinics tend to operate within a more structured and systematic framework, ensuring smoother appointment scheduling and continuity of care—factors that are known to positively influence satisfaction (14). In contrast, undergraduate students, being in the earlier stages of clinical training, may experience difficulties managing longer procedures, providing detailed treatment explanations, or navigating unanticipated complications, all of which may prolong treatment duration and waiting times.

Patients at undergraduate clinics may expect a slower, learning-oriented pace and appreciate detailed care and consistent attention from a single student. In contrast, socioeconomically advantaged patients accustomed to private settings might prioritize efficiency and polished communication, which could explain lower satisfaction rates in such groups. Moreover, demographic factors such as age, marital status, and income appear to moderate patient perceptions of care. Personalized communication, trust-building, and attention to patient-specific preferences significantly improve satisfaction (24). Thus, enhancing undergraduate training should include not only technical proficiency but also patient-centered communication—through simulated interviews, real-time feedback, and time-management exercises. Tools such as virtual patient simulations and structured peer/expert feedback have shown promise in boosting communication skills .

An important limitation of this study is that only a partial version of the DSQ was used (2). The survey corresponded to only three themes (attitude, quality, and convenience) out of the six themes and 23 items in the updated DSQ, while other dimensions such as cost, pain management, and patients' perceived needs for prevention were excluded. Therefore, the findings provide only a partial reflection of overall patient satisfaction and should be interpreted with this limitation in mind. Another limitation of this study is that the type and number of teeth treated (e.g., anterior, premolar, or molar) were not stratified. Because molar treatments are generally more complex and time-consuming than anterior teeth, this variability may have influenced treatment duration and consequently affected patient satisfaction scores. Future studies should analyze satisfaction outcomes by tooth type to provide more standardized comparisons. Another limitation is that sociodemographic factors were analyzed using univariate methods rather than multivariate analyses. More comprehensive multivariate approaches (e.g., logistic regression) could provide deeper insights into the combined effects of these variables on patient satisfaction. The absence of such analyses may limit the interpretability of our findings. Previous studies have conducted two separate surveys before and after treatment as part of continuous assessment (3,11). However, the possibility of biased responses, as patients might perceive their pre-treatment answers as potentially influencing their upcoming care, cannot be ignored. Conducting the survey post-treatment in this study eliminated such bias and can be considered a strength.

The experiences of patients receiving endodontic treatment reflect the quality of clinical practice and the students' level. In particular, comparisons of treatments performed by undergraduate and postgraduate students are critical for understanding the effects of different levels of clinical education on patient satisfaction. Based on these studies, adjusting endodontic treatment programs at universities to provide students with more hands-on experience may be an important step in improving patient satisfaction. Furthermore, the development of additional support and feedback mechanisms specific to postgraduate students in clinical education may further improve the quality of treatment outcomes.

Conclusion

Patients treated by postgraduate students reported higher satisfaction scores, which may be related to their greater clinical experience, advanced theoretical training, and relatively more structured clinical environment in which they work. These findings suggest that differences in satisfaction do not necessarily reflect superior care but may instead be associated with the stage of clinical education and organizational factors.

From a practical perspective, the results highlight the importance of strengthening undergraduate curricula with specific educational interventions. These may include structured communication training, modules on time management, and simulation-based exercises to enhance technical proficiency and patient-centered care. Incorporating such targeted strategies could help reduce dissatisfaction related to prolonged treatment times and waiting periods and foster more positive patient experiences. This study shows the effect of student levels on patient satisfaction, while also revealing that socio-demographic factors are also an important factor affecting the success of clinical practice.

Acknowledgements: The authors would like to thank all the patients who participated in this survey.

Authorship Contributions: Concept: M.S.O.; Design: M.S.O., F.K.; Supervision: M.S.O.; Materials: F.K., F.O.; Data: F.K., F.O.; Analysis: F.K.; Literature search: F.K., F.O.; Writing: M.S.O., F.K.; Critical revision: M.S.O., F.K., F.O.

Use of AI for Writing Assistance: Not declared

Source of Funding: None declared.

Conflict of Interest: None declared.

Ethical Approval: The study protocol was approved by the Firat University Non-Interventional Research Ethics Board (Date: 18.07.2024, No: 2024/10-14).

Informed consent: Written informed consent was obtained from patients who participated in this study.

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ORIGINAL ARTICLE

Turk Endod J 2026;11(1):38–44
doi: 10.14744/TEJ.2025.74436

Shaping performance of local nickel-titanium rotary file systems on resin blocks

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Purpose: The increasing development and clinical adoption of nickel-titanium (NiTi) rotary systems in Türkiye highlights the need for performance comparisons with widely used reference instruments. This study aimed to evaluate the shaping ability of locally manufactured files (EndoPlus Universal Gold-EPUG and EndoArt Action Gold-EAG vs. ProTaper Gold-PTG) in terms of canal transportation, weight loss, and changes in prepared canal area using standardized resin blocks with 30° curvature and 16 mm length.

Methods: Twenty-four blocks with known initial weights were photographed under a stereomicroscope at 4× magnification, randomly divided into three groups, and prepared with rotary files up to size F2 following each system's sequence. Irrigation with 2 mL saline was performed after each instrument. Post-instrumentation weights were recorded using a precision balance, while canal transportation at apical, middle, and coronal levels and canal area changes were calculated by superimposing pre- and post-instrumentation images with ImageJ software. Data were analyzed using one-way and two-way ANOVA with Bonferroni post-hoc testing at a 0.05 significance level.

Results: Instrument fractures occurred in one sample from PTG (S2), four from EPUG (three S2, one S1), and two from EAG (S2). No statistically significant differences were found among the groups regarding canal transportation and shaped area changes (p=0.43 and 0.06, respectively). The greatest transportation was observed coronally in all groups (p=0.001). Coronal transportation was significantly higher than apical transportation in the PTG and EAG systems (p=0.001 and p=0.048, respectively). Weight loss was significantly different among all groups (PTG: 3.16±0.45 mg; EPUG: 4.63±0.26 mg; EAG: 5.90±0.63 mg; p=0.001).

Conclusion: Within the limitations of this study, the shaping performance of locally manufactured systems appeared comparable, though further research in extracted human teeth is recommended.

Keywords: Alloys; nickel titanium; root canal preparation.

Introduction

One of the fundamental requirements for the success of root canal treatment is the mechanical preparation of the canal system in a way that enables thorough cleaning and three-dimensional obturation.(1) The instrumentation of the root canal is a key stage in endodontic treatment and is considered a predictive factor for the long-term success of therapy when properly performed. Ideally, the mechanical preparation should provide the canal with a continuously tapered shape from the coronal portion to the apical third while preserving the original anatomy, respecting multi-

Cite this article as: Kaya BE, Özyürek EU. Shaping performance of local nickel-titanium rotary file systems on resin blocks. Turk Endod J 2026;11:38-44.
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Submitted: September 16, 2025 Revised: October 07, 2025 Accepted: October 10, 2025 Published: April 27, 2025

planar curvatures, and maintaining the apical foramen as small as possible.(2) The success of root canal shaping is not only evaluated by the enlargement of the canal but also by the ability to maintain the original canal path without deviation. Such deviations, known as transportation, particularly in the apical region, may compromise the adaptation and sealing of the root filling, thereby jeopardizing the treatment outcome.(3,4)

Recently, rotary nickel–titanium (NiTi) instruments have become an integral part of the endodontic armamentarium.(5) In addition to greater flexibility and shorter preparation time, their super elasticity has been associated with fewer procedural errors, such as zipping, ledge formation, or transportation, compared with stainless steel files.(6,7) NiTi rotary instruments have evolved considerably over the years and are now widely used in clinical practice. Both manufacturing processes and thermal treatments significantly influence their mechanical properties and overall performance.(8) Currently, a wide variety of NiTi systems with different cross-sectional designs and heat-treatment technologies are available in the international market.(5,9) ProTaper Gold (PTG, Dentsply Tulsa Dental Specialties, Tulsa, OK, USA) is a multi-file system composed of three shaping files (SX, S1, S2) and five finishing files (F1–F5) used in continuous rotation. PTG maintains the same design as its predecessor, ProTaper Universal (Dentsply Maillefer), featuring multiple progressive tapers, a convex triangular cross-section, and a modified guiding tip.(10) However, the high cost and limited accessibility of international brands have driven the development of locally manufactured NiTi rotary systems as alternative solutions for clinical practice. EndoArt Action Gold (EAG, Inci Dental, Istanbul, Türkiye) is a NiTi rotary system designed for efficient endodontic preparation, with a convex triangular cross-section, manufactured from CM (controlled memory)-wire and coated with gold plating, which enhances cyclic fatigue resistance and flexibility. EAG files have variable taper like PTG files and similar numbers of shaping and finishing files as the PTG system. There is also a blue alternative to this file system with 21-, 25- and 31-mm options.(11) Another system produced in Türkiye, EndoPlus Universal Gold (EPUG, Turkuaz Sağlık Hizmetleri, Denizli, Türkiye), is a heat-treated NiTi rotary system with a concave triangular cross-section. There are also silver and blue types of files with 19-, 21-, 25- and 31-mm length alternatives. EndoPlus files have an MDR (medical device regulations) certificate. This certificate governs the production and distribution of medical devices in the European Union.(12) Like PTG and EAG, EPUG includes 3 shaping files (Sx-19/.04, S1-18/.02, S2-20/.04) and 5 finishing files (F1-20/.07, F2-25/.08, F3-30/.09, F4, F5); however, data on the mechanical properties or shaping performance of this locally manufactured file system remain limited.(13,14) A recent study reported that scanning electron microscopy analysis of fractured types of EndoPlus files' (EndoPlus Flex Plus Gold X2) tips displayed classic cyclic-fatigue features, and energy dispersive X-ray spectroscopy confirmed a NiTi composition.(14) While internationally recognized systems such as PTG have been extensively studied in terms of both mechanical features and shaping ability(10,15), there is a significant lack of evidence concerning locally manufactured systems such as EAG and EPUG. Clinicians, both nationally and internationally, may widely use these NiTi files if studies yield positive results. Therefore, shaping performance of these files has to be further evaluated. Furthermore, assessing transportation alone is not sufficient, since canal area changes and weight loss are also clinically relevant parameters. Only a limited number of studies in the literature have simultaneously evaluated these three parameters.(16) While canal area change reflects the extent of canal enlargement and morphological transformation, weight loss directly demonstrates the amount of dentin removed; excessive removal weakens the canal wall and may negatively influence prognosis.(17,18) Hence, the combined evaluation of transportation, area change, and weight loss provides a multidimensional assessment of rotary systems in terms of both centering ability and dentin preservation. Specifically, no study to date has evaluated the effects of the aforementioned local systems on transportation, area change, and dentin removal. Therefore, the present study aimed to compare the shaping outcomes of PTG, EAG, and EPUG rotary systems in terms of canal transportation, area change, and weight loss. The null hypothesis was that PTG, EPUG, and EAG would not differ in (i) transportation at apical/middle/coronal levels, (ii) canal area change, and (iii) weight loss.

Materials and Methods

Sample Selection

The sample size was determined by power analysis using the G*Power program (Version 3.1.9.4, Kiel University). Based on previous studies(19,20), with an effect size of 0.7, an alpha error probability of 0.05, and a power of 80%, a total of 24 samples (n=8 per group) were included. Twenty-four resin block canals (Endo Training-Block, Dentsply Maillefer, Ballaigues, Switzerland) with a single 30° curvature and known initial weights were photographed under a stereomicroscope (SZ61; Olympus Corporation, Taichung, Taiwan) at 4× magnification (Fig. 1). The blocks were randomly assigned to three groups according to the shaping system to be used: ProTaper Gold (PTG, Dentsply

Fig. 1. A mechanism made of glass lamellae that allows stereomicroscope images of resin blocks to be taken from the same angle at all time.

Maillefer, Ballaigues, Switzerland), EndoPlus Universal Gold (EPUG, Turkuaz Sağlık Hizmetleri, Denizli, Türkiye) and EndoArt Action Gold (EAG, İnci Dental, Istanbul, Türkiye).

Sample Preparation

All shaping procedures were performed by a single experienced operator, and a new file was used for each specimen. Prior to shaping, a glide path was prepared in all samples with #10 and #15 stainless steel K-files (D-perfect, Shenzhen Guangdong, China) at the working length (WL). Each group was shaped according to the manufacturer's recommended sequence, speed, and torque, using an X-Smart endodontic motor (Dentsply Maillefer, Ballaigues, Switzerland):

PTG group: SX [to half of the canal length 300 rpm; 5.1 Ncm-19 (tip diameter)/.045(taper)], S1 (300 rpm; 5.1 Ncm-18/.02), S2 (300 rpm; 1.5 Ncm-20/.04), F1 (300 rpm; 1.5 Ncm-20/.07), and F2(25/.08) files were used at 300 rpm and 3.1 Ncm torque at WL, respectively.

EAG group: SX (300 rpm-3Ncm), S1, S2, F1, and F2 files at 300 rpm and 2.6 Ncm torque was used during preparation of simulated canals, respectively.

EPUG group: Sx-19/.04, S1-18/.02, S2-20/.04, F1-20/.07, F2-25/.08 were used during preparation of simulated canals, respectively.

After each shaping step, apical patency was confirmed with an ISO #10 K-file (D-perfect) advanced 1 mm beyond the WL. The canals were irrigated with 2 mL sterile distilled water as in a previous study(8) using a 30-G side-vented needle (Scope Endo FX, JECT, Türkiye) after every step. At the end of shaping after the final irrigation step, simulated canals were dried with paper points, re-weighed, and photographed again under the stereomicroscope.

Stereomicroscope Analysis and Transportation Measurement

All resin blocks were examined under a stereomicroscope under the same conditions, both before and after shaping. Images were obtained at 4× magnification using a colored stereomicroscope (SZ61) equipped with an integrated digital camera. All images were exported in PNG format and recorded for analysis. Pre- and post-shaping images were superimposed on the same plane using ImageJ software (v1.54c, NIH, USA) (Fig. 2A-C). During the superimposition process, only horizontal and vertical shifts were corrected using the "Align image by translation" command, while magnification and rotation were kept constant. The superimposed images enabled direct visualization of changes in canal morphology. Transportation analysis was performed separately in three regions of the canal (coronal, middle, and apical) as in previous studies.(21,22) In each region, the positions of the canal walls before and after shaping were manually identified on the superimposed images, and the differences in distance between the inner (concave) and outer (convex) walls were measured. The transportation value was calculated using the following formula: Transportation = inner wall distance – outer wall distance.

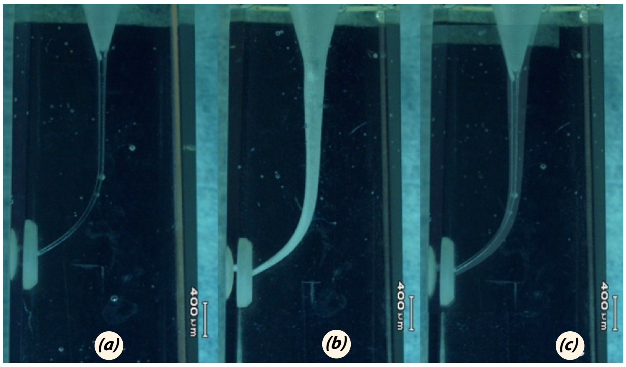

Fig. 2. Stereomicroscopic images of resin blocks showing the initial view **(a)**, the post-instrumentation view **(b)**, and the superimposed images **(c)**.

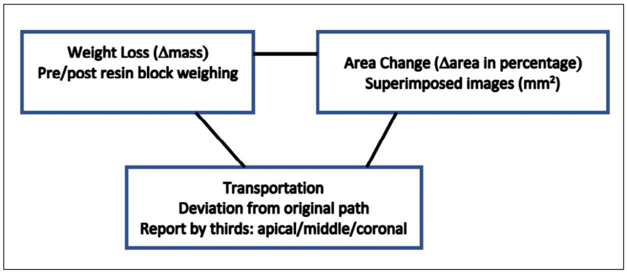

Fig. 3. Schematic representation of experimental setup.

Positive values indicated transportation toward the convex (outer) direction, whereas negative values indicated transportation toward the concave (inner) direction. All measurements were performed by the same investigator and at the same screen magnification to ensure standardization. The absolute values of transportation were used for statistical analysis.

Weight Change

Each resin block was weighed before and after shaping using an analytical balance with a precision of 0.0001 g (Radwag, Radom, Poland). All measurements were performed under a dry surface and stable environmental conditions. Three separate measurements were obtained for each sample, and their mean values were used for analysis. The weight difference between the post-preparation and the pre-preparation represented the amount of resin material removed during canal preparation and was recorded as weight loss in milligrams.

Area Change

For each resin block, canal areas before and after shaping were calculated using stereomicroscopic images. The images were analyzed with ImageJ software (v1.54c, National Institutes of Health, USA). The images were first converted to 8-bit grayscale format, and the canal lumen boundaries were manually delineated. The canal area was then measured in mm^2 using the "Analyze → Set Measurements → Area" command. The difference between the post-shaping and pre-shaping area values was considered as the increase in canal area. This value provided quantitative data regarding the canal enlargement effect of the file systems. All measurements were performed under identical magnification and contrast conditions by the same operator. Schematic representation of the experimental setup takes place at Figure 3.

Complications during experiments

During shaping, instrument fractures occurred in one sample of the PTG group (S2), four samples of the EPUG group (3-S2 and 1-S1) and two samples of the EAG group (2-S2). Acrylic resin blocks were eliminated, and new blocks were further included in the experiments.

Statistical Analysis

The transportation data were analyzed using two-way ANOVA with the Bonferroni post-hoc test, whereas weight and area changes were evaluated using one-way ANOVA with the Bonferroni post-hoc test. The significance level was set at $p<0.05$. SPSS software (v23, IBM Corp., Armonk, New York, USA) was used for statistical analysis.

Results

The results of the study are presented in Table 1. No

Table 1. Results of evaluated parameters

File systems	Parameters	Mean	SD	Min	Max
PTG Sx-F2	Transportation in m				
	Apical Third	54.94[a]	22.51	31.62	90.10
	Middle Third	80.26[ab]	35.03	48.00	141.65
	Coronal Third	117.19[b]	47.07	55.36	197.35
	Weight Difference in mg	3.16*	0.45	2.50	3.60
	Area Difference in percentage (%)	147.77	19.15	125.17	176.99
EPUG Sx-F2	Transportation				
	Apical Third	65.47[a]	21.11	44.18	113.35
	Middle Third	69.30[a]	25.19	42.80	114.53
	Coronal Third	90.99[a]	31.41	43.9	137.10
	Weight Difference	4.63"	0.26	4.30	5.10
	Area Difference	130.52	10.60	120.79	147.88
EAG Gold Sx-F2	Transportation				
	Apical Third	54.82[a]	20.47	31.49	94.41
	Middle Third	75.89[ab]	19.18	45.18	106.51
	Coronal Third	90.72[b]	31.30	58.54	156.76
	Weight Difference	5.90^	0.63	5.10	7.00
	Area Difference	131.49	14.25	114.49	152.75

a. b: reveal statistical difference between root thirds of same file system (for PTG group p=0.001, for EAG group p=0.048, for EPUG group p=0.182). *,",^: reveal statistical difference between weight loss of different file systems (p=0.001, for all comparisons). PTG: ProTaper Gold; EPUG: EndoPlus Universal Gold; EAG: EndoArt Action Gold; m: micron; mg: milligram.

statistically significant differences were observed among the file systems in terms of transportation values or area changes of simulated canals (p=0.43 and 0.06, respectively). In all groups, the highest transportation occurred in the coronal region (p=0.001). In the PTG and EAG systems, coronal transportation was significantly higher than the apical transportation (p=0.001 and p=0.048, respectively). Weight loss was significantly different among all groups (PTG: 3.16±0.45 mg; EPUG: 4.63±0.26 mg; EAG: 5.90±0.63 mg; p=0.001).

Discussion

In this study, the shaping performances of the locally manufactured EPUG and EAG rotary NiTi systems were evaluated in resin blocks in comparison with the internationally well-established PTG system. This study found no between-system differences in transportation or canal area change. The greatest transportation occurred coronally in all groups. Weight loss differed among systems (PTG<EPUG<EAG). Accordingly, the null hypothesis was accepted for transportation and area change but rejected for weight loss.

Root canal transportation was defined as any measurable deviation of the prepared canal from its original centerline/curvature, assessed by pre- and post-instrumentation image superimposition (e.g., micro-CT or standardized radiographs), indicating nonconcentric dentin removal and canal relocation.(23) A comprehensive recent review categorizes apical transportation, as an intra-operative error that can adversely influence periapical healing after root canal treatment.(24) Therefore, evaluating the transportation potential of file systems is important. Transportation could be calculated either with superimposed 2-dimensional images obtained via stereomicroscope(25,26) or cone-beam computed tomography.(27) Both methods have advantages and disadvantages. Superimposing images obtained with a stereomicroscope is a nondestructive, quick and low-cost method that allows fine sampling along the canal and is excellent for transparent or dyed resin blocks.(26) In the present study, the mean transportation value in the coronal region for the PTG, EPUG, and EAG groups was 0.12 mm, 0.09 mm and 0.09 mm, respectively. Several resin block studies that evaluated transportation and shaped area quantitatively through pre/post image superimposition have reported findings consistent with the present study.(10,15,25-27) Comparisons of PTG with different file systems such as WaveOne Gold (Denstply Maillefer, Ballaigues, Switzerland), TruNatomy (Dentsply Sirona, Maillefer, Ballaigues, Switzerland), Reciproc Blue (VDW, Munich, Germany) revealed no substantial differences in overall transportation, with the greatest deviations occurring coronally or in the middle/coronal regions.(15,25,26) Previous studies using one of these transportation evaluation methods reported for PTG 0.10-0.16 mm, 0.07-0.13 mm and 0.07-0.11 mm transportation at coronal (7 mm from apex), middle (5 mm from apex) and apical thirds (3mm from apex), respectively.(21,22,26) In the literature, studies evaluating shaping characteristics of locally manufactured EAG and EPUG are limited.(28) Mainly their cyclic fatigue characteristics are evaluated.(13,14) A recent study reported a mean apical transportation of 0.23 mm for another heat-treated EndoArt file, using CBCT cross-sections of extracted primary molars.(28) The differences in apical transportation may be attributed to factors such as the use of extracted teeth, the method of calculating transportation from cross-sections, or the specific type of EndoArt file used; in the current study, the mean apical transportation was 0.054 mm. Transportation tends to concentrate around the curved mid-coronal region, while apical deviation is usually smaller and kept below clinically critical thresholds. Mechanistically, curvature and taper drive this pattern: Larger coronal tapers and straightening forces produce asymmetric dentin removal coronally, whereas heat-treated NiTi better maintains apical curvature and typically keeps apical transportation <0.3 mm—the level beyond which sealing may be compromised.(4) None of the file systems exceeds this value in any of the evaluated thirds. These data support the present finding of higher coronal vs. apical transportation and align with guidance that canal curvature and taper selection are primary intraoperative risk factors for transportation.(29)

Change in the area of the simulated root canal was one of the parameters that was evaluated in the present study. The amount and pattern of canal enlargement produced during instrumentation are known to be dependent on the endodontic file system used. In the present study, no significant differences were observed among PTG, EPUG, and EAG with respect to changes in the shaped canal area. This outcome may be explained by the fact that EPUG and EAG were manufactured with taper values and geometric features closely resembling those of PTG. Previous investigations have highlighted that canal enlargement is strongly influenced by the design and kinematic properties of the instrument(30), and that geometric characteristics such as taper play a crucial role in the amount of dentin removed from canal walls.(10) Therefore, the absence of significant differences among the tested systems appears consistent with their comparable design philosophy and taper configuration.

Several studies that quantitatively assessed resin removal or weight loss have reported system-dependent differences in the amount of removed material, even when transportation values were similar.(8,25) This parameter quantitatively demonstrated the extent of material removal from the resin block in each system. Results of the current study indicate that cutting efficiency (and consequently weight change) may vary independently of shaping accuracy. In the present study, the weight-loss gradient observed (PTG<EPUG<EAG) is consistent with these findings, suggesting meaningful differences in cutting aggressiveness among systems that may not necessarily translate into clinically relevant variations in shaping accuracy. Similarly, Cecchin et al.(25) evaluated the cutting efficiency of different rotary NiTi instruments based on weight-loss analysis and reported significant differences among systems. Nevertheless, because resin blocks have lower microhardness compared with dentin and may soften due to heat generation during instrumentation(25,31), weight loss results may not fully represent clinical conditions. Therefore, findings from resin block studies should be corroborated by investigations in extracted human teeth to ensure their clinical applicability.(31)

Fracture of NiTi instruments has long been discussed as one of the major complications in endodontic treatment. The main mechanisms reported in the literature are cyclic fatigue and torsional loading, while in clinical conditions both factors often play a role simultaneously.(26) In the present study, the distribution of fractured instruments (PTG: 1, EPUG: 4, EAG: 2) reveals the need for further studies regarding local file systems. Mainly S2 (20/.04) (total 6 times) files were fractured in the simulated canals. Reported instrument fractures in simulated canals are generally low—several resin-block studies document no separations at all—yet incidence is system- and setup-dependent, as earlier standardized-block work with ProFile showed measurable fracture rates under severe curvature and highlighted operator effects.(32) Furthermore, it has been reported that the ProTaper Universal S2 exhibits the lowest cyclic-fatigue life among the new S1, S2, F1, F2 files.(33)

Simulated canals are widely accepted and considered a reliable model for investigating shaping efficiency because they provide anatomical standardization.(10,34) On the other hand, there are several limitations of the current study, such as the assessment of only one curvature angle, the two-dimensional limitation of ImageJ and stereomicroscopic analysis, and the sensitivity of weight measurements.

Conclusion

In resin-block models, weight loss, area/width change, and transportation provide complementary views of shaping behavior. Weight loss reflects overall cutting and, by proxy, dentin sacrifice; area change indicates the magnitude and distribution of enlargement relevant to irrigant exchange and obturation; transportation quantifies curvature maintenance, with apical deviation being most prognostically relevant. While these metrics are not direct surrogates for clinical outcomes, their comparative patterns help identify file systems that balance debridement with dentin preservation. Accordingly, the current finding of similar area changes and small transportation across PTG, EPUG, and EAG suggests broadly comparable shaping philosophies; clinically, this supports selecting among these systems based on handling, taper strategy, and case anatomy, while adhering to minimally invasive enlargement to preserve dentin.

Authorship Contributions: Concept: B.E.K., E.U.O.; Design: B.E.K., E.U.O.; Supervision: B.E.K., E.U.O.; Fundings: B.E.K., E.U.O.; Data: B.E.K., E.U.O.; Analysis: B.E.K., E.U.O.; Literature Search: B.E.K., E.U.O.; Writing: B.E.K., E.U.O.; Critical Revision: B.E.K., E.U.O.

Use of AI for Writing Assistance: Not declared

Source of Funding: None declared.

Conflict of Interest: The authors declare that they have no conflict of interest.

Ethical Approval: Not required.

Informed consent: Not required.

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ORIGINAL ARTICLE

Turk Endod J 2026;11(1):45–53
doi: 10.14744/TEJ.2025.03016

Efficacy of different irrigation solutions and techniques for removing intracanal medicaments used in regenerative endodontics: An in vitro study

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Purpose: This study assessed the efficacy of various irrigation solutions (EDTA, EDTA with benzalkonium chloride [BAC], ethanol, and glycolic acid) and techniques (conventional needle irrigation, sonic, and ultrasonic systems) for removing calcium hydroxide Ca(OH)2 and double antibiotic paste (DAP) medicaments.

Methods: $Ca(OH)_2$ and double DAP were placed in the canals of extracted single rooted human mandibular premolars. The specimens were divided into groups based on the irrigation solutions and techniques (conventional needle irrigation, sonic and ultrasonic activation) used. After removal of the medicaments, residues were evaluated using stereomicroscope. The Mann-Whitney U, the Kruskal-Wallis and by Dunn-Bonferroni post hoc tests were used to analyze the data.the study results at a 95% confidence level.

Results: The lowest residue scores were observed with 17% EDTA and 17% EDTA with BAC, regardless of irrigation techniques for $Ca(OH)_2$, and with 17% EDTA, 17% EDTA with BAC, and ethanol for DAP ($p<0.05$). The highest scores were obtained with 10% glycolic acid. The methods of irrigation showed similar effectiveness in each solution group.

Conclusion: EDTA and EDTA + BAC solutions provided the lowest residue scores, confirming EDTA's effectiveness regardless of the irrigation method. While BAC or ethanol may enhance intracanal medication removal, glycolic acid likely caused precipitation, leading to higher scores.

Keywords: Calcium hydroxide; double antibiotic paste; benzalkonium chloride; glycolic acid; ethanol.

Introduction

The process of root development of permanent teeth can be interrupted by decay or trauma resulting in incomplete root tips, thin dentin walls, and shorter root canal length (1). Apexification therapy with calcium hydroxide ($Ca(OH)_2$) or calcium silicate-based materials has been used for years for the treatment of these teeth. Alternatively, regenerative endodontic treatments (RETs) are emerging as an alternative treatment due to their potential to support the development of root thickness and length (2). With RETs, $Ca(OH)_2$ or combinations of antibiotics are used as intracanal medicaments for the disinfection of root canal. In recent years, double antibiotic paste (DAP) is now preferred over triple antibiotic paste (TAP) for RETs

Cite this article as: Ilgen S, Aslantas EE. Efficacy of different irrigation solutions and techniques for removing intracanal medicaments used in regenerative endodontics: An in vitro study. Turk Endod J 2026;11:45-53.
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Submitted: March 19, 2025 Revised: September 01, 2025 Accepted: September 11, 2025 Published: April 27, 2026

because of its reduced cytotoxicity and lower potential for tooth discoloration (3). Studies highlight that DAP is equally effective in eradicating bacterial biofilms while minimizing adverse effects (4). However, a common issue with applied intracanal medicaments is that they cannot be entirely removed from the root canal walls. Ethylenediaminetetraacetic acid (EDTA) is the most commonly used final irrigation solution in endodontics to dissolve inorganic tissues and remove intracanal medicaments. Also, EDTA significantly improves the efficacy of RETs by inducing the release of growth factors from the dentin matrix (5). For improved penetration depth of irrigation solutions, increased dentin permeability, and enhanced cleaning efficiency of canal walls, surfactants are added to irrigation solutions (6,7). One such surfactant, benzalkonium chloride (BAC), is a common cationic detergent used in ophthalmology to prevent contamination of eye solutions (8). In dentistry, BAC provides antimicrobial properties in dentin bonding agents and orthodontic composite resins (9,10). As such, the addition of a surfactant to EDTA is expected to benefit cell attachment.

In addition, studies investigating the use of alcohol solutions have shown that final irrigation with ethanol increases the wettability of root dentin by reducing surface tension and enhances $Ca(OH)_2$ removal from the apical third (11,12).

Glycolic acid (GA), also known as hydroxyethanoic acid or hydroxyacetic acid, is a colorless, odorless, and water-soluble substance that can be used for acid etching of enamel and dentin (13). GA has been reported to eliminate Gram positive and Gram negative bacteria and is used in the production of some antibiotics (14). Acid can eliminate free radicals and stimulate fibroblast production by inducing the formation of collagen fibers (15). Additionally, the fact that GA is more compatible with the environment and biodegradable could make it a viable solution for the final irrigation of root canals.

Improving the effects of irrigation solutions with physical methods and enhancing the level of disinfection of root canals has been a focus of interest. Irrigation with conventional needles (CNI) is a common and simple clinical application. However, this practice can also lead to problems given its lower degree of disinfection due to the vapor lock effect or if the needle tip is not inserted deep enough in the root canals.

The EndoActivator (Dentsply Tulsa, OK, USA) device generates sonic energy for irrigation of root canal systems. The sonic energy generated can cause a swirling movement of the solution in the pulp chamber and root canals, resulting in strong solution movement. During passive ultrasonic irrigation (PUI), acoustic flow and cavitation occur allowing the solution to flow from the apical to coronal direction within the root canal. These activation methods are applied to help improve the penetration and flow of irrigation into hard-to-reach areas of the root canal (16).

In a comprehensive literature review, few studies were found that compare the removal of DAP and $Ca(OH)_2$ paste that are used in RETs with various final irrigation solutions (eg, 17% EDTA, 17% EDTA with 0.008% BAC, 10% GA, and 70% ethanol) and irrigation methods (eg, CNI, sonic activation [SA], and PUI). Therefore, the aim of this study was to compare the effectiveness of various irrigation solutions and methods for DAP and $Ca(OH)_2$ paste removal in RETs. The null hypothesis of the study was that there would be no difference between the removal of DAP and $Ca(OH)_2$ paste between irrigation solutions and methods.

Materials and Methods

This study was approved by Hacettepe University's ethics committee (No: GO 22/247/2022/05-05, Date: 05/05/2022) and conducted according to Declaration of Helsinki. The study used a total of 252 single-rooted maxillary central and lateral incisor teeth from individuals aged 18 to 65 years that were extracted due to periodontal disease. Radiographs were taken from various angles for all teeth to confirm the presence of single canals. The teeth were examined under magnification using an operating microscope (Zeiss S7, Carl Zeiss, Germany) and those exhibiting caries, resorption, cracks, root fractures, or previous root canal treatment were excluded. Following radiographic and microscopic evaluations, teeth with a similar root morphology were selected. Soft tissue debris on the teeth was removed with a brush and calculus was removed mechanically with a periodontal scaler.

All teeth were decoronized at the cemento-enamel junction. Root canals were shaped with a ProTaper Universal rotary system (Dentsply-Maillefer, Ballaigues, Switzerland) using up to a F5 file at the specified working length. Between each file, 2 mL of 5.25% sodium hypochlorite (NaOCl) was used for irrigation of the root canals. For the final irrigation, 2 mL of 5.25% NaOCl followed by 2 mL of 17% EDTA was used. The root canals were then dried with paper points. To create an immature tooth form and to remove the apical deltas, the apical 3 mm of the specimens were removed with diamond discs and standardized to an average root length of 12±1 mm. To evaluate the canals after medicament removal, two longitudinal grooves were prepared on the buccal and lingual surfaces of each root using diamond discs ensuring not to damage the inner dentin layer of the root canal (17). The specimens were stored in saline to prevent dehydration before applying intracanal medicaments.

First, specimens were randomly assigned into two main groups: DAP or $Ca(OH)_2$ paste treated groups and then subsequently split into four subgroups for which the final irrigation solutions were to be applied. To evaluate the efficacy of irrigation methods, the subgroups were further divided into three groups, resulting in a total of 24 study groups (n=10 teeth per group). In addition, three positive and three negative control samples were prepared for DAP and $Ca(OH)_2$ groups.

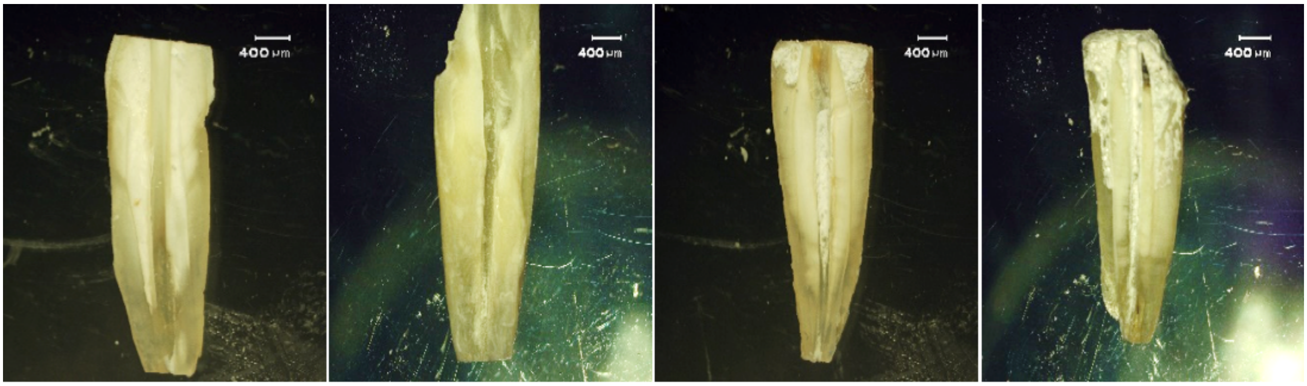
The $Ca(OH)_2$ paste was made by mixing powder and glycerin-containing liquid (Kalsin, Aktu Tic., İzmir, Türkiye) according to the manufacturer's recommendation. For the preparation of the DAP, equal amounts of metronidazole (Flagyl 500 mg, Sanofi, Lüleburgaz-Kırklareli, Türkiye) and ciprofloxacin (Cipro 500 mg, Biofarma, Istanbul, Türkiye) were ground in a mortar and then mixed 1:1 with glycerin-containing liquid (Kalsin). $Ca(OH)_2$ and DAP was applied to the root canals with #40 Lentulo spirals until the extrusion of paste was observed apically. Six untreated teeth were used as the negative control for DAP and $Ca(OH)_2$ groups. The apical root of the teeth was sealed with dental wax and the coronal part temporarily sealed with cotton pellets and Cavit (3M ESPE, St. Paul, MN, USA). The specimens were placed in a silicone impression material (President Dental, Allerhausen, Germany) and incubated in Eppendorf tubes for 2 weeks at 37°C and 100% humidity.

Commercially purchased 17% EDTA (Werax, Izmir, Türkiye) was used. 17% EDTA (Werax, Izmir, Türkiye) with 0.008% BAC (Dermosept Zefiran, Istanbul, Türkiye), 10% GA (Smart Kimya, İzmir, Türkiye), and 70% ethanol were freshly prepared immediately before the removal procedures.

For CNI, 27-gauge (ISO 0.41 mm) needles (Genject, Ankara, Türkiye) were used. With irrigation needles placed in the teeth 2 mm shorter than the working length, 2.5 mL of solution was applied to the root canal for 30 seconds with up-and-down movements. This procedure was repeated eight times for each specimen, using a total 20 mL of solution per specimen.

The large (Blue, 35/.04) tip of the EndoActivator (Dentsply Tulsa, OK, USA) was used for SA. After each 5 mL of solution was applied to the root canals, the device was moved up and down in the root canal for 30 seconds and repeated four times. For PUI, a single 20/.02 ultrasonic tip of EndoUltra (Vista Dental Products, Wisconsin, USA) was used. The series in the SA group was repeated ensuring to avoid contact of the ultrasonic tip with the walls. In the SA and PUI groups, 20 mL of solution was used for each sample, similar to the CNI group. The total solution activation time for each sample in the activation groups was 2 minutes. The placement and removal of medicaments was performed by a single researcher (S.I.). The evaluation of the samples was performed independently by two researchers (S.I. and E.E.A.). In cases of disagreement, the same sample was re-evaluated by both researchers and a consensus was agreed.

After removal of the medicament, the root canals were dried with paper cones. The roots were split in two with a hammer applied to thin cement spatula positions in the notches. Two distinct specimens were obtained from each tooth. Both samples were scrutinized using a stereomicroscope and the fragment with a higher residue was scored. The specimens were examined under 25x magnification using an Olympus SZ61 stereomicroscope (Olympus, Tokyo, Japan) and imaged using an Olympus DP12 camera (Olympus, Tokyo, Japan) attached to the microscope. Two observers independently evaluated and scored the stereomicroscope images of the teeth three times at 1-week intervals. Scoring was performed according to the criteria defined by Aksel et al. (18) (Fig. 1). Interobserver agreement



Score 1 Score 2 Score 3 Score 4

Fig. 1. Representative examples of medicament removal scoring and scoring criteria of samples.

was determined by Cohen's kappa test.

Data analyses were conducted with IBM SPSS Statistics v26 software. Comparisons between two independent groups were assessed by the Mann–Whitney U Test, while comparisons involving more than two independent groups were performed using the Kruskal–Wallis test. In cases where a significant difference was found among the groups following the Kruskal–Wallis test, the Dunn–Bonferroni multiple comparison test was used to identify the specific groups contributing to the difference. A 95% confidence interval (p=0.05) was used for all tests.

Results

$Ca(OH)_2$ removal

All irrigation methods in the EDTA group and SA and PUI in the 17% EDTA + 0.008% BAC group, were significantly more effective in removing Ca(OH)2 compared with the positive control group ($p<0.05$). However, no significant differences were found between irrigation methods within the same groups ($p>0.05$; Table 1). The GA group showed the least Ca(OH)2 removal compared with the negative control group ($p<0.05$). None of the

Table 1. Scoring results of calcium hydroxide paste groups

Solution	Irrigation Method	Median	Percentile 25 (Q1)	Percentile 75 (Q3)	Mean
	CNI[ı,y]	1.50	1.00	2.00	1.50
17% EDTA	SA[h,x]	1.00	1.00	2.00	1.40
	PUI[i,z]	2.00	1.00	2.00	1.70
17% EDTA + 0.008% BAC	CNI	2.00	2.00	2.00	2.20
	SA[d,f]	1.00	1.00	1.00	1.00
	PUI[e,g]	1.00	1.00	1.00	1.10
	CNI	2.00	2.00	2.00	2.00
70% Ethanol	SA	2.00	2.00	3.00	2.30
	PUI	2.00	2.00	2.00	2.10
	CNI[a,ı]	4.00	4.00	4.00	3.80
10% Glycolic Acid	SA[b,f,h]	4.00	3.00	4.00	3.60
	PUI[c,g,i]	4.00	4.00	4.00	3.80
Negative Control[a,b,c,j]		1.00	1.00	1.00	1.00
Positive Control[d,e,j,x,y,z]		4.00	4.00	4.00	4.00

BAC: Benzalkonium Chloride; CNI: Conventional Needle Irrigation; PUI: Passive Ultrasonic Irrigation; SA: Sonic Activation. *Same letters indicate a significant difference between the groups ($p<0.05$).

Table 2. Scoring results of the double antibiotic paste experimental groups

Solution	Irrigation Method	Median	Percentile 25 (Q1)	Percentile 75 (Q3)	Mean
17% EDTA	CNI[ı,y]	1.50	1.00	2.00	1.50
	CNI	2.00	2.00	2.00	2.10
	SA[o,u]	1.00	1.00	2.00	1.40
	PUI[ö]	1.50	1.00	2.00	1.50
17% EDTA + 0.008% BAC	CNI[p,ü]	2.00	1.00	2.00	1.60
	SA[r]	2.00	1.00	2.00	1.80
	PUI[t]	1.00	1.00	2.00	1.30
	CNI	2.00	2.00	3.00	2.30
70% Ethanol	SA[s]	2.00	2.00	2.00	1.90
	PUI[n,ş]	1.00	1.00	2.00	1.30
	CNI[k,ü]	4.00	4.00	4.00	3.80
10% Glycolic Acid	SA[l,u]	3.00	3.00	4.00	3.30
	PUI[m,ş,t]	3.00	3.00	3.00	3.20
Negative Control[k,l,m]		1.00	1.00	1.00	1.00
Positive Control[n,o,ö,p,r,s]		4.00	4.00	4.00	4.00

BAC: Benzalkonium Chloride; CNI: Conventional Needle Irrigation; PUI: Passive Ultrasonic Irrigation; SA: Sonic Activation. *Same letters indicate a significant difference between the groups ($p<0.05$).

Table 3. Comparative evaluation of the CNI group for both intracanal medicaments

	Median	Percentile 25 (Q1)	Percentile 75 (Q3)	Mean	P
CNI + EDTA					
$Ca(OH)_2$	1.50	1.00	2.00	1.50	0.035*
DAP	2.00	2.00	2.00	2.10	
CNI + EDTA^BAC					
$Ca(OH)_2$	2.00	2.00	2.00	2.20	0.52
DAP	2.00	1.00	2.00	1.60	
CNI + Ethanol					
$Ca(OH)_2$	2.00	2.00	2.00	2.00	0.28
DAP	2.00	2.00	3.00	2.30	
CNI + GA					
$Ca(OH)_2$	4.00	4.00	4.00	3.80	1.00
DAP	4.00	4.00	4.00	3.80	

BAC: Benzalkonium Chloride; GA: Glycolic Asid; CNI: Conventional Needle Irrigation. *The marked value indicates a statistically significant difference ($p<0.05$).

irrigation methods in the GA group could effectively remove $Ca(OH)_2$ ($p>0.05$; Table 1).

DAP removal

Similar to the Ca(OH)2 group, no significant differences were found between activation methods for the same irrigation solutions ($p>0.05$). SA and PUI used with 17% EDTA significantly improved canal cleanliness compared with the positive control group ($p<0.05$). SA and PUI with 17% EDTA + 0.008% BAC were also highly effective in removing antibiotic paste ($p<0.05$; Table 2). Additionally, SA and PUI with 70% ethanol showed significantly better removal of DAP compared with the positive control group ($p<0.05$; Table 2).

Comparative data analysis

The Mann–Whitney U test was used for pairwise comparisons of $Ca(OH)_2$ and DAP removal scores (Tables 4–6). With the CNI method, EDTA was significantly more effective in removing $Ca(OH)_2$ than DAP ($p<0.05$; Table 3). Using the SA method, $Ca(OH)_2$ was better removed when combined with EDTA + BAC ($p<0.05$; Table 4). PUI combined with ethanol resulted in significantly more DAP removal compared to the control ($p<0.05$; Table 5).

Discussion

In this study, maxillary central and lateral incisors from individuals aged 18–65 years were included. Due to the required sample size, full homogeneity could not be achieved; however, teeth with similar root canal morphology were selected based on radiographic and microscopic evaluation. As the study focused solely on the mechanical removal of medicaments—not their dentinal tubule pen-

Table 4. Comparative evaluation of the SA group for both intracanal medicaments

	Median	Percentile 25 (Q1)	Percentile 75 (Q3)	Mean	P
SA + EDTA					
$Ca(OH)_2$	1.00	1.00	2.00	1.40	1.00
DAP	1.00	1.00	2.00	1.40	
SA + EDTA^BAC					
$Ca(OH)_2$	1.00	1.00	1.00	1.00	0.007*
DAP	2.00	1.00	2.00	1.80	
SA + Ethanol					
$Ca(OH)_2$	2.00	2.00	3.00	2.30	0.165
DAP	2.00	2.00	2.00	1.90	
SA + GA					
$Ca(OH)_2$	4.00	3.00	4.00	3.60	0.28
DAP	3.00	3.00	4.00	3.30	

BAC: Benzalkonium Chloride; GA: Glycolic Asid; SA: Sonic Activation. *The marked value indicates a statistically significant difference ($p<0.05$).

Table 5. Comparative evaluation of the PUI group for both intracanal medicaments

	Median	Percentile 25 (Q1)	Percentile 75 (Q3)	Mean	P
PUI + EDTA					
$Ca(OH)_2$	2.00	1.00	2.00	1.70	0.481
DAP	1.50	1.00	2.00	1.50	
PUI + EDTA^BAC					
$Ca(OH)_2$	1.00	1.00	1.00	1.10	0.481
DAP	1.00	1.00	2.00	1.30	
PUI + Ethanol					
$Ca(OH)_2$	2.00	2.00	2.00	2.10	0.004*
DAP	1.00	1.00	2.00	1.30	
PUI + GA					
$Ca(OH)_2$	4.00	4.00	4.00	3.80	0.023*
DAP	3.00	3.00	3.00	3.20	

BAC: Benzalkonium Chloride; GA, Glycolic Asid; PUI: Passive Ultrasonic Activation. *The marked value indicates a statistically significant difference ($p<0.05$).

etration—this limitation can be considered as negligible.

None of the intracanal medicaments could be completely removed from the root canals with the tested irrigation solutions and techniques. Remnants of intracanal medicaments might also affect the properties of root canal sealer, such as hardening, adaptation, and penetration. However, with RETs, antibiotic paste residues have been shown to have a detrimental effect on stem cells in the apical papilla (19). Conversely, the positive or negative effect of $Ca(OH)_2$ paste residues on the bonding of tricalcium silicate-based materials to root canal dentin, which remains unclear in the literature. Some studies have shown that the detachment resistance of calcium silicate-based materials bonded to $Ca(OH)_2$-treated dentin is affected and even increased (20). However, these results have not yet been confirmed in the oral environment; therefore, the necessity for effective removal of intracanal medicaments from root canals remains until further studies are conducted.

In endodontics, there is increasing interest in the use of surfactants and changing the wetting properties by adding surfactants to solutions. As such, there are various studies in which BAC is used in combination with NaOCl (21-23). Bukiet et al. (23) reported that 0.008% BAC added to 2.4% NaOCl solution did not change the amount of free chlorine in NaOCl and also did not affect its cytotoxicity. Eren et al. (24) evaluated the effects of BAC when added to 17% EDTA solution at varying concentrations (0.008% and 0.1%) on the release of TGF-β1 and the level of dentin binding and proliferation of dental pulp stem cells (DPSCs). Both EDTA solutions with and without BAC increased DPSC binding and proliferation ($p>0.05$), while TGF-β1 release did not show a significant difference compared with the control group. There are few studies on the efficacy of BAC when added to 17% EDTA solution to remove intracanal medicaments; therefore, in our study, 0.008% BAC was added to 17% EDTA.

Given its low surface tension, the use of ethanol solution and its effects has been investigated in endodontics. Recent studies show that 70% ethanol does not change the inorganic content of dentin after removal of $Ca(OH)_2$ and can additionally increase the wetting properties of solutions by increasing surface energy (11). Dias-Junior et al. (12) showed that irrigation with 70% ethanol was significantly more effective than 2.5% NaOCl and 17% EDTA-T (17% EDTA + 0.2% lauryl sodium sulfate) in removing $Ca(OH)_2$ from root canals. On the other hand, Arslan et al. (25) reported that ethanol caused more TAP residues in root canals compared with 1% NaOCl combined with PUI. However, no study on the efficacy of ethanol in removing DAP exists. Therefore, 70% ethanol was included in our study to evaluate its effectiveness in removing intracanal medicaments.

GA is a colorless, odorless, and water-soluble substance. Due to its acidic nature, its effects on the removal of debris and intracanal medicaments have been investigated. The effectiveness of GA in removing the smear layer from the canal walls after root canal preparation was reportedly similar to EDTA and citric acid. Since GA, which was shown to be less cytotoxic than EDTA by Bello et al. (26), is a biodegradable acid, its use as an irrigation solution could be promising. In previous studies, GA has been tested at many different concentrations (27,28). However, since its negative effects on the apatite to collagen ratio and dentin microhardness have been shown at increasing concentrations (29), it was used at a concentration of 10% in our study.

When the mean results of both intracanal medicaments groups were analyzed, EDTA and EDTA with BAC solution groups had lower scores for removal. Studies comparing 17% EDTA solution with different final irrigation solutions for the removal of $Ca(OH)_2$ and antibiotic paste from root canals confirm the strong efficacy of the solution. Salgado et al. (30), reported that the combined use of NaOCl and EDTA-T had higher efficacy for the removal of $Ca(OH)_2$ paste from root canals compared with citric acid and NaOCl alone. Üstün et al. (31), compared the efficacy of 17% EDTA solution for the removal of TAP from root canals with peracetic acid and etidronic acid and reported the superior efficacy of 17% EDTA over the other solutions. In the literature, there is no study in which BAC was added to EDTA for the removal of intracanal medicaments. In our study, the SA and PUI subgroups of the EDTA with BAC irrigation group showed a similar efficacy to the EDTA only solution group, but produced lower residual scores, especially for the removal of $Ca(OH)_2$ paste ($p>0.05$). These results could be explained by the fact that BAC might have improved the wetting properties of the solution.

In our study, 70% ethanol showed an effective removal efficiency in the SA and PUI subgroups of the DAP group compared with the positive control group ($p<0.05$), which was not observed for $Ca(OH)_2$ ($p>0.05$). Arslan et al. (25) compared 17% EDTA with 100% ethanol for the removal of TAP and showed that the removal efficiency of both solutions was similar ($p>0.05$). Dias-Junior et al. (12) compared the efficacy of 70% ethanol and 17% EDTA-T for the removal of Ca(OH)2 and showed that 70% ethanol produced significantly cleaner root canal walls ($p<0.05$). These results could be explained by the low surface tension of ethanol, which allows it to clean deeper areas of the dentinal tubules compared with other solutions.

Conversely, the ethanol + PUI subgroup in our study showed an effective removal efficiency compared with the GA + PUI subgroup ($p<0.05$). 10% GA showed the lowest removal efficiency, causing the highest scores in both medicament groups. Altıntaş et al. (32) compared the effectiveness of 17% EDTA, 10% GA, and 70% ethanol for the removal of $Ca(OH)_2$ that was applied to root canals. Similar to our study results, 10% GA had the highest residual scores. On the other hand, Keskin et al. (33) removed $Ca(OH)_2$ paste placed in simulated resorption cavities in extracted teeth with 5%, 10% GA, 17% EDTA, and 10% citric acid solutions. Similar to our study, CNI and PUI were used as irrigation techniques. In the group activated with PUI, 10% GA removed more $Ca(OH)_2$ compared with other irrigation solutions ($p<0.05$). In the CNI group, the level of $Ca(OH)_2$ removal was not affected by the different solutions used ($p>0.05$). The positive results obtained with GA solution in the mentioned study are not consistent with our study, which might be due to the small size of the simulated cavities and final rinsing with distilled water. Observationally, after irrigation with GA, a salt-like precipitate formed within and around the canals. This precipitate dissolved completely upon rinsing with distilled water after the experiment. It is possible that this precipitate was a salt formed as a reaction between GA and $Ca(OH)_2$ and DAP. Therefore, irrigation with distilled water following the use of GA is recommended.

Each of the solution groups in our study were evaluated individually and the efficacies of CNI and activation methods (SA and PUI) were similar ($p>0.05$). In the literature, studies comparing needle irrigation or other activation methods show varied results. Some studies highlight the superiority of PUI over the EndoActivator (34,35), while others suggest that that these methods have similar efficacy for the removal of intracanal medicaments (36,37). However, a number of studies have reported the superiority of EndoActivator and PUI over CNI (38,39). Sarıçam et al. (40) compared different irrigation needle tips and the effectiveness of EndoActivator in their study where 17% EDTA solution was used as irrigation solution for the removal of antibiotic paste. According to micro-CT data, there was no significant difference between the effectiveness of needle irrigation and EndoActivator ($p>0.05$). However, Lloyd et al. (41) compared the effectiveness of the EndoUltra PUI device with CNI for the removal of $Ca(OH)_2$ paste that was applied to the mesial canals of mandibular molars. However, in our study, tips with different diameters were used in sonic and ultrasonic activation. A 35/04 tip was preferred for the EndoActivator due to its adaptation to the wide canals created in the samples. It is reported that during PUI, an ultrasonic tip freely oscillating within the root canal has a greater effect than a tip that contacts the canal wall (42). Additionally, EndoUltra has a single type of tip, which is sized 20/02. Although its smaller tip diameter compared with the EndoActivator was expected to negatively affect medicament removal, our results did not indicate inferior performance in terms of removal efficiency. The tip diameter alone might not determine the success of irrigation; other factors, such as activation, also appear to play a considerable role. Nevertheless, this issue remains one of the limitations of the study.

Conclusion

In our study, EDTA and EDTA + BAC solutions provided the lowest residue scores, highlighting EDTA's effectiveness for the removal of $Ca(OH)_2$ paste from root canals regardless of the irrigation method. While BAC or ethanol can enhance intracanal medication removal, GA likely caused precipitation, leading to higher scores.

Acknowledgements: This research was presented as an poster in FDI World Dental Federation World Dental Congress 12-15 September 2024 İstanbul, Türkiye.

Authorship Contributions: Concept: S.I., E.E.A.; Design: S.I., E.E.A.; Supervision: E.E.A.; Fundings: S.I., E.E.A.; Materials: S.I.; Data: S.I., E.E.A.; Analysis: S.I.; Literature Search: S.I., E.E.A.; Writing: S.I.; Critical Revision: E.E.A.

Use of AI for Writing Assistance: Not declared

Source of Funding: None declared.

Conflict of Interest: None declared.

Ethical Approval: This study was approved by Hacettepe University's ethics committee (No: GO 22/247/2022/05-05, Date: 05.05.2022)

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ORIGINAL ARTICLE

Turk Endod J 2026;11(1):54–62
doi: 10.14744/TEJ.2025.92408

Influence of heat-treated Ni-Ti rotary files and irrigant type on the accuracy of integrated apex locators: An in vitro study

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Purpose: This study investigated the effect of different nickel–titanium file systems and irrigation protocols on the accuracy of working length measurements during root canal preparation.

Methods: A total of 72 extracted mandibular central incisors were decoronated at 18 mm. Actual lengths (AL) were determined using a hand file and digital caliper under a microscope. Teeth were divided into four main groups based on irrigation solution, and then into two subgroups by file system: 2.5% or 5% NaOCl with/without 9% HEDP, combined with either WaveOne Gold(WOG) or WaveOne(WO). Root canals were shaped using WOG or WO files with a VDW Gold Reciproc motor in an alginate model simulating the oral environment, following the respective irrigation protocol. Electronic lengths (EL) were determined using an integrated electronic apex locator. EL–AL differences were calculated and analyzed using Kruskal-Wallis and Mann-Whitney U tests ($p<0.05$).

Results: No significant differences in EL–AL values were observed among the main irrigation solution groups or between files with different heat treatments ($p>0.05$). All tested conditions showed clinically acceptable accuracy.

Conclusion: These findings suggest that the type of file system and irrigation solution, including continuous chelation, do not compromise the reliability of EL determination during endodontic treatment.

Keywords: Chelating agents; endodontics; nickel-titanium; root canal preparation; sodium hypochlorite.

Introduction

One of the most critical steps for performing a successful root canal treatment is to accurately determine the working length. The apical constriction, also known as the minor foramen, serves as a key anatomical reference point for effective treatment (1). The studies that examined periapical tissues following root canal therapy have consistently demonstrated that the best clinical outcomes are achieved when treatment is terminated at the apical constriction level. Working length can be determined by using tactile sensation, radiographic evaluation, checking for the presence of moisture on paper points, having root canal morphology knowledge, and so on. The most commonly used

Cite this article as: Mumcu AK, Ozdemir Tekin ZY, Kurnaz S, Manti AS, Kiraz G, et al. Influence of heat-treated Ni-Ti rotary files and irrigant type on the accuracy of integrated apex locators: An in vitro study. Turk Endod J 2026;11:54-62.
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Submitted: September 01, 2025 Revised: October 25, 2025 Accepted: November 06, 2025 Published: April 27, 2026

method is the combination of periapical radiographs and electronic apex locators (EALs) (2).

The fundamental operating principle of EALs is based on the assumption that human tissues possess specific electrical properties. EALs determine the apical foramen location by measuring the changes in the resistance or impedance of dental tissues (3). To ensure rapid and efficient root canal preparation, manufacturers have integrated EALs into endodontic motors, allowing working length control during instrumentation (4). These hybrid devices not only regulate torque and speed but also enable the real-time monitoring of the apical limit while mechanically shaping the root canals using nickel-titanium (Ni-Ti) files. This is paramount for preventing over- or under-instrumentation during root canal treatment. Under-instrumentation can result in the retention of microorganisms and pulp remnants in the uninstrumented areas of the root canal system, which compromises the success of endodontic treatment (5). Conversely, over-instrumentation may lead to the extrusion of instruments, irrigants, pulp debris, microorganisms, and their toxins beyond the apical foramen, causing acute periapical irritation. If not corrected, over-instrumentation may further result in overfilling, leading to treatment failure (6).

The measurement accuracy of EALs depends on various factors, such as the type and size of the instrument used and the irrigation solutions applied (7). Ni-Ti files, frequently used in endodontic treatment because of their superelasticity and flexibility, undergo different heat treatments to improve their mechanical properties and enhance their fracture resistance. Owing to these favourable characteristics, heat-treated Ni-Ti rotary file systems are widely utilised in endodontic practice (8,9). However, the studies that evaluated EALs' accuracy when used in conjunction with heat-treated Ni-Ti files are limited (7,10).

During the mechanical instrumentation of root canals, a smear layer is formed on the radicular dentin surface. This layer may harbour bacteria and can hinder the penetration of antimicrobial agents and root canal filling materials into the dentinal tubules (11). Alternating irrigation with ethylenediaminetetraacetic acid (EDTA) and sodium hypochlorite (NaOCl) is recommended for effectively removing the layer. NaOCl, commonly used at concentrations ranging between 0.5% and 6%, is a non-specific proteolytic agent with notable tissue-dissolving capability and pronounced antimicrobial and anti-biofilm properties. However, NaOCl alone cannot completely eliminate the smear layer or prevent hard tissue debris accumulation. Such debris may act as a physical barrier, impeding NaOCl's access to the root canal system's anatomical intricacies and thereby reducing its antimicrobial efficacy (12). To overcome this limitation and facilitate inorganic debris removal, a chelating agent such as EDTA, typically used at concentrations ranging between 15% and 17%, is applied after NaOCl irrigation for one to two minutes. While EDTA is widely used in daily clinical practice, it has several drawbacks, including cytotoxicity, reduced bonding strength of resin-based filling materials, limited effectiveness in removing the smear layer from the apical third, depletion of free chlorine when mixed with NaOCl, and precipitate formation when combined with chlorhexidine (13).

Recently, the Dual Rinse irrigating solution (Medcem, Weinfelden, Switzerland) was introduced to the market, which combines NaOCl with etidronic acid (1- hydroxyethane-1, 1-diphosphonic acid; HEDP). It simultaneously provides chelating and disinfecting actions. The term "continuous chelation" does not refer to the removal of an already formed smear layer but rather to the prevention of its formation during instrumentation by the continuous use of the Dual Rinse irrigating solution. The HEDP–NaOCl combination offers clinical advantages by maintaining the solution's tissue-dissolving ability without increasing NaOCl's cytotoxicity (14). Moreover, the electrochemical properties and conductivity of irrigation solutions influence impedance measurements in electronic apex locators, which may lead to deviations in working length measurements depending on the irrigant used during root canal preparation (15).

The irrigation solutions used in the cleaning and shaping phases of endodontic treatment play a critical role in effectively disinfecting the root canal system. The electrolytes present in root canals are considered one of the primary factors that influence the accuracy of certain EALs' working length measurements (16). In this context, understanding the effects of the various irrigants used in root canal treatment on EAL accuracy is quite significant. In addition to irrigation solution type, the mechanical properties of Ni-Ti file systems used during root canal instrumentation may also influence the accuracy of integrated apex locators (IALs). Heat-treated NiTi files such as WaveOne Gold demonstrate superior flexibility and greater resistance to cyclic fatigue compared to conventional NiTi instruments due to their proprietary thermal processing (17). In contrast, WaveOne files, manufactured from M-Wire NiTi alloy, show reduced flexibility and shape memory, resulting in different behavior during canal preparation (17). Numerous studies have investigated the impact of different irrigation solutions on EAL accuracy, but no comprehensive study, to the best of our knowledge, has evaluated the effect of heat-treated Ni-Ti rotary file systems, in combination with various concentrations of

NaOCl and continuous chelation, on the measurement accuracy of IALs. This study evaluated the effect of using two heat-treated Ni-Ti files, in combination with varying concentrations of NaOCl and continuous chelation, on the accuracy of IALs during root canal preparation performed with an integrated endomotor. The following null hypothesis was tested: The combined use of NaOCl at different concentrations and continuous chelation, together with heat-treated Ni-Ti files, has no statistically significant effect on the measurement accuracy of IALs.

Materials and Methods

Sample size calculation and inclusion/exclusion criteria

This in vitro study received ethical approval from the Kütahya university ethics committee (Reference No: 2024/10-11, Date: 12/08/2024) and the study is conducted according to Declaration of Helsinki. Sample size estimation using G*Power (version 3.1.9.7) revealed that allocating nine samples to each group would provide 80% statistical power at a 0.05 significance level with an effect size of 0.5. The manuscript of this laboratory study has been written according to Preferred Reporting Items for Laboratory studies in Endodontology (PRILE) 2021 guidelines.

A total of 72 extracted human mandibular central incisors with approximately similar root dimensions were selected for this study. The inclusion criteria were: single straight root canal, fully developed apex, intact root structure, and root canal curvature less than 10°, measured according to Schneider's method (18). The exclusion criteria were: previously root canal–treated teeth, primary teeth, teeth with caries, restorations, internal or external root resorption, root fractures or cracks, calcified canals, or open apices. Clinical examination confirmed that the selected teeth were free of caries, restorations, and signs of resorption. Standardized periapical radiographs were taken from the buccal, lingual, mesial, and distal aspects to confirm canal morphology and exclude anatomical variations. The specimens were also examined under a dental operating microscope to detect any cracks or structural defects. All teeth were obtained with informed consent and ethical approval from the Department of Oral and Maxillofacial Surgery, Kütahya Health Sciences University, and were extracted for orthodontic or periodontal reasons. Immediately after extraction, the teeth were rinsed with phosphate-buffered saline, and the periodontal tissues were removed from the root surfaces using a curette.The specimens were stored in saline solution at 4°C until use.

Experimental design

For standardization, all the teeth were decoronated to a working length of 18 mm, which was done by marking the root surface with an acetate pencil and a digital caliper and creating a flat reference surface at 18 mm with a diamond fissure bur. A #10 K-file (Dentsply Maillefer, Ballaigues, Switzerland) was used to verify the apical patency, and the teeth in which a #20 K-file (Dentsply Maillefer, Ballaigues, Switzerland) fit snugly at the apex were included. During initial canal patency verification, teeth in which a #20 K-file (Dentsply Maillefer, Ballaigues, Switzerland) did not passively reach the apical foramen were excluded and replaced with new specimens meeting the inclusion criteria; therefore, the total sample size was maintained (n=72).

Before the experimental measurements, the digital caliper (Hogetex, Germany; 0.01 mm precision) was verified using a 10 mm gauge block to ensure measurement accuracy. The actual length (AL) was determined when the tip of a #15 K-file (Dentsply Maillefer, Ballaigues, Switzerland) became visible at the apical foramen under ×19.4 magnification using a dental operating microscope (OMS 2350, Zumax Company, China). A reference point was marked on the coronal surface of each tooth to ensure consistent positioning during all measurements. The distance between the rubber stopper and the file tip was then measured using a digital caliper under microscopic magnification, and this value was recorded as the AL. For each tooth, the measurement was repeated three times consecutively by a single operator, and the mean value was calculated. To ensure standardization, the electronic length (EL) was subsequently measured 0.5 mm short of the AL for all specimens. To minimize potential bias, all recorded working lengths were documented according to the assigned specimen numbers by another researcher (A.K.M.) who was not involved in the measurement procedures.

Experimental groups

The teeth were randomly divided into eight experimental groups according to the type of irrigation solution and the Ni-Ti alloy of the rotary instruments used during root canal preparation (n=9), using a computer-generated random number sequence at randomizer.org. (n=9). (Table 1)

Freshly prepared alginate (Tropicalgin, Zhermack Spa, Badia Polesine, Italy) was placed into plastic containers. The root specimens prepared up to the cementoenamel junction (CEJ), along with the labial clip of the EAL integrated into the VDW Gold Reciproc (VDW GmbH, Munich, Germany) device, were embedded in the unset alginate. To maintain proper conductivity and moisture levels, all the measurements were completed within 30 minutes after the alginate moulds were prepared. The EAL function of the VDW Gold Reciproc endomotor was operated under software version 1.0. The VDW Gold Reciproc endomo-

Table 1. Group classification according to the type of irrigating solution and Ni-Ti file system

Groups	İrrigation Solution	Ni-Ti File
Group 1a	2.5% NaOCl	WOG #25.07
Group 1b	2.5% NaOCl	WO #25.08
Group 2a	5.25% NaOCl	WOG #25.07
Group 2b	5.25% NaOCl	WO #25.08
Group 3a	2.5% NaOCl +9% HEDP	WOG #25.07
Group 3b	2.5% NaOCl +9% HEDP	WO #25.08
Group 4a	5.25% NaOCl +9% HEDP	WOG #25.07
Group 4b	5.25% NaOCl +9% HEDP	WO #25.08

Ni-Ti: Nickel Titanium; WOG: WaveOne Gold; WO: WaveOne; NaOCl: Sodium hypochlorite; HEDP: Etidronic acid.

tor (VDW, Munich, Germany) was then calibrated, and its integrated EAL function and "auto-apex-stop" function were activated.

To determine the electronic length (EL), irrigation was performed according to the experimental groups. In Groups 1 and 2, 0.5 mL of 5.25% NaOCl (Wizard, Rehber Chemistry, Istanbul, Turkey) was used. In Groups 3 and 4, a Dual Rinse solution was prepared by dissolving 0.9 g of Dual Rinse® HEDP powder (Medcem, Weinfelden, Switzerland) in 10 mL of 5.25% NaOCl, following the manufacturer's instructions. Then, 0.5 mL of the prepared NaOCl/Dual Rinse solution was used to irrigate the root canals of the teeth embedded in the alginate model. The excess irrigant from the coronal area was removed using a cotton sponge. In groups 1a, 2a, 3a, and 4a, the ELs were determined using the 25/07 WaveOne Gold file system (Dentsply Maillefer, Ballaigues, Switzerland), which operates in reciprocating motion and is manufactured with a gold heat-treated Ni-Ti alloy. In groups 1b, 2b, 3b, and 4b, the ELs were determined using the 25/08 WaveOne file system (Dentsply Maillefer, Ballaigues, Switzerland), which also operates in reciprocating motion. For both file systems, the VDW Gold Reciproc endomotor (VDW GmbH, Munich, Germany) was operated in the preset "Reciproc All" mode, which provides a manufacturer-controlled reciprocating motion equivalent to approximately 300 rpm. In this mode, torque is automatically regulated by the motor according to canal resistance, and the numeric settings are not user-modifiable. According to Fidler et al. (19), the Reciproc All mode involves an engaging (CCW) angle of 186.34°±1.02, a disengaging (CW) angle of 65.07°±0.93, an engaging speed of 428.32±7.61 rpm, and a disengaging speed of 261.06±7.72 rpm, confirming an asymmetric reciprocation corresponding to a mean dynamic equivalent of approximately 300 rpm.

During instrumentation with the WaveOne Gold and WaveOne files, the file was removed after every three pecking motions to clean the debris with a moist sponge. The root canals were then irrigated with 1 mL of the corresponding solution: NaOCl (groups 1 and 2) or Dual Rinse (groups 3 and 4). Irrigation was performed using a 30-gauge side-vented needle (NaviTip, Ultradent, South Jordan, UT, USA) inserted 2 mm short of the working length. All irrigants were used at room temperature (approximately 23 °C) and left in the canal for about 1 min before aspiration. Recapitulation was performed with a #15 K-type file (Dentsply Maillefer). These steps were repeated until the file stopped automatically via the "auto-apex-stop" function. Following this, the operator aligned the rubber stopper with the coronal reference point of the tooth, withdrew the instrument from the root canal, and determined the length indicated by the integrated EAL using a digital caliper. Each EL was measured and recorded separately for every specimen. All the procedures were conducted by a single experienced operator familiar with the VDW Gold Reciproc endomotor system's built-in EAL functionality. The measurements were obtained using a digital caliper (Hogetex, Germany) with 0.01 mm precision under a dental operating microscope (×19.4) (Fig. 1).

To evaluate the measurement discrepancies, ALs were subtracted from the ELs. A positive result (+) indicated that the EL exceeded the AL, whereas a negative value (–) indicated a shorter EL. A difference of 0 signified complete agreement between the two values. Measurements within ±0.5 mm of the AL were considered clinically acceptable.

Statistical analysis

The data distribution's normality was assessed using the Shapiro–Wilk test. The data did not follow a normal distribution, and the Kruskal–Wallis test was used for intergroup comparisons. When significant differences were found,

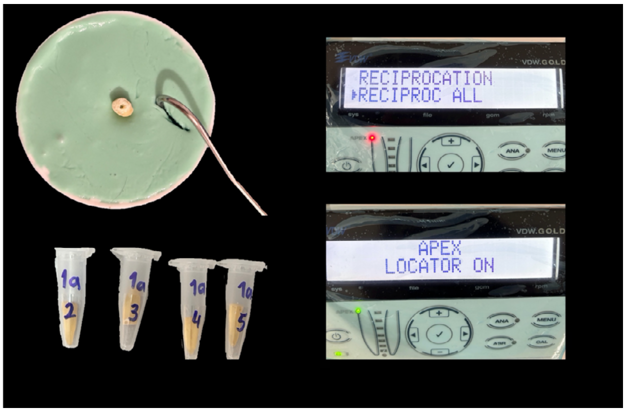

Fig. 1. Experimental setup displaying the specimen model and device adjustment prior to testing.

pairwise comparisons were performed using the Mann–Whitney U test. All the statistical analyses were conducted using SPSS software (IBM SPSS Statistics for Windows, ver.26; IBM Corp., Armonk, NY, USA), and the significance level was set at $p<0.05$.

Results

The Shapiro–Wilk test revealed that the data was not normally distributed. Non-parametric statistical methods were thus employed ($p<0.05$).

The differences in deviation values, calculated based on the difference between EL and AL, were compared across the eight groups using the Kruskal–Wallis test. A statistically significant level was set at $p<0.05$. Table 2 presents the mean differences and standard deviations between the ELs and ALs obtained using various irrigation solutions and heat-treated Ni-Ti files. Table 3 provides a detailed overview of the EL–AL difference distribution across different reference intervals.

No statistically significant differences were observed in the deviations between EL and AL among the groups using different irrigating solutions ($p>0.05$). Similarly, there were no significant differences in the EL–AL values between file systems with different heat treatments ($p>0.05$). These findings indicate that neither the type of irrigating solution nor the file system had a statistically significant effect on the accuracy of the electronic working length measurements.

The Bland–Altman analysis showed a mean bias of 0.03 mm with 95% limits of agreement between –0.79 mm and +0.86 mm. A total of 73.6% of all measurements were within the clinically acceptable ±0.5 mm range, indicating good agreement between EL and AL measurements (Fig. 2).

Discussion

This study aimed to evaluate the influence of two nickel-titanium (Ni-Ti) file systems differing in heat treatment

Table 2. Mean value and standard deviation (SD) of the EL-AL difference for varying irrigation solutions and heat treatment Ni-Ti file

Groups	Overall Accuracy (a)	WaveOne Gold (b)	WaveOne	p1
	Mean ± SD	Mean ± SD	Mean ± SD	
EL – AL (mm)				
Group 1 (2.5% NaOCl)	0.41±0.304	0.371±0.208	0.451±0.387	0.965
Group 2 (5.25% NaOCl)	0.296±0.192	0.312±0.189	0.280±0.205	0.565
Group 3 (2.5% NaOCl + 9%HEDP)	0.327±0.223	0.404±0.234	0.251±0.193	0.112
Group 4 (5.25% NaOCl + 9%HEDP)	0.305±0.291	0.252±0.250	0.358±0.334	0.401
p2	0.522			

EL: Electronic length; AL: Actual length; Ni-Ti: Nickel Titanium; WOG: WaveOne Gold; WO: WaveOne; NaOCl: Sodium hypochlorite; HEDP: Etidronic acid.
p1 represents the statistical significance of differences in EU-AL values among different heat treatment file types. p2 indicates the statistical significance of differences in EL-AL values across varying irrigation solutions.

Table 3. Distribution of the EL-AL difference across groups defined by varying reference intervals

EL - AL (mm)	Group 1 (2.5% NaOCl)		Group 2 (5% NaOCl)		Group 3 (2,5% NaOCl+9% HEDP)	
	WOG	WO	WOG	WO	WOG	WO
	n (%)	n (%)	n (%)	n (%)	n (%)	n (%)
<-0.50	1 (11.1)	3 (33.3)	0 (0)	0 (0)	1 (11.1)	0 (0)
-0.5 to -0.01	1 (11.1)	4 (44.4)	1 (11.1)	2 (22.2)	2 (22.2)	6 (66.6)
0.00	0 (0)	0 (0)	0 (0)	0 (0)	1 (11.1)	0 (0)
0.01 to 0.50	6 (66.6)	1 (11.1)	6 (66.6)	6 (66.6)	3 (33.3)	2 (22.2)
>0.50	1 (11.1)	1 (11.1)	2 (22.2)	1 (11.1)	2 (22.2)	1 (11.1)

EL: Electronic length; AL: Actual length; WaveOne Gold: WOG; WaveOne: WO; HEDP: Etidronic acid; NaOCl: Sodium hypochlorite. Negative values represent a file position coronal to the perforation, while positive values indicate an apical file position.

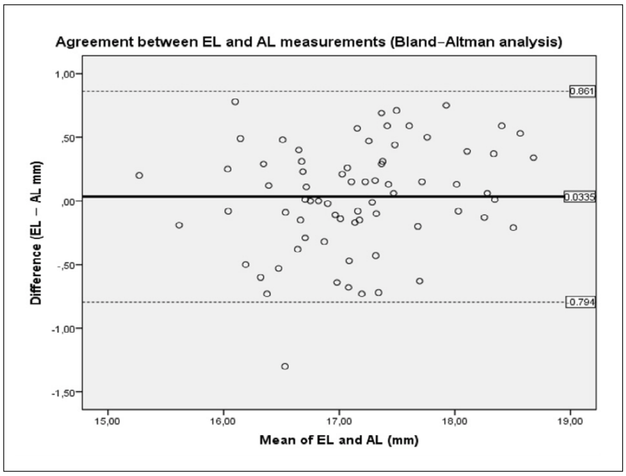

Fig. 2. Bland–Altman plot showing agreement between electronic (EL) and actual (AL) working length measurements. The solid line represents the mean bias (0.03 mm), and the dashed lines represent the 95% limits of agreement (–0.79 mm and +0.86 mm).

status, applied together with various irrigation protocols involving different concentrations of NaOCl, with or without continuous chelation, on the accuracy of EALs integrated into an endodontic motor during root canal preparation. Neither the thermal characteristics of the file systems nor the type and concentration of the irrigants were found to produce a statistically significant effect on the electronic working length measurements. The null hypothesis was thus accepted.

The accuracy of working length determination in endodontic procedures has improved with the introduction of EALs, which enable reliable measurements without necessitating a completely dry canal environment. These devices function by completing an electrical circuit through the patient's body and measuring impedance at the file tip using multiple frequencies to identify the apical constriction (20). Moreover, the integration of EALs into endodontic motors has enhanced both the efficiency and precision of root canal treatments by allowing continuous monitoring of the apical limit throughout instrumentation. One such motor, the Gold Reciproc motor, integrates an EAL, enables real-time working length control with both reciprocating and rotary file systems, and offers independent length measurements. According to the manufacturer, its LED display offers a real-time visualisation of the file tip's location in distinct canal zones. In a previous study, the Gold Reciproc motor was found to offer accurate working length determination, which confirms its reliability and effectiveness as an integrated endodontic device. We thus selected the Gold Reciproc motor with a reciprocating file system for our study (4).

Various electroconductive media, including saline, gelatine, agar-agar, and alginate, were employed in previous in vitro studies to assess the effectiveness of EALs (21,22). Among these, alginate has been frequently identified as the most dependable medium for assessing EAL measurement accuracy, a conclusion supported by numerous investigations (23,24). In a comparative study by Duran-Sindreu et al. (25), no statistically significant differences were observed between the results obtained from in vivo conditions and those using alginate-based in vitro models, thus reinforcing its validity. Because of its favourable properties—high elasticity, suitable viscosity, effective electrical conductivity, and ease of manipulation—we chose alginate as the embedding medium. These characteristics enable it to closely conform to the root surface and offer a realistic simulation of periodontal tissue (26).

EALs' accuracy has been widely investigated in relation to various instrumentation sizes (27), irrigating solutions (1), and file systems with differing heat treatments (7). However, limited data exist concerning the performance of integrated EALs when used with Ni-Ti rotary systems that differ in thermal treatment alongside varying concentrations of NaOCl and continuous chelation protocols. Our study was designed to address this research gap, and our findings offer valuable contributions to the literature.

Nickel-titanium (Ni-Ti) instruments are widely employed in root canal preparation due to their unique properties of super elasticity and shape memory (8). These characteristics are derived from the alloy's ability to exist in two distinct crystallographic phases: austenite and martensite. The martensitic phase is known to be more ductile and flexible, exhibiting higher resistance to cyclic fatigue compared to the austenitic phase. The phase state is temperature-dependent: When the temperature exceeds the austenitic finish (Af) point, the alloy assumes an austenitic structure. Conversely, at temperatures below the martensitic finish (Mf), the material enters the martensitic phase (9). In certain Ni-Ti instruments, heat treatment is applied to increase the Af temperature, enabling the instrument to retain the martensitic phase at room temperature. This thermal modification enhances mechanical performance, providing increased flexibility and improved resistance to fracture compared to conventional Ni-Ti files (9). However, a notable difference in electrical resistivity between the austenitic and martensitic phases has been reported, raising questions regarding the influence of these structural changes on the accuracy of EALs, which rely on electrical conductivity for working length determination (28). However, the research on the effect of heat-treated Ni-Ti files on EAL performance is limited. Sarıyılmaz et al. (10) evaluated the impact of reciprocating Ni-Ti files, including WaveOne Gold and WaveOne, on the accuracy of apex locator-integrated endomotors. Their findings indicated no statistically significant differences between the file types, concluding that heat treatment did not negatively affect the reliability of working length measurements. Similarly, Heo et al. (7) assessed the accuracy of two different EALs using heat-treated Ni-Ti glide path files (ProGlider and HyFlex EDM) and found no significant deviations in measurement accuracy, supporting the conclusion that heat treatment does not impair EAL function. Consistent with these findings, our study demonstrated that heat-treated Ni-Ti files do not adversely affect the accuracy of EALs. Our finding aligns well with that of the aforementioned studies, reinforcing the notion that thermally modified instruments can be reliably used in electronic working length determination.

A material's electrical resistance is primarily determined by three fundamental factors: resistivity, length, and cross-sectional area (3). In this study, the length of the instruments was kept constant across all groups as part of the experimental design. However, minor variations in taper and cross-sectional geometry were present among the tested files. Additionally, there were significant differences in the electrical resistivity between the austenitic and martensitic phases of Ni-Ti alloys (28). Due to these structural and material-related differences, it was reasonable to expect some variation in electrical resistance among the instruments. However, Sarıyılmaz et al. (10) reported identical electrical resistance values of WO and WOG files. In this study, the EAL-integrated endodontic motor produced similar accuracy with both WO and WOG files, suggesting that minor changes in resistance—potentially resulting from thermal processing or manufacturing differences—may not have a clinically significant impact on the measurement accuracy of EAL-integrated endodontic motors during working length determination between these files, and the similar results observed between the WO and WOG files in our study may be attributed to these factors. Nevertheless, further comprehensive studies are required to validate these findings.

Root canal treatment aims to remove pulp tissue and reduce bacterial load to levels compatible with periapical health, which remains difficult due to the anatomical complexity of the root canal system (29). Despite different instrumentation techniques, studies have shown poor debridement and insufficient disinfection. Recent research has thus focused on irrigants with strong antibacterial and tissue-dissolving capabilities to support mechanical cleaning (30). The NaOCl–EDTA combination is considered the gold standard for dissolving necrotic tissue, removing the smear layer, and killing microorganisms, but both solutions have high surface tension, limiting their penetration into canal irregularities. Moreover, their interaction consumes the available chlorine and reduces NaOCl's effectiveness (31).

The combined use of NaOCl and HEDP was recently proposed, with several studies reporting the enhanced antimicrobial activity of this mixture compared to NaOCl alone (32,33). Due to its increasing use and reported advantages and the limited literature on this topic, we investigated this approach in our study. NaOCl, a commonly used irrigant due to its strong antimicrobial and tissue-dissolving capabilities, has raised concerns because of its electroconductive nature, which could potentially interfere with electronic measurements (11,34). Diemer et al. (34) demonstrated that different concentrations of sodium hypochlorite do not compromise the accuracy of apex locator readings. Our study supports this finding and further expands the current knowledge by that the EAL accuracy remains unaffected even when NaOCl is used in conjunction with continuous chelation protocols. This novel finding broadens the existing understanding by demonstrating that apex locator accuracy is maintained even under continuous chelation conditions—a factor not previously addressed in the literature. Based on our findings, the combined use of NaOCl and HEDP solutions does not affect the accuracy of IALs and appears to be a viable option in clinical practice.

Our study is inherently limited by the lack of vital tissue and the absence of electroconductive substances, such as blood and saliva, that are typically present in clinical settings. Moreover, the electrical resistance of the alginate used to simulate the periodontal ligament does not fully replicate the properties of actual periodontal tissues. Our results' applicability is also confined to the particular tooth type and EAL models tested in this study.

Conclusion

Within the limitations of this in vitro study, neither the thermal treatment of NiTi file systems nor the use of different irrigating solutions, including NaOCl alone or combined with HEDP, significantly influenced the accuracy of the IALs during root canal preparation. The findings indicate that the combined use of NaOCl and HEDP represents a safe and effective irrigation strategy that does not compromise working length determination, supporting its potential clinical applicability in endodontic practice.

Authorship Contributions: Concept: A.K.M., S.K., A.S.M.; Design: A.K.M, G.K.; Supervision: A.K.M., G.K.; Funding: A.K.M., S.K., A.S.M., G.K.; Materials: E.S., E.C., F.C., E.B.C., A.T., D.O.D.; Data: A.K.M, Z.Y.O.T.; Analysis: A.K.M., S.K.; Literature Search: A.K.M., Z.Y.O.T., G.K.; Writing: A.K.M., S.K.; Critical Revision: A.S.M., G.K.

Use of AI for Writing Assistance: Not declared

Source of Funding: None declared.

Conflict of Interest: None declared.

Ethical Approval: Ethical approval was not required for this study.

Informed consent: Written informed consent was obtained from patients who participated in this study.

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ORIGINAL ARTICLE

Turk Endod J 2026;11(1):63–67
doi: 10.14744/TEJ.2025.98705

Age-dependent patterns of root canal curvature in mandibular first molars

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Purpose: This laboratory study aimed to evaluate age-related differences in root canal curvature of human mandibular first molars using high-resolution micro-computed tomography (micro-CT).

Methods: Mesial roots of extracted human mandibular first molars (n=93) were collected and classified into three age groups: ≤30 Years, 31–59 years, and ≥60 years. The root canal curvature was evaluated in both the mesiodistal and buccolingual planes using micro-CT reconstructions analyzed in AutoCAD according to Pruett's method.

Results: Curvature values were consistently greater in the buccolingual than in the mesiodistal plane across all age groups. Mesiobuccal and mesiolingual canals exhibited similar patterns, and no significant differences were observed among the age groups (p>0.05).

Conclusion: Mandibular first molars exhibited consistent canal curvature across age groups. Although age did not significantly affect this parameter, careful preparation and appropriate instrument selection remain essential for mesial canals in all patients.

Keywords: Aging; curvature; mandibular molar; micro-CT; root canal.

Introduction

The complexity of root canal morphology is one of the major determinants in endodontic treatment success. This includes the canal configuration, accessory canals, and isthmuses, as well as apical deltas (1). Among these, root canal curvature is particularly critical because it directly influences the mechanics of shaping, the effectiveness of irrigation, and the quality of obturation (2–5), thereby playing a decisive role in the long-term success of endodontic therapy. Excessive curvature increases the risk of procedural errors such as ledging, transportation, instrument separation, and perforation, which may compromise long-term prognosis. Thus, a precise understanding of root canal curvature is essential for both clinical decision-making and the development of safer instrumentation techniques (6).

Age is an important factor influencing root canal morphology and, consequently, treatment complexity. Secondary dentin deposition, calcification, and canal sclerosis occur progressively with aging, leading to narrowing of the

Cite this article as: Basar O, Pirimoglu B, Keles A, Keskin C. Age-dependent patterns of root canal curvature in mandibular first molars. Turk Endod J 2026;11:63-67.
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Submitted: October 16, 2025 Revised: November 08, 2025 Accepted: November 26, 2025 Published: April 27, 2026

canal lumen and alterations in root canal anatomy (7,8). Although several studies (9–11) have examined the effect of aging on canal diameter, pulp chamber volume, and dentin thickness, the influence of aging on canal curvature has not been fully clarified. This gap is especially relevant in mandibular molars, given their anatomical complexity, including multiple roots and the frequent curvature of mesial canals, all of which increase the difficulty of endodontic procedures (12).

Over the years, several methods have been proposed to measure root canal curvature. (13–16) The most widely used approach was introduced by Schneider (16), which measures the angle of curvature in two-dimensional radiographs. The Schneider technique yields a 2D angle on radiographs, which is simple yet insensitive to the tightness of the bend and to out-of-plane curvature. The Pruett method (5) characterizes curvature by both the angle and the radius of the best-fit circular arc to the curved segment. Reporting angle and radius offers a more clinically meaningful descriptor of curvature severity than angle alone. As a result, curvature assessment frameworks that incorporate both angular deviation and the radius of curvature offer a more comprehensive understanding of root canal geometry (17–19). In addition, compared with conventional radiography and cone beam computed tomography (CBCT), micro-computed tomography (micro-CT) enables precise evaluation of curvature in multiple planes and offers reliable quantitative measurements of canal geometry (2).

To date, only limited evidence has examined whether age affects canal curvature and whether this influence varies among different root canals. Clarifying this relationship is important for anticipating clinical challenges in elderly patients and refining strategies for root canal preparation. Accordingly, this study tested the null hypothesis that age does not have a significant effect on root canal curvature.

Materials and Methods

The manuscript of this laboratory study was written according to the Preferred Reporting Items for Laboratory Studies in Endodontology (PRILE) 2021 guideline (20). The study protocol was approved by the local ethics committee (OMU KAEK-2024/46). It involved extracted human teeth and was conducted in accordance with the Declaration of Helsinki. The required sample size was calculated as 18 specimens per group (effect size: 2.70). To allow balanced allocation across the three age groups and to further increase statistical robustness, the final sample size was set to 31 teeth per group (total n=93).

A total of 93 human mandibular first molars with complete root formation, free of caries, resorption, or prior endodontic treatment, were collected from patients with known ages after informed consent, in accordance with the Declaration of Helsinki. Micro-CT imaging was performed with the Skyscan 1172 unit (Bruker, Kontich, Belgium) at 13.68 µm resolution, operating at 100 kV and 100 µA, with 180° rotation steps of 0.6°. An Al–Cu alloy filter was used, and images were reconstructed with NRecon (v.1.7.1.1; Bruker-microCT) applying standardized parameters for smoothing (3), contrast adjustment (0.011–0.019), and 15% beam hardening correction. The selected specimens were divided into three age-based groups: ≤30 Years, 31–59 years, and ≥60 years. Three-dimensional models were obtained using CTAn (version 1.18.8.0+, Bruker-microCT) and visualized in CTVol (v.2.3.1.0, Bruker-microCT). The alignment of mesiodistal (MD) and buccolingual (BL) directions was ensured by DataViewer (v.1.5.6 Bruker micro-CT).

Root canal curvature was evaluated in both the MD and BL planes using three-dimensional reconstructed micro-CT images using AutoCAD (Autodesk, San Rafael, USA). Curvature was characterized according to the method described by Pruett et al. (5) which defines the canal curvature as a segment of a circular arc. Two parameters were recorded for each canal:

(1) The angle of curvature (θ, in degrees), defined as the angle subtended between the straight-line segments extending from the canal orifice to the point of maximum deflection, and from that point to the apical terminus;

(2) the radius of curvature (r, in millimeters), calculated as the radius of the circular arc that best fits the curved portion of the canal.

All analyses were performed by an experienced researcher on micro-CT images who was blinded to the patients' ages (B. P.).

All statistical analyses were performed using SPSS (v.21 IBM, Chicago, IL, USA) with a 5% significance threshold. Normality was assessed with the Shapiro–Wilk test (p>0.05), and homogeneity of variances was confirmed with Levene's test (p>0.05). Based on these assumptions, one-way ANOVA was used for group comparisons.

Results

The mean radius and angle of curvature for the mesiobuccal (MB) and mesiolingual (ML) canals, measured in both BL and MD directions, are summarized in Table 1. Across all groups, curvature in the BL direction was consistently more pronounced than in the MD direction, as reflected by higher mean curvature angles. No statistically significant differences were observed in either curvature angle or radius among the three age groups (≤30 years, 31–59

Table 1. Descriptive statistics (mean± standard deviation) for curvature values (mm) and angle (°)

Root Canal	Direction	Age	Radius of curvature (mm)	Angle of curvature (°)
MB Canal	BL direction	≤30 years	12.1±0.99	36.0±9.98
		31–59 years	11.3±0.70	37.1±10.6
		≥60 years	13.4±0.82	31.5±8.40
	MD direction	≤30 years	11.8±0.42	20.1±13.4
		31–59 years	9.56±1.13	19.6±8.18
		≥60 years	10.0±1.94	18.2±8.71
ML Canal	BL direction	≤30 years	11.5±0.65	37.6±8.40
		31–59 years	10.9±0.74	37.6±10.7
		≥60 years	12.5±0.93	39.0±12.7
	MD direction	≤30 years	11.7±1.56	19.1±10.9
		31–59 years	9.56±0.37	19.6±8.40
		≥60 years	10.0±0.34	15.1±12.7

MB: Mesiobuccal; ML: Mesiolingual; BL: Buccolingual; MD: Mesiodistal.

years, and ≥60 years) for both the MB and ML canals in either BL or MD direction (p>0.05).

Discussion

Root canal curvature is an important factor influencing shaping, irrigation, and the risk of procedural errors (6). Since aging alters dentin and canal morphology, its possible effect on curvature has been questioned. The results of this study indicated that root canal curvature was consistent across age groups in mandibular first molars. Although mesial canal curvatures showed a tendency to increase with advancing age, this trend did not reach statistical significance. The findings suggest that while age may influence factors such as dentin thickness and apical diameter —as previously demonstrated in several studies (21,22) — its effect on root canal curvature does not appear to be significant based on the available evidence and requires further investigation. Consistent with our results, Keskin et al. (23) demonstrated, through micro-CT evaluation of mandibular first molars, that mesial canal curvature was not associated with age. It was shown that while root canal volume and surface area decreased with age, the overall root canal configuration did not exhibit substantial alterations. This apparent stability of curvature despite age-related reductions in canal volume and surface area may be explained by several factors. First, secondary dentin apposition and calcification typically occur concentrically, producing a uniform narrowing of the lumen rather than directional changes in the canal pathway (24). Second, the overall curvature of the root canal is largely established during tooth development and remains stable once root formation is complete, indicating that age-related changes predominantly influence canal dimensions rather than trajectory (25). Third, dentin sclerosis and apical narrowing alter the internal diameter and working length but are unlikely to modify the long-axis orientation of the canal. Finally, while volumetric and surface area changes reflect micro-morphological alterations, curvature is a macro-anatomical parameter that tends to remain constant unless disrupted by pathologic or iatrogenic processes (26). Taken together, these considerations help to explain why curvature did not vary significantly with age, even though other morphometric parameters did.

Mesial canals consistently demonstrated higher curvature than distal canals, corroborating previous anatomical studies reported in the literature (6,27), which made them a suitable focus for detailed evaluation in this study. Even though no significant age-related differences were detected, the consistently higher curvature of mesial canals confirms that they demand greater clinical attention in all patients. The presence of frequent isthmuses, narrower diameters, and sharper curvatures in mesial canals further increases the difficulty of negotiation and shaping (28). Clinically, these features highlight the importance of establishing a secure glide path, using pre-curved hand files, and selecting instruments with enhanced flexibility regardless of age (29). Moreover, conservative taper preparations and minimally invasive shaping approaches are particularly advisable in mesial canals to reduce the risk of iatrogenic errors (30). These findings reinforce the view that mesial canals inherently present greater challenges than distal canals, and careful technique remains essential across all age groups. Although canal curvature did not differ significantly among age groups, the clinical relevance of evaluating this parameter in the context of aging remains important. Age-related dentin sclerosis, and decreased pulp space volume increase the difficulty of canal negotiation and cleaning, particularly in curved canals (21).

Clinically, the predominance of buccolingual curvature highlights an important limitation of conventional periapical radiographs, which visualize the canal anatomy primarily in the mesiodistal plane and therefore tend to underestimate the true three-dimensional extent of curvature (31). This limitation can lead to inaccurate assessment of canal complexity and potential misjudgment of instrumentation risk, particularly in mesial roots where double-plane curvatures are common (15). In contrast, three-dimensional imaging modalities such as micro-CT and CBCT enable visualization of the canal trajectory in both BL and MD directions, offering a more comprehensive understanding of root canal anatomy (32).

A notable strength of this study is the use of high-resolution micro-CT for accurate visualizations. Although curvature measurements were performed on two-dimensional projections of the reconstructed images using AutoCAD, this approach allowed accurate and reproducible determination of curvature parameters in both MD and BL planes. The high scanning resolution of micro-CT minimized observer bias and ensured consistent identification of the curvature path (32,33). While true three-dimensional curvature modeling was not applied, the bidirectional evaluation of curvature provided a reliable approximation of canal geometry and allowed meaningful comparisons among age groups.

The sample was limited to mandibular first molars with complete root formation, which restricts the generalizability of the findings to other tooth types and developmental stages, a limitation of the study. In addition, although micro-CT provides highly accurate three-dimensional reconstructions, it remains an in vitro technique that cannot fully reproduce clinical conditions and patient-related biological variability. The cross-sectional design also prevents the assessment of longitudinal changes in the same teeth over time, which may underestimate the dynamic nature of age-related alterations (33). Future investigations should broaden the scope by including multi-center datasets and diverse ethnic cohorts to better capture geographic variability and population-level patterns. Analyzing age as a continuous variable may reveal subtle associations with canal curvature, while adding indices such as calcification, dentin hardness, root length, and isthmus presence would provide a more complete view of age-related changes (9). Incorporating longitudinal imaging of extracted teeth or serial in vivo CBCT datasets from patients could further clarify temporal dynamics, although the use of CBCT solely for research purposes is not recommended in endodontics (34). In addition to age, other biological and environmental factors, including gender, systemic conditions, and restorative status may also influence root canal morphology. Considering these variables in future studies could yield a more complete picture. Finally, anatomical features are recommended to be associated with clinically relevant endpoints, including shaping errors, instrument separation, irrigation efficacy, and postoperative pain. Such studies would bridge laboratory observations with patient-centered outcomes, ultimately refining treatment protocols across different age groups.

Authorship Contributions: Concept: C.K., O.B.; Design: C.K.; Supervision: C.K., A.K.; Data: B.P.; Analysis: C.K.; Literature Search: O.B.; Writing: O.B.; Critical Revision: C.K.

Use of AI for Writing Assistance: Not declared

Source of Funding: The authors received no financial support or funding for this study.

Conflict of Interest: All the authors have contributed significantly to this research project and are in agreement with this manuscript. There is no conflict of interest between the authors.

Ethical Approval: The study protocol was approved by the local ethics committee of Ondokuz Mayıs University (No: OMU KAEK-2024/46).

Informed consent: Written informed consent was obtained from patients who participated in this study.

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ORIGINAL ARTICLE

Turk Endod J 2026;11(1):68–76
doi: 10.14744/TEJ.2025.58070

To evaluate structural loss during selective re-treatment of mandibular incisors between conventional and static guided technique using customized re-treatment bur - an in vitro study

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Purpose: The present study aimed to compare and evaluate the extent of structural loss during selective endodontic retreatment of mandibular incisors using conventional burs versus customized retreatment burs.

Methods: Twenty-six extracted mandibular anterior teeth exhibiting two canals, confirmed through intraoral periapical radiographs in the mesiodistal dimension, were selected for the study. Access cavity preparation was selectively performed for buccal canal and lingual canal was intentionally missed. Biomechanical instrumentation and obturation was completed for buccal canal following copious irrigation with 5.25% sodium hypochlorite, 0.9% saline, and 17% EDTA. The lingual canals were intentionally left untreated. Access cavity was restored using composite resin. Preoperative cone-beam computed tomography (CBCT) scans were acquired for all samples. The specimens were then randomly allocated into two groups:

• Group A: Selective retreatment performed using a customized long-shank parallel round bur guided by a static 3D-printed template to locate the missed lingual canal.

• Group B: Selective retreatment carried out using a conventional small round bur (#1) under 10× magnification.

Following the retreatment procedures, postoperative CBCT scans were obtained. Volumetric substance loss was calculated using image analysis software by comparing pre- and postoperative scans.

Results: Group A exhibited significantly lower volumetric structural loss than Group B. The use of a customized guided bur enabled precise localization of the untreated canal with minimal removal of dentinal tissue.

Conclusion: Selective endodontic retreatment of mandibular anterior teeth with two canals, when performed using a guided endodontic approach with a customized bur, results in significantly reduced structural loss compared to the conventional technique. This method enhances accuracy and preserves tooth structure, offering a clinical advantage in retreatment cases.

Keywords: Mandibular anteriors with 2 canals; selective retreatment; static guided endodontics.

Cite this article as: Dave D, Shah P, Arora A, Patel H, Kapoor S, Chawda N. Evaluation of the content quality and reliability of Youtube videos on endodontic retreatment. Turk Endod J 2026;11:68-76.

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Submitted: Jul 23, 2025 Revised: October 27, 2025 Accepted: November 11, 2025 Published: April 27, 2026

Introduction

Guided Endodontics is an innovative technique that enhances accuracy and precision in root canal treatments by utilizing CBCT and 3D-printed guides. These guides assist clinicians in navigating access cavity preparation with minimal structural loss, improving treatment predictability and post-operative healing, which is particularly valuable in retreatment cases, as it reduces learning curve and increases success rates (1).

Mandibular anterior teeth present challenges in endodontic access due to their small size and high prevalence of two canals (2). Research indicates the occurrence of second canals in right central incisor (33.5%), left central incisor (30%), right lateral incisor (33.5%), and left lateral incisor (36.5%). Gender variations also exist, with second canals found in 15.2% of men and 20.4% of women. The most common canal configuration is Vertucci Type 1, followed by Types 3, 2, 5, and 4. Traditional lingual access, often preferred for aesthetic and restorative reasons, can make canal location more challenging, further emphasizing the benefits of guided techniques (3).

The most common un-treated canals in the mandible were observed in lateral incisors with a 33.3% prevalence (4). Selective root retreatment is emerging as a conservative alternative to full retreatment, targeting only the diseased root while preserving unaffected canals. Unlike the traditional "all-or-none" approach, this technique leverages CBCT to assess periapical pathosis and selectively retreat affected areas. By minimizing unnecessary removal of restorative and obturation materials, it helps preserve more natural tooth structure (5).

One challenge in guided endodontics is selecting effective bur. Standard burs often struggle to penetrate restorations efficiently, trap debris, or fracture due to heat buildup. Many have round tips and inadequate land areas, leading to debris entrapment and ineffective use within guided stents. Long-shank burs also experience tip displacement, reducing precision. While some clinicians use implant drills for better penetration, their large size makes them impractical for mandibular anterior teeth. To address these limitations, a specialized bur was used in a study to effectively and conservatively penetrate the coronal structure or restorative material while ensuring efficient debris removal during access cavity preparation (2).

Need for the study: There is a lack of literature in CBCT based guided endodontic retreatment of mandibular anterior teeth with customized bur to evaluate the substance loss of teeth during access cavity preparation.

Null hypothesis: There is no difference in structural loss between conventional retreatment technique and static guided retreatment technique using customized bur of selective retreatment.

Materials and Methods

The study is approved by the Manubhai Patel Dental College Ethics Committee (No: IEC/MPDC_242/CONS-46/22, Date: 22/09/2022) and conducted according to Declaration of Helsinki.

26 freshly extracted mandibular anterior teeth were collected from Oral Surgery Department of Manubhai Patel Dental College and Hospital. Teeth were stored in 0.9% sterile saline solution and disinfected using a 95% alcohol solu-

Table 1. Volumetric substance loss in group A and group B

	Group A		Group B	
Sample No:	**Pre- intervention**	**Post- intervention**	**Pre- intervention**	**Post- intervention**
1	5.95	8.92	26.32	29.52
2	21.62	7.234	35.82	39.62
3	10.02	7.734	10.28	12.38
4	8.613	4.734	6.25	14.86
5	12.47	2.91	13.69	12.25
6	10.77	14.46	10.77	15.56
7	12.43	16.54	8.988	21.56
8	14.82	7.246	14.81	22.06
9	25.92	15.99	10.84	18.06
10	30.9	15	14.92	14.42
11	16.67	7.443	23.68	18.96
12	17.79	8.25	18.15	17.87
13	22.62	10.42	20.89	22.21
Mean Value	16.20	9.76	16.57	19.95

tion. Based on an estimated 49% difference in substance loss between the two groups, a minimum of 13 teeth per group was selected to achieve 95% confidence and 80% statistical power (Table 1).

Formula for sample size calculation:

- n=Sample size per group
- $Z_{1-\alpha}$=Z-score corresponding to the desired confidence level (e.g., 1.96 for 95%)
- $Z_{1-\beta}$=Z-score corresponding to the power of the test (e.g., 0.84 for 80% power)
- SD=Estimated standard deviation of the outcome variable
- d=Effect size (difference in means between groups)

Inclusion Criteria: Permanent mandibular anterior teeth with two canals, confirmed using IOPA in mesiodistal view. Only non-carious teeth with intact anatomy were selected to ensure standardized conditions for the study

Exclusion Criteria: Teeth with cracks or fractures, anatomical or morphological variations, or a single canal were excluded from the study. Additionally, grossly carious teeth and samples that did not exhibit two canals in the CBCT scan after RCT were also excluded.

In all 26 samples, access was performed using a #1 round bur (Mani, Japan). Root canal negotiation and apical patency were then achieved using a #10 K-file (Mani, Japan), but only in buccal canal, leaving the lingual canal untouched until the instrument tip appeared at apical foramen. Working length was set 1 mm short of this point (Fig. 1).

Root canal preparation was done using NeoEndo S rotary files (25/4) (Orikam Health India Pvt. Ltd.) with an ENDO MATE DT Endomotor and 16:1 contra-angle, as per manufacturer's instructions. Reaming and filing were combined with copious irrigation. Canals were irrigated with 6 mL of 2.5% NaOCl, 6 mL of 17% EDTA (Biodinamica, Brazil), and again 6 mL of 2.5% NaOCl, each agitated ultrasonically (Irrisonic, Brazil) in three 20-second cycles. Final rinse was with 5 mL distilled water.

Following instrumentation, canals were dried with sterile paper points and master cone radiographs were taken. Only buccal canals were obturated using single cone technique with gutta-percha and AH Plus sealer, simulating missed lingual canals. Coronal sealing was done with flowable composite, followed by composite restoration, finishing, and polishing. Samples were embedded in clear cold-cure resin (4×3 cm) for CBCT scanning. Pre-intervention CBCT (Veraview Pox 3D R-200, J. Morita, Japan) confirmed buccal canal obturation. Samples were divided into Group A (static guided retreatment, n=13) and Group B (conventional retreatment, n=13). CBCT scans were stored as DICOM files for analysis.

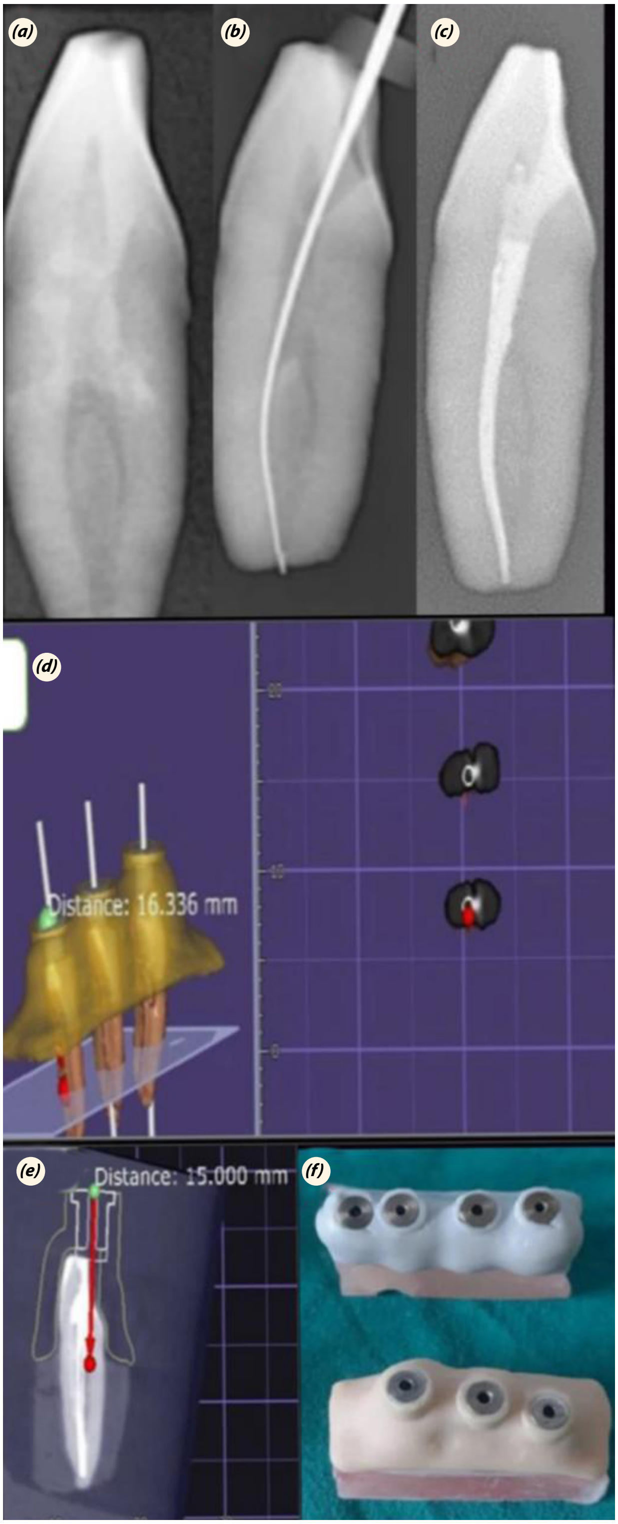

Fig. 1. **(a)** IOPA radiograph taken keeping the tooth in mesio-distal Position (showing 2 canals in mandibular incisors); **(b)** Working length into buccal canal; **(c)** Obturation of only buccal canal was carried out for all 26 sample teeth. **(d)** Virtual planning for static guided endodontic retreatment (Group A) **(e)** Virtual identification of lingual canal with customized bur length (Group A) **(f)** 13 sample with static guided retreatment stent to locate the untreated canals (Group A).

Group A Methodology

Selective Retreatment with Guided Endodontics (N=13)

In this group (n=13), the previously untreated or missed lingual canal was accessed using a customized long-shank tungsten carbide bur (Design Patent No. 351977-001) guided through a static endodontic template (Fig. 2). The previously obturated teeth were embedded in acrylic blocks (dimensions: 4 cm×2 cm) to facilitate handling and stability. A pre-intervention cone-beam computed tomography scan was performed to confirm the presence of two canals in the mandibular anterior teeth and to aid in the virtual planning of static guided endodontic retreatment.

Digital impressions of both the tooth models and template site were captured using a 3D scanner (Shining 3D Autoscan DS-200, China). The corresponding STL and DICOM files were imported into the Exocad Dental CAD software (Exocad GmbH, Germany), where anatomical alignment of the scans was performed to ensure accuracy.

To guide access to the missed lingual canal, a virtual model of a customized bur (1 mm diameter) was integrated into the planning. Based on this, a surgical guide template was designed with a 1 mm diameter sleeve and 3D printed (Nextdent B.V., 3D Systems, Netherlands). Each operator was provided with the printed guide and corresponding bur. The procedures were then executed using the static guided technique to accurately localize and access the untreated lingual canal in each sample.

For Group A, a customized bur was fabricated to overcome the restricted access typically encountered at the orifice level of mandibular anterior teeth. This tungsten carbide bur was specially designed with a 31 mm long shank and a 1 mm diameter. It featured lateral flutes for effective debris evacuation and a round tip with an adequate land area to minimize iatrogenic damage. The bur design facilitated precise access through the 3D-printed guide while reducing heat generation during preparation.

Clinical procedures were conducted using this guided approach. When the previously untreated lingual canal was successfully located and negotiated, a periapical radiograph was obtained with a #10 K-file in place to confirm canal patency and treatment success. Subsequently, a post-intervention CBCT scan (4×4 cm field of view, 2.39 mGy, 90 kV, 5 mA; J. Morita Manufacturing Corp., Kyoto, Japan) was performed for all samples. The scans were evaluated by an experienced radiologist to assess and compare substance loss resulting from the intervention.

Group B Methodology

Selective Retreatment with Conventional Endodontics (N=13)

Using pre-intervention CBCT data, linear measurements were recorded from the lingual incisal edge to the point of canal bifurcation to guide re-entry and localization of the untreated lingual canal. Selective retreatment was then initiated by penetrating the coronal composite restoration with a small round bur (BR-45, Mani, Takenzawa, Japan), under 10× magnification (DNT Dental Microscope, Gurgaon, Haryana). This approach was meticulously guided by the preoperative CBCT measurements to enhance accuracy in locating the canal orifice.

Upon successful access and negotiation of the untreated lingual canal, a periapical radiograph was taken with a K-file in situ to confirm canal patency and treatment success. A post-intervention CBCT scan was subsequently performed on all samples to assess and compare substance loss following the procedure.

Volumetric Analysis (Group A + B)

Volumetric analysis of CBCT data was performed using Ez-3Di software (version 5.0.0.2, Vatech, South Korea). Measurements were obtained from the lingual access open-

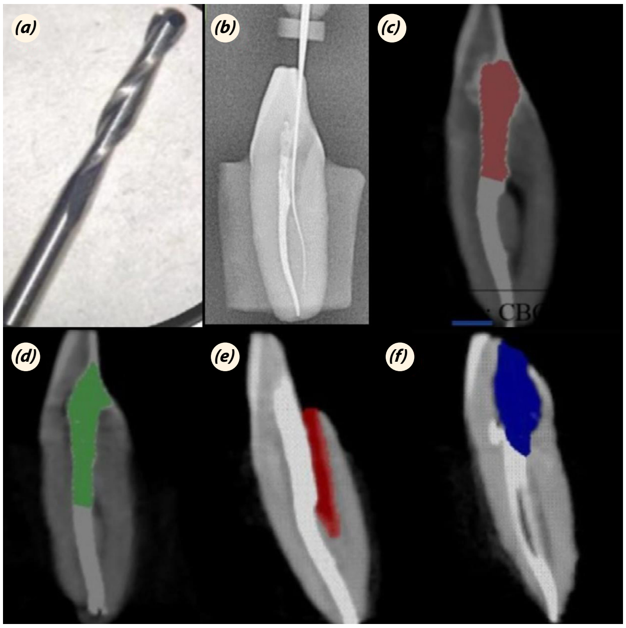

Fig. 2. **(a)** A customized Tungsten Carbide bur with a length of 31 mm and a diameter of 1.00 mm with lateral flutes and a round tip with the sufficient land area was used to facilitate the removal of debris during access preparation; **(b)** Untreated canal was negotiated with #10 k file and the length of the same was verified on IOPA. (Group A); **(c)** CBCT scans taken for volume analysis in Group A Calculated From the lingual access opening upto the level of bifurcation Group A (n=13); **(d)** CBCT scans taken for volume analysis in Group B Calculated From the lingual access opening upto the level of bifurcation Group B (n=13); **(e)** Volumetric loss of Group A (guided) While locating missed lingual canal Avg substance loss: 9.76 mm^3 **(f)** Volumetric Loss of Group B (conventional) while Locating missed lingual canal Avg substance Loss: 19.9 5mm^3

ing to the point of canal bifurcation in the mandibular anterior teeth across all 26 samples, where the buccal canal had been previously obturated. These initial volumes were used to standardize the comparison of substance loss between guided access preparations (Group A) and conventional techniques (Group B).

Following completion of the procedures, post-intervention CBCT scans were acquired for all models in both groups. Volumetric substance loss was again assessed using Ez-3Di software. All measurements were performed by a single calibrated observer to maintain consistency. The slice thickness and slice interval set to 0.1 mm. Measurements were conducted primarily in the sagittal plane, with corroborating data obtained from corresponding coronal and axial sections. The extent of tooth structure loss was quantified up to the canal orifice and extended to the level of exposed gutta-percha in both treatment groups.

Results

The statistical analysis was done using Statistical Package for Social Sciences (SPSS) software, version 20.0 (IBM, USA). Descriptive analysis was performed. Independent t-test was applied for comparison of substance loss in two groups. An independent t-test was performed to compare the means between two independent groups and determine whether the observed differences were statistically significant. Chi-square test was applied for comparison of the categorical variables and to determine whether the observed distribution differed significantly from what was expected by chance between the two groups.

Pre-operative CBCT volumes were similar between the groups: 16.20 mm^3 (Group A) and 16.57 mm^3 (Group B). Post-operatively, mean substance loss was significantly lower in Group A (9.76 mm^3) compared to Group B (19.95 mm^3), where treatment was performed under 10× magnification. The difference was statistically significant ($t=4.186$), indicating greater structural preservation with the static guided technique. An experienced radiologist conducted all CBCT volume assessments.

An independent t-test was conducted to compare the amount of substance loss between Group A (Conventional technique) and Group B (Static guided technique). The mean substance loss for Group A was 9.76±4.39, whereas Group B demonstrated a significantly higher mean substance loss of 19.95±7.59 (Table 2) The statistical analysis revealed a t-value of 4.186 with a p-value <0.001, indicating that the difference between the two groups was highly significant. This suggests that the static guided technique resulted in significantly less substance loss compared to the conventional technique. The findings highlight the choice of technique has a substantial impact on the extent of structural loss during the procedure.

Discussion

Endodontic and retreatment procedures can weaken tooth structure due to dentin dehydration and hard tissue removal, especially in patients with parafunctional habits. To improve the prognosis of retreated teeth, preserving remaining tooth structure is essential. Guided endodontics offers a minimally invasive solution by using 3D-printed guides to locate canals, previously used mainly for calcified cases (6,7). This in-vitro study applied the technique to detect missed lingual canals in mandibular anterior teeth. Compared to conventional methods, guided endodontics reduces unnecessary dentin loss and improves precision, even when magnification is used (8)

Modern restorative dentistry and endodontics emphasize preserving healthy tooth structure through minimally invasive techniques. While primary root canal therapy has a high success rate (86–98%), retreatment becomes more complex when it fails (9). A systematic review by Torabinejad et al. (10) found nonsurgical retreatment to be more successful (83%) than surgical approaches (71.8%) over 4–6 years. Success depends on proper shaping, disinfection, and three-dimensional obturation; failure in these steps increases the risk of treatment failure (11).

Several factors have been identified as contributors to endodontic failure, including persistent bacterial infection, inadequate obturation, and the presence of untreated or missed canals. Notably, missed canals have been reported to account for 12% to 42% of root canal treatment (RCT) failures across various populations (11). Mandibular permanent anterior teeth are known to exhibit significant anatomical variability. Approximately 15% of single-rooted mandibular anterior teeth possess two canals, and up to 5% may have two roots with separate canals (12). Retrospective CBCT studies further reveal that 30% to 40% of

Table 2. Comparison of substance loss between groups using independent t-test

Group	N	Mean	Std. Deviation	t-value	p-value
Group A	13	9.76	4.39		
Group B	13	19.95	7.59	4.186	<0.001

mandibular central and lateral incisors and canines exhibit two canals (13).

Accurate identification and treatment of all canals in mandibular anterior teeth are essential for a favorable prognosis. Missed canals may harbor persistent microorganisms, potentially leading to or sustaining apical periodontitis and thereby compromising treatment outcomes (11).

Conventional retreatment often leads to excessive tooth structure loss, weakening the tooth and increasing the risk of microcracks and thermal damage from high-speed rotary instruments (6). Studies by Lertchirakarn, Palamara, and others have shown that remaining dentin directly influences a tooth's resistance to lateral forces and fracture, highlighting the need to preserve root thickness. Elective retreatment of mandibular anterior teeth, supported by conservative methods like CBCT planning and 3D printing, offers a promising alternative to traditional techniques (14).

Static Guided Endodontic Retreatment (SGER) is an emerging solution for anatomically complex or small teeth, such as mandibular anteriors, where preserving tooth structure is critical to prognosis (15). It is particularly advantageous for abutment teeth under fixed prostheses, as it minimizes substance loss. Overall, SGER offers a conservative, time-efficient, and patient-friendly approach by preserving natural tooth structure and improving patient comfort (5).

The static guided endodontic technique requires CBCT confirmation of lesions, allowing for selective treatment and preservation of unaffected canals, thereby reducing unnecessary intervention. However, CBCT has limitations—beam hardening from gutta-percha can obscure anatomy, and its spatial resolution may be inadequate for visualizing fine canal structures, as noted by Buchgreitz et al. (16,17).

It's also emphasized that inaccuracies in CBCT settings—such as low image quality, excessive slice thickness (>1 mm), and improper threshold values—can impair the precision of guided endodontic planning, leading to deviations during treatment execution (18).

Static guided endodontics offers high precision and tissue conservation but involves added time, cost, and planning for CBCT imaging and guide fabrication, limiting its widespread use. Still, CBCT and 3D-guided techniques have improved retreatment accuracy and personalized care. 3D-printed guides allow anatomy-specific treatment. A systematic review found similar accuracy between static (98.5%) and dynamic (94.5%) navigation, though dynamic systems are more costly and complex (19).

In the present study, volumetric substance loss was compared between conventional access cavities and those created using static guided access techniques. As part of the selective endodontic approach, only the buccal canal—containing sealed gutta-percha—was targeted and accessed. The decision to selectively treat or retreat one or more roots should always be guided by comprehensive clinical and radiographic evaluation, including assessment of the tooth's structural integrity following access preparation (20).

Conventional long-shank burs present several limitations, including heat generation and debris accumulation at the working end, which reduce cutting efficiency. Moreover, due to their tapered design from shank to tip, these burs often exhibit instability or "wobble" when used through the guiding sleeve of a 3D-printed template (21). To address these issues, a customized bur was specifically engineered for guided endodontic applications. Fabricated from a tungsten carbide rod, the bur features a parallel shank and a rounded tip, enabling more precise and controlled removal of tooth structure during access cavity preparation. This design minimizes wobbling, enhances procedural accuracy, and ensures a centered path under lateral forces. The bur includes lateral cutting blades extending up to 10 mm from the tip, which facilitate efficient debris removal while maintaining alignment. This innovative bur, patented in India (Design Patent No. 351977-001), allows for a more effective and conservative access opening with minimal dentin loss (19).

Virtual planning for the static guided endodontic retreatment was carried out using a 3D scanner (Shining 3D Autoscan DS-200, China). The scan data (STL) and CBCT imaging files (DICOM) were imported into the Exocad Dental CAD software for 3D alignment and planning. The virtual guide was designed by positioning a virtual sleeve over the intended access path. Once alignment was verified, the STL file was finalized, and a surgical template with integrated guide sleeves was fabricated for clinical use (19).

Static Guided Endodontics (SGE) poses several intraoperative challenges, particularly related to thermal damage. Heat generated by friction at the bur tip can lead to the formation of microcracks on the tooth surface, and excessive temperatures may adversely affect the periodontal ligament (PDL) and adjacent alveolar bone. Therefore, continuous cooling via irrigation is essential to mitigate these risks during the procedure (22). In the present in-vitro study, three mandibular anterior tooth samples were excluded due to fractures caused by heat accumulation during guided access preparation. These were replaced by three additional samples selected using the same inclusion criteria.

A laboratory study by Zubizarreta-Macho et al. (18) compared two computer-aided navigation systems to traditional freehand methods for access cavity preparation, finding that static navigation provided superior accuracy despite a relatively high mean angular deviation of 10°. Similarly, Perez et al. (23) reported that static guided endodontics achieved apical gutta-percha access in 87.5% of cases, with root curvature being the main limitation. The technique was also more time-efficient than traditional methods using ultrasonic tips or long-stem drills.

Similarly, it's reported that static guided endodontics yielded faster and more satisfactory outcomes compared to traditional techniques such as post removal using milling devices and treatment under a dental operating microscope (24). It's also emphasized that static guidance is most effective in teeth with straight canals. As noted, rigid, non-deformable nature of drill restricts its use to straight segments of canal; attempting to navigate beyond canal curvature may lead to procedural errors or damage to surrounding structures (20).

A retrospective study by Galino Buniag et al. (25) remains the only one to date with a one-year follow-up, confirming that static guided endodontic treatment is clinically as effective as conventional methods. Connert et al. (26) reported that digital planning—including scanning, guide design, and 3D printing—averaged 9.4 minutes. In a later preclinical study, the same team showed that static guidance significantly reduced treatment time (11.3 min vs. 21.8 min for freehand methods). While planning may seem time-intensive initially, it becomes more efficient with experience and ultimately reduces chairside time, dentin loss, and iatrogenic risks (1).

To minimize iatrogenic errors in delicate teeth like mandibular anteriors, magnification tools are essential during retreatment. Precise treatment of missed canals requires advanced imaging such as CBCT, which helps identify untreated canals and provides accurate measurements to the bifurcation level, supporting effective planning and execution (21).

In this study, pre-intervention CBCT scans were utilized for all samples, focusing on teeth in which only the buccal canals had been obturated, leaving the lingual canals untreated. These scans confirmed that both Group A and B exhibited comparable baseline values, thereby establishing uniformity for valid comparative analysis of access cavity techniques. Volumetric analysis of substance loss was performed using CBCT measurements from the lingual incisal edge to the furcation area, specifically targeting the missed lingual canals.

In Group A, a customized bur designed for guided endodontic access was employed to locate and treat missed lingual canals. In contrast, Group B utilized a conventional small round bur. The results demonstrated that conventional technique caused significantly greater damage to internal tooth morphology and compromised fracture resistance when compared static guided approach. Post-intervention CBCT data were analyzed using Ez-3Di software (version 5.0.0.2, Vatech, South Korea). The findings revealed that volumetric substance loss was minimal in Group A but significantly higher in Group B. Statistical analysis using independent t-test confirmed that differences in post-intervention substance loss between two groups were statistically significant.

These findings are consistent with those reported, who compared substance loss between conventional and guided retreatment techniques. In their study, mean volumetric loss in conventional retreatment group (Group 1) was 27.64 mm³, whereas guided retreatment group demonstrated significantly less loss, averaging only 11.73 mm³. The difference was statistically significant, with a t value of 4.591 and P=0.001 (19). The reduced substance loss observed in Group A of the present study can be attributed to the use of a customized bur, featuring a 1 mm diameter along its entire parallel working blade and a round cutting tip. This design facilitates highly controlled and conservative access cavity preparation, thereby preserving the internal tooth structure more effectively.

Based on these results, guided access preparation emerges as a promising technique for endodontic retreatment, especially in locating missed canals. The use of a static guide simplifies the clinician's task, shortens treatment time, and enhances accuracy while preserving natural tooth structure. This study supports guided endodontics as a conservative alternative to conventional methods, offering reduced substance loss and potentially improving the long-term prognosis of retreated teeth.

Limitations of the Study

Despite promising results, several limitations exist. Guided endodontics relies heavily on high-quality imaging and software, requiring precise patient positioning and stability. Treatment planning is more time-consuming and costly due to CBCT, intraoral scans, and guide fabrication, which may limit patient access. Anatomical variability of the second canal's location in mandibular anterior teeth affects volumetric data and leads to inconsistent results. Additionally, during retreatment, irrigants like 5.25% sodium hypochlorite used on missed canals may compromise the apical seal of previously treated canals. Finally, as an in-vitro study, the findings cannot be directly applied clinically, underscoring the need for in-vivo trials with larger populations to confirm these outcomes.

Future Scope

Looking ahead, Augmented Reality (AR) navigation holds great promise for enhancing guided endodontics. By overlaying radiographic images and navigation paths directly onto the operator's field of view via a head-up display or microscope, AR allows real-time visualization of both 3D guidance and the operative site without shifting focus. Though already applied in neurosurgery, AR has yet to be clinically adopted in endodontics. Further clinical trials are needed to validate its potential for improving precision and treatment outcomes.

Conclusion

Compared to freehand techniques, guided endodontic procedures significantly improve accuracy. Selective re-treatment using a customized long shank parallel round bur with static guided endodontics enabled precise access cavity preparation through 3D-printed templates aligned with CBCT and intraoral scans. This method effectively located missed lingual canals in mandibular anterior teeth while minimizing dentin loss. As such, it offers a highly precise, minimally invasive approach that preserves healthy tooth structure, making it a preferred option for conservative endodontic retreatment.

Authorship Contributions: Concept: D.D., P.S., A.A., H.P., S.K., N.C.; Design: D.D., P.S., S.K.; Supervision: D.D., P.S., A.A., S.K.; Fundings: D.D., P.S., A.A., H.P., S.K., N.C., Materials: D.D., P.S., A.A., H.P., S.K., N.C.; Data: D.D., A.A., N.C.; Analysis: D.D., P.S., N.C.; Literature Search: D.D., P.S., A.A., H.P., S.K.; Writing: D.D., H.P., N.C.; Critical Revision: D.D., H.P., S.K.

Use of AI for Writing Assistance: Not declared

Source of Funding: None declared.

Conflict of Interest: We declare that we have no conflict of interest related to this study.

Ethical Approval: The study is approved by the Manubhai Patel Dental College Ethics Committee (No: IEC/MPDC_242/CONS-46/22, Date: 22/09/2022)

Informed consent: Not applicable.

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ORIGINAL ARTICLE

Turk Endod J 2026;11(1):77–84
doi: 10.14744/TEJ.2025.63383

Effects of preheating on degree of conversion, flexural strength and flexural modulus of bulk-fill resin composites

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Purpose: The aim of this study was to investigate the effects of preheating on the degree of conversion (DC), flexural strength (FS) and flexural modulus (FM) of bulk-fill resin composites with varying viscosities and filler contents.

Methods: Four bulk-fill resin composites - EverX Posterior (EXP), EverX Flow Bulk (EXF), Filtek One Bulk Fill (ONE), SDR Plus Flow (SDR) - and a conventional composite - Filtek Z250 (Z250) - as a control group were evaluated. Each composite was divided into three subgroups: [1] Room temperature (20±1°C), [2] preheated to 39°C, and [3] preheated to 55°C. DC, FS and FM results of the specimens were evaluated. Statistical analysis included one-way ANOVA and post hoc Tukey tests ($p<0.05$).

Results: At room temperature, Z250 exhibited the lowest DC (41.32%), significantly lower than EXP (52.11%) and other bulk fill composites. FS values for Z250 (145.68 MPa), EXF (152.19 MPa) and EXP (157.24 MPa) at room temperature were comparable but higher than for ONE (100.70 MPa) and SDR (114.95 MPa). Preheating increased the DC and FS of Z250 and EXP but not of EXF, ONE or SDR.

Conclusion: Preheating is recommended to enhance the properties of viscous, fiber-reinforced (EXP) and conventional hybrid (Z250) composites for stress-bearing restorations. In contrast, it offers no significant mechanical advantage for the flowable bulk-fill composites tested (EXF, SDR, ONE), underscoring that the benefit of preheating is highly material-dependent.

Keywords: Bulk-fill; degree of conversion; flexural modulus; flexural strength; preheating.

Introduction

Resin composites are among the most widely used restorative materials in dentistry. With the technological developments in the polymers and fillers it contains, resin composites with diverse properties that can be preferred for different clinical situations have been developed (1). Among these innovations, 'bulk-fill' resin composites have been developed, offering the significant clinical advantage of being placed in thicker layers than conventional resin composites, which is particularly beneficial in large posterior cavities (2).

Low and high viscosity bulk-fill resin composites generally have different polymerisation initiator system designed to provide higher transparency and better deep polymerisation compared to conventional resin composites. These properties allow them to be placed in a single layer with a

Cite this article as: Karadag G, Hancerliogullari D, Iren AY, Ceylanoglu E. Effects of preheating on degree of conversion, flexural strength and flexural modulus of bulk-fill resin composites. Turk Endod J 2026;11:77-84.
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Submitted: September 29, 2025 Revised: November 17, 2025 Accepted: November 24, 2025 Published: April 27, 2026

thickness of 4 mm or even 5 mm without the need for incremental layering, while still achieving a sufficient degree of conversion (DC) to ensure high physical and mechanical properties (3). DC of the C=C double bonds significantly influences critical properties such as physical, mechanical and biocompatibility of resin composites, with higher DC generally leading to improved mechanical properties (4). Many bulk-fill resin composites have been investigated for various parameters such as DC, polymerisation stress, mechanical properties or microleakage. Some studies suggest that bulk-fill composites are similar to conventional resin composites in terms of physical and mechanical properties (5-7). However, some other studies have found that bulk-fill resin composites used in 4 mm layers have reduced physical and mechanical properties compared to conventional composites used in 2 mm layers (8-10).

The physical and mechanical properties of resin composites are directly related to the composition of the material (11,12). In 2013, a short fiber-reinforced composite (everX Posterior; GC, Tokyo, Japan) was introduced to replace lost dentin with a material with similar mechanical properties (13). This composite, which can be used in 4mm layers, has very good mechanical properties in the bulk-fill resin composite group (14,15). Due to the high viscosity of everX Posterior, the manufacturer launched a low viscosity form in 2019 (everX Flow Bulk; GC, Tokyo, Japan) (16).

Preheating resin composites prior to their placement in the cavity is a clinically utilized technique to potentially enhance their handling and properties (17). The primary clinical advantage is the increased fluidity of the material, which facilitates easier placement and improved adaptation to the prepared cavity walls (18,19). Furthermore, a fundamental benefit of preheating is its ability to increase the degree of conversion (DC) of the resin matrix (20). This enhanced polymerization efficacy, in turn, contributes to the improvement of the material's mechanical properties (21). However, studies have also demonstrated that these beneficial effects are not universal and may vary depending on the specific technique employed and the particular composition of the resin composite (22).

Tooth or restoration fractures occurring in teeth restored with resin composites are the most important factors affecting the success of the treatment (23,24). The material properties related to fractures, such as crack propagation resistance, deformation under occlusal load, and marginal degradation, are typically evaluated by determining the basic material parameters of flexural strength (FS), flexural modulus (FM) and fracture toughness (25). The term "flexural strength" is defined as the failure stress of a material, as measured in bending. In contrast, the term "flexural modulus" is defined as the stiffness of a material, as measured in bending (26).

While the effects of preheating on conventional resin composites have been investigated, there is a lack of evidence regarding its influence on the newer generation of short fiber-reinforced bulk-fill composites (EXP and EXF). Therefore, this study aimed to evaluate the effects of preheating at two different temperatures (39°C and 55°C) on the DC, FS, and FM of a range of bulk-fill composites with varying viscosities and filler contents, with a specific focus on addressing this gap in the literature.

The null hypotheses were as follows:

1. There is no difference in the DC, FS and FM between different resin composites.

2. The preheating process does not affect the DC, FS and FM of resin composites.

Materials and Methods

This in vitro study was conducted following the 2021 PRILE guidelines (27). In this study, four different bulk-fill resin composites: EverX Posterior (GC Corporation, Tokyo, Japan), Everx Flow Bulk (GC Corporation, Tokyo, Japan), 3M Filtek One Bulk Fill (3M ESPE, St. Paul, MN, USA), SDR Plus Flow (Dentsply, Milford, DE, USA) and a conventional composite as a control group: Z250 (3M ESPE, St. Paul, MN, USA) were evaluated. The properties of all composites tested are shown in Table 1.

The sample size for the study was determined a priori using a power analysis. The analyses were performed using the G*Power 3.1 software, based on the effect sizes reported in the study by Sarosi et al. (4). For a one-way ANOVA test, the significance level (α) was set at 0.05 and the statistical power ($1-\beta$) at 0.80. For the DC, a very high effect size (Cohen's $f \approx 0.8$) was used and 5 samples per experimental group (5 materials × 3 temperatures = 15 groups) were deemed sufficient. For the flexural tests, a medium effect size ($f \approx 0.4$) was considered, leading to a requirement of 10 samples per group.

Degree of Conversion

A stainless steel mold with a diameter of 10 mm and a thickness of 2 mm was used to prepare the specimens. A subgroup of each material (n=5) was prepared from resin composites that were stored at room temperature (20±1°C) and no preheating was applied. The other two subgroups were produced from resin composites that were preheated for 10 minutes in a preheating unit (Ena Heat Composite Heating Conditioner, Micerium, Genova, Italy) at T1 (39°C) and T2 (55°C) modes. The resin composites placed in the mold were covered with a mylar

Table 1. Resin composites tested in the study

Material	Manufacturer	Composition	Lot Number
3M Filtek Z250 (Z250) Microhybrid Resin Composite	3M ESPE, St. Paul, MN, USA	Resin Matrix: BIS-GMA, UDMA, BIS-EMA Inorganic Filler: zirconia-silica, particul size range of 0.01 – 3.5 µm Filler Load (w/V%): 77.5/60	10504771
everX Posterior (EXP) Short Fiber-Reinforced Composite	GC Tokyo, Japan	Resin Matrix: Bis-GMA, PMMA, TEGDMA Inorganic Filler: Short E-glass fiber filler, barium glass Filler Load (w/V%): 74.2/53.6	2309201
everX Flow (EXF) Flowable Short Fiber-Reinforced Composite	GC Tokyo, Japan	Resin Matrix: Bis-EMA, TEGDMA, UDMA Inorganic Filler: Short E-glass fiber filler, barium glass Filler Load (w/V%): 70/46	2312091
3M Filtek One Bulk Fill (ONE) High Viscosity Bulk Fill Resin Composite	3M ESPE, St. Paul, MN, USA	Resin Matrix: AUDMA, Dimethacrylate AFM, UDMA, DDMA Inorganic Filler: 20 nm silica particles, 4-11 nm zirconia particles, 100 nm ytterbium trifluoride, zirconia, and silica nanocluster Filler Load (w/V%): 76.5/58.4	10639667
SDR Plus Flow (SDR) Bulk Fill Flowable Resin Composite	Dentsply, Milford, DE, USA	Resin Matrix: UDMA, di-methacrylate resin, di-functional diluents Inorganic Filler: barium and strontium alumino-fluoro-silicate glasses, photoinitiators, colorants Filler Load (w/V%): 68/45	2305000193

Bis-GMA: bisphenol A glycidyl methacrylate; Bis-EMA: ethoxylated bisphenol A-dimethacrylate; UDMA: urethane dimethacrylate; TEGDMA: triethylene glycol dimethacrylate; PMMA: polymethylmethacrylate; AFM: addition-fragmentation monomer; AUDMA: aromatic urethane dimethacrylate; DDMA: 1,12-dodecane dimethacrylate; w: weight; V: volume.

strip and polymerised with an LED unit (3M Elipar, 1200 mW/cm2) for 20 seconds. The prepared specimens were stored in distilled water at 37°C for 24 hours. The DC was measured using Fourier Transform Infrared Spectroscopy (FTIR). The normalised absorbance of the functional group of the uncured ($C{=}C_{uncured}/C{=}O_{uncured}$) and cured ($C{=}C_{cured}/C{=}O_{cured}$) specimens was used to calculate the DC according to the formula:

$$DC=(1-(C{=}C_{cured}/C{=}O_{cured})/(C{=}C_{uncured}/C{=}O_{uncured}))x100$$

Flexural Strength and Flexural Modulus

For the three-point bending test, a stainless steel mold with dimensions (25x2x2 mm) recommended by the ISO 4049/2009 specification was used to prepare the specimens. All composites were divided into 3 subgroups (n=10), as were the specimens prepared for the DC test. The composites placed in the mold were covered with a glass to obtain a smooth surface and excess composite was removed. The specimens were polymerised for 20 seconds at 3 points from both ends and the centre of the specimen using an LED unit with the tip in perpendicular contact with the glass surface. The back surface was then polymerised for 20 seconds at 3 points as on the front surface.

The dimensions of the specimens were measured using a digital caliper (Series 500 Caliper, Mitutoyo America Corp, Aurora, IL, USA) and any dimensional discrepancies were corrected using 400, 600 and 1200 grit SiC papers until the desired values (±0.01 mm) were achieved. The prepared specimens were stored at 37°C for 24 hours. A three-point bending test (Fig. 1) was then performed using a 2 mm diameter cylindrical tip, a speed of 0.5 mm/min and a gap of 20 mm using a computer-controlled universal testing machine (DL 2000; Instron Universal Testing Machine). The breaking load (N) and deflection (mm) of the specimens were recorded. The FS in megapascals (MPa) and FM in gigapascals (GPa) were calculated using the following equations:

$$FS = 3FL/2bh^2$$

$$FM = (F/d).(L^3/4bh^3).(10^{-3})$$

*F: Force (N), L: Distance between supports (mm), b: Specimen width (mm), h: Specimen height (mm), d: Amount of bending (mm)

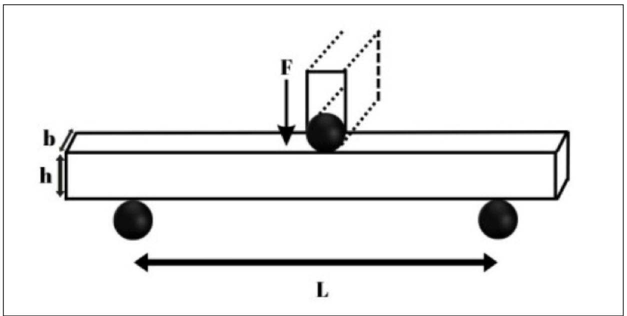

Fig. 1. Three-point bending test.

Statistical Analysis

SPSS (version 24.0; IBM, Armonk, NY, USA) was used for statistical analysis. The normality of the variables was analyzed with the Shapiro-Wilk test. As the data were normally distributed in all groups, one-way analysis of variance (ANOVA) and post-hoc Tukey tests were performed for all data, with $p<0.05$ deemed significant.

Results

Table 2 shows the DC of all composites at all temperature groups. When the groups applied at room temperature were evaluated independently, Z250 (41.32%) had the lowest DC. Although the DC of EXP (52.11%) at room temperature was significantly higher than that of Z250, it was significantly lower than that of all other bulk-fill composites. Preheating significantly increased the DC of Z250 and EXP, but had no significant effect on EXF, ONE and SDR.

FS values of all groups are presented in Table 3. When the groups applied at room temperature were evaluated independently, no difference was observed between Z250 (145.68 MPa), EXF (152.19 MPa) and EXP (157.24 MPa) in terms of FS. However, these composites exhibited significantly higher FS than ONE (100.70 MPa) and SDR (114.95 MPa). When the composites were evaluated individually, it was found that the preheating process did not affect the FS of EXF, ONE and SDR, but caused a significant increase in the FS of Z250 and EXP.

FM values of all groups are shown in Table 4. SDR showed significantly lower FM than all other composites

Table 2. Mean values of DC (%)

Material	Room Temperature	T1(39°C)	T2 (55°C)
Z250	41.32 (3.04)^{Aa}	53.58 (3.41)^{Ab}	60.62 (3.16)^{Ac}
EXF	62.64 (3.74)^{Ba}	60.67 (3.30)^{Aba}	60.35 (3.44)^{Aa}
EXP	52.11 (3.03)^{Ca}	60.43 (3.85)^{ABb}	64.86 (3.84)^{Ab}
ONE	60.79 (3.90)^{Ba}	59.62 (3.46)^{Aba}	58.02 (3.22)^{Aa}
SDR	63.87 (3.31)^{Ba}	62.87 (4.07)^{Ba}	61.54 (3.40)^{Aa}

*The same uppercase letters mean there is no statistically significant difference between the groups in same column. The same lowercase letters means that there is no significant difference between the groups in same line.

Table 3. Mean values of FS (MPa)

Material	Room Temperature	T1(39°C)	T2 (55°C)
Z250	145.68 (2.41)^{Aa}	168.70 (3.73)^{ABb}	151.11 (4.17)^{Aab}
EXF	152.19 (5.64)^{Aa}	146.60 (4.65)^{ACa}	129.57 (2.32)^{Ba}
EXP	157.24 (4.53)^{Aa}	183.35 (1.36)^{Bb}	170.00 (1.58)^{Aab}
ONE	100.70 (5.72)^{Ba}	122.07 (4.94)^{CDa}	108.35 (5.55)^{Ba}
SDR	114.95 (4.61)^{Ba}	120.39 (2.10)^{Da}	107.93 (5.28)^{Ba}

*The same uppercase letters mean there is no statistically significant difference between the groups in same column. The same lowercase letters means that there is no significant difference between the groups in same line.

Table 4. Mean values of FM (GPa)

Material	Room Temperature	T1(39°C)	T2 (55°C)
Z250	9.37 (0.28)^{Aa}	10.70 (0.51)^{Aba}	9.36 (0.27)^{Aa}
EXF	9.09 (0.27)^{ACa}	8.76 (0.45)^{ACa}	8.62 (0.22)^{Aa}
EXP	12.46 (0.17)^{Ba}	12.95 (0.32)^{Ba}	12.91 (0.15)^{Ba}
ONE	7.71 (0.19)^{Ca}	7.24 (0.34)^{Cab}	6.19 (0.16)^{Cb}
SDR	3.70 (0.06)^{Da}	3.56 (0.15)^{Dab}	2.87 (0.07)^{Db}

*The same uppercase letters mean there is no statistically significant difference between the groups in same column. The same lowercase letters means that there is no significant difference between the groups in same line.

at all temperature applications. However, EXP showed the highest average FM value for all temperature treatments. Preheating did not make a statistically significant difference to the FM of Z250, EXF and EXP. For ONE and SDR composites it was observed that preheating at 55°C significantly reduced the FM compared to room temperature application.

Discussion

In the present study, the effect of preheating at different temperatures on the DC, FS and FM of four different bulk-fill resin composites, which were introduced to the market for use in high stress-bearing areas and to increase the fracture resistance of restorations, was investigated. The study revealed that there were significant differences between the tested composites in terms of their DC, FS and FM. In addition, the preheating process was found to have a significant effect on the DC, FS and FM values of some composites. Therefore, both of our null hypotheses were rejected.

In the current literature, while preheating of dental resins has been applied within a broad range of 30-69°C (28), concerns exist regarding the use of very high temperatures due to the potential for pulpal damage from temperature increases exceeding 5.5°C (29). However, experimental data suggests that these concerns may be mitigated in a clinically applicable context. For instance, it has been demonstrated that placing a composite resin preheated to 60°C increased pulp temperature by only 0.8°C, whereas light curing for 15 seconds caused a more significant increase of 4.5-5°C (30). Based on this literature and common practice in previous in-vitro studies, we therefore selected the preheating temperatures of 39°C and 55°C for this investigation.

The process of polymerisation has a significant effect on the mechanical and biological properties of resin composites (1). In addition to intrinsic factors such as co-monomer composition and ratio, filler content, photoinitiator type and concentration, there are also extrinsic factors such as light spectrum, irradiation protocols, temperature and light guide tip positioning that affect the DC of light-cured resin composites (31). DC can be obtained by direct (FTIR, FTIR-ATR and FTIR-Raman spectroscopy) and indirect methods (microhardness, depth of cure, differential scanning calorimetry, differential thermal calorimetry) (32). In the current study, the DC of the resin composites tested was evaluated by FTIR spectroscopy.

When the specimens prepared at room temperature were examined, the highest DC was observed in SDR, which has the lowest inorganic filler content. It was also observed that the DC decreased with increasing filler content in the other composites except ONE. It is an expected result that increasing the filler content decreases the DC as it is accepted that increasing the amount of filler particles is an obstacle to polymer chain propagation (33). The exception of ONE to this rule is thought to be related to the AFM (addition-fragmentation monomer) in its organic content. These results obtained from our study are also similar to the literature (34).

Preheating of resin composites increases the system temperature, which reduces viscosity and improves molecular mobility, increases the collision frequency of reactive radicals, and delaying diffusion-controlled propagation, thereby improving final DC (20). As expected, in this study, preheating increased the DC of viscous composites with high filler content such as Z250 and EXP. However, it did not increase the DC of EXF, SDR and ONE, on the contrary, it caused a minimal decrease. Similar to our study, Lempel et al. (35) showed that preheating may have a positive effect on the DC in viscous composites, while it may have a negative effect in less viscous composites. The authors stated that this may be due to differences in the monomer content of the composites and a faster cooling process in composites with less filler. During cooling, the polymer formation has excessive heat loss. This deprives the system of the energy required for polymer chain propagation. The gel phase interval may be reduced, autodeceleration occurs, leading to premature vitrification and a reduction in the DC (36).

The FS and FM values of resin composites are considered to be critical indicators of the material's resistance to fracture under normal masticatory conditions (25,26,37). Although different tests can be used to measure these values, the three-point bending test is recommended as the gold standard. In this study, to measure the FS and FM of resin composites, specimens were prepared to the dimensions (25x2x2 mm) specified in ISO 4049/2009 (38) and three-point bending tests were performed. The same method has been preferred in many previous studies (13,39,40).

All composites tested in our study exhibited FS values above the 80 MPa threshold specified in ISO 4049/2009 for polymer-based restorative materials used in posterior restorations at all temperature applications (37). Among the bulk-fill composites, the highest FS values at room temperature were observed in the EXP and EXF groups containing short E-cam fibers. These composites showed significantly higher FS values than other bulk-fill composites (ONE and SDR) that did not contain fibers. These results are in parallel with similar studies in the literature (12,41). According to the authors, EXP and EXF allow stress to be transferred from the matrix to the fibers thanks to the fibers they contain, thus providing effective reinforcement. In addition, these randomly oriented fibers also act as crack stoppers and strengthen the material (39). Therefore, it is possible that the high FS value exhibited by EXP and EXF may be related to the short E-glass fiber content.

Although EXF had similar FS values to EXP at room temperature, it had a significantly lower FM than EXP. This is interesting because it means that EXF, with a lower FM and similar FS, can be subjected to a higher load before failure. However, it was also found that lower FM creates less stress during polymerisation (41,42). In addition, EXF has the advantage of being easier to manipulate and place, especially in the posterior region of the oral cavity, due to its low viscosity. The same situation was observed between the ONE and SDR groups. Although SDR, with its lower viscosity, had similar FS values, it had a significantly lower FM than ONE.

Many studies have been carried out to investigate the effect of preheating on the physical and mechanical properties of resin composites. However, the results of these studies are not always consistent (28). The success of the technique depends on many variables such as material formulation, type of organic matrix, inorganic fillers, heating time and temperature, and light activation technique (43). Therefore, there is a lack of evidence regarding the effect of preheating on the physical and mechanical properties of resin composites. However, there is no study in the literature that investigates the effect of preheating on the flexural properties of short fiber-reinforced resin composites such as EXP and EXF. Therefore, in the present study, the effect of preheating at two different temperatures (39°C and 55°C) on the FS and FM values of 5 different resin composites, including short fiber-reinforced resin composites, was investigated.

Among the tested resin composites, the groups of Z250 and EXP with 39°C preheating treatment showed significantly higher FS values than those applied at room temperature. Although the FS value of the 55°C preheated groups of the same composites was higher than those applied at room temperature, this difference was not significant. These results are similar to the studies reporting that preheating increases the FS values of Z250 (44,45). In the present study, preheating increased the FS of Z250 and EXP, but had no effect on FM. Therefore, it can be said that preheating has a positive effect on the flexural properties of these composites.

In contrast to the Z250 and EXP groups, the EXF, ONE and SDR groups did not show any significant difference in the FS after preheating at the both temperatures. However, ONE and SDR showed significantly lower FM after preheating at 55°C. Similar studies have reported that preheating has a positive effect on the FS of some composites, while making no significant difference to others (46,47). This discrepancy may be due to variations in resin composite formulations, such as monomer composition and filler content.

Although a strength of this study was that it evaluated popular bulk resin composites on the market, one of its major limitations was that only certain resin composites were tested. There are many resin composites on the market with different chemical contents and mechanical properties. Therefore, the results of the study cannot be generalized to all resin composites. Another limitation of the study is that the standard specimens prepared according to ISO standards in this study cannot exactly simulate the clinical scenario. Therefore, it is recommended that this in vitro study be supported by clinical studies.

Conclusion

This in vitro study demonstrates that the clinical benefit of preheating is highly material-dependent. Preheating is recommended for viscous, fiber-reinforced (EverX Posterior) and conventional hybrid (Filtek Z250) composites to enhance their mechanical properties in stress-bearing restorations. In contrast, preheating provided no significant mechanical advantage for the flowable bulk-fill composites tested (EverX Flow Bulk, SDR Plus Flow, Filtek One Bulk Fill). For clinical practice, 39°C emerges as the prudent temperature choice, balancing efficacy with a safer physiological profile compared to higher temperatures.

Authorship Contributions: Concept: G.K., D.H.; Design: G.K., D.H.; Supervision: G.K.; Data: D.H., E.C.; Analysis: D.H., E.C.; Literature search: G.K., D.H., A.Y.I., E.C.; Writing: G.K., D.H.; Critical revision: G.K., D.H., A.Y.I., E.C.

Use of AI for Writing Assistance: Not declared

Source of Funding: This work was supported by Scientific Research Projects Coordination Unit of Kırıkkale University. Project number: 2024/035.

Conflict of Interest: None declared.

Ethical Approval: Not applicable.

Informed consent: Not applicable.

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ORIGINAL ARTICLE

Turk Endod J 2026;11(1):85–92
doi: 10.14744/TEJ.2025.86548

An in vitro comparison of the retreatment efficacy of different root canal sealers and solvents

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Purpose: The aim of this study was to compare the effectiveness of different root canal filling solvents in removing filling material with AH Plus or MTA-Fillapex from premolar teeth with artificially created lateral canals.

Methods: One hundred twenty extracted single-rooted premolar teeth with standardized artificial lateral canals were prepared and obturated using AH Plus or MTA-Fillapex with a warm vertical compaction technique. Retreatment was performed using ProTaper Universal Retreatment instruments with four different conditions: No solvent (control), chloroform, endosolv, and eucalyptol solvent. Residual filling material in the main canals was evaluated under a stereomicroscope using pixel-based image analysis, while residual filling material in the lateral canals was assessed radiographically. Main canal data were analyzed using two-way ANOVA and post-hoc tests, whereas lateral canal data were reported descriptively.

Results: The type of sealer did not significantly affect the amount of residual filling material in the main canal. In contrast, the solvent type had a significant effect. Endosolv resulted in significantly less residual filling material compared with chloroform, eucaliptol, and the control group. In the lateral canals, no method provided measurable and consistent removal, and therefore only descriptive analysis was performed.

Conclusion: Endosolv was the most effective solvent for removing root canal filling materials from the main canal. However, the anatomical complexity of lateral canals limits the effectiveness of all retreatment procedures.

Keywords: Endodontic retreatment; lateral canal; root canal filling removal; solvents.

Introduction

The primary objective of endodontic retreatment is the complete removal of existing root canal filling materials, effective disinfection of the root canal system, and subsequent three-dimensional obturation (1). For successful retreatment, removing as much of the previous root canal filling as possible is essential to allow for the effective elimination of pathogenic microorganisms and necrotic tissue remnants (2,3). However, complete removal of the filling

Cite this article as: Sariyilmaz E, Misirci K. An in vitro comparison of the retreatment efficacy of different root canal sealers and solvents. Turk Endod J 2026;11:85-92.

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Submitted: December 03, 2025 Revised: December 08, 2025 Accepted: December 09, 2025 Published: April 27, 2026

material is often challenging due to the complexity of root canal anatomy and the physicochemical properties of the materials used (4,5).

Within these complex anatomical structures, lateral canals and accessory pathways are defined as critical regions that significantly affect endodontic success (6,7). Although it has been reported that tissues within lateral canals and apical ramifications are not adequately affected by irrigation and instrumentation (8), it is frequently observed that these areas become filled by the mechanical extrusion of sealer or gutta-percha during obturation. Therefore, the dissolution of residual filling material at the entrances of lateral canals during retreatment is of considerable clinical importance.

Studies have demonstrated that the complete removal of root canal filling materials using current instruments and techniques during retreatment is not always achievable (5,9,10). Histological evaluations of teeth with apical periodontitis have revealed that bacteria may remain protected within residual filling materials (8). The use of solvents to facilitate the removal of gutta-percha and sealers during retreatment has been considered advantageous in some studies (11,12). Rossi-Fedele and Ahmed (13) reported that when solvents are used particularly at the initial stage of retreatment, they may increase file penetration into the root canal but may negatively affect cleaning efficacy; conversely, when applied after instrumentation, they may reduce the amount of remaining filling material. Nevertheless, there is no consensus regarding the use of solvents. Some investigations have shown that solvent application results in the formation of a softened gutta-percha layer on the canal walls, which may render the retreatment procedure more difficult and time-consuming (14,15). In the existing literature, the effects of gutta-percha solvents have mainly been evaluated within the main root canal (11,12,14,15) and the isthmus (5); however, evidence regarding their effectiveness in lateral canals remains very limited, particularly in canals filled with epoxy resin–based or MTA-based sealers.

The aim of this study was to evaluate the efficacy of different root canal filling solvents in removing AH Plus– and MTA-Fillapex–based fillings from the main canal and from artificially created lateral canals in premolar teeth obturated using thermoplasticized techniques, using radiographic and stereomicroscopic analyses.

The null hypotheses tested in this study were defined as follows:

H_{01}: The type of root canal sealer has no effect on the efficacy of sealer removal from the main root canal during retreatment performed with different solvents.

H_{02}: Different root canal filling solvents used during endodontic retreatment have no effect on the efficacy of removal of the previous root canal filling material from the main root canal.

H_{03}: Different root canal filling solvents used during endodontic retreatment have no effect on the efficacy of removal of the previous filling material from the lateral canals.

Materials and Methods

Ethical approval for this study was obtained from the Ordu University Clinical Research Ethics Committee (Decision No: 2020-07, Date: 16/01/2020) and it was conducted according to the Declaration of Helsinki.

The total number of samples required for the study was determined based on a data from the previous study (16) using the G*Power 3.1 software package (Heinrich Heine University, Dusseldorf, Germany). The minimum required total sample size was calculated as 120 (n:15) based on the F test family, an effect size of 0.4722424, an alpha-type error of 0.05, and power of 0.85.

A total of 120 single-rooted mandibular premolar teeth of similar size and dimensions, extracted for periodontal or prosthetic reasons, were used in this study. Teeth with straight roots, complete root development, and without caries, restorations, calcifications, or root resorption were included. Root curvature was assessed using the Schneider method, and only teeth exhibiting a curvature between 0° and 10° were selected. Soft tissue remnants and debris were removed from the root surfaces using periodontal curettes.

The crowns of the teeth were removed to standardize the working length to 15 mm. The working length was determined as 1 mm short of the apical foramen. Root canals were prepared up to a Reciproc Blue 40/.06 instrument (VDW, Munich, Germany) and irrigated with 2.5% NaOCl. Final irrigation was performed using 17% EDTA, distilled water, and 2.5% NaOCl, after which the canals were dried with paper points.

On the mesial and distal surfaces of the teeth, three simulated lateral canals were created at distances of 3, 6, and 9 mm from the apex using a #15 K-reamer (VDW, Munich, Germany) mounted on a low-speed handpiece operating at 20,000 rpm. According to the type of root canal sealer to be used (AH Plus or MTA-Fillapex), the teeth were randomly divided into two main groups, with 60 teeth in each group.

Root canal obturation of 60 teeth was performed using AH Plus (Dentsply/Maillefer, USA), while MTA-Fillapex (Angelus, Brazil) was used for the remaining 60 teeth. A continuous wave of condensation technique with heat was used for obturation of all root canals. Apical filling was achieved by cutting a master cone coated with sealer using the Elements Free Obturation System (SybronEndo) and condensing it with hand pluggers (SybronEndo, Orange, CA, USA). For obturation of the middle and coronal thirds of the canals, thermoplasticized gutta-percha heated in a backfill device was used, and condensation was performed with hand pluggers at each stage.

All 120 obturated teeth were embedded in silicone blocks. To obtain standardized radiographs using the parallel technique, a phosphor plate holder was positioned relative to the X-ray tube. Radiographic images were acquired using identical exposure parameters (60 kVp, 7 mA, 0.1 s) from the same distance and at the same angle for all specimens. After radiographic evaluation of the root canal fillings, samples in which the lateral canals were inadequately filled were excluded and replaced with newly prepared specimens.

The teeth in each main group were further subdivided into four subgroups according to the type of solvent used (no solvent, chloroform, Endosolv, and eucalyptol).

Control Group (No Solvent): Only ProTaper Universal Retreatment files were used for the removal of root canal fillings. The D1 (30/.09) file was used in the coronal third, the D2 (25/.08) file in the middle third, and the D3 (20/.07) file in the apical third to remove the filling material. The files were mounted on a VDW Gold Reciproc endomotor (VDW, Munich, Germany) and operated at 500 rpm and 3 N·cm torque, in accordance with the manufacturer's instructions, using gentle apical pressure.

Chloroform Group: The retreatment files D1 (30/.09), D2 (25/.08), and D3 (20/.07) were used at 500 rpm and 3 N·cm torque according to the manufacturer's recommendations. After use of the D1 file in the coronal region, 0.2 mL of chloroform was applied for 2 minutes. The D2 file was then used in the middle third with the same application of 0.2 mL chloroform. The D3 retreatment file was used throughout the procedure to remove the filling material from the apical third of the root canal. A total volume of 0.4 mL chloroform was used for each tooth.

Endosolv Group: All procedures performed in the chloroform group were followed identically, using a total of 0.4 mL Endosolv (Septodont, Paris, France) instead of chloroform.

Eucalyptol Group: All procedures performed in the chloroform group were followed identically, using a total of 0.4 mL eucalyptol (Kalsin, Aktu Ticaret, İzmir, Türkiye) instead of chloroform.

In all groups, the root canals were irrigated with 2.5 mL of 2.5% NaOCl solution between each instrumentation step. Final apical preparation was performed using an R50 (50/.05) file (VDW). During the final irrigation protocol following preparation, the canals were sequentially irrigated with 5 mL of 17% EDTA to remove the smear layer, 2.5 mL of distilled water, and subsequently 5 mL of 2.5% NaOCl, after which the root canals were dried with paper points.

Radiographs of all 120 retreated teeth were obtained again using the parallel technique with the same exposure parameters as those used before retreatment. The post-retreatment radiographs were compared with the pre-retreatment images. The efficacy of the root canal filling solvents in the lateral canals was evaluated by calculating the ratio of the dissolved material to the total amount of material within the lateral canal using the pixel-counting method in Adobe Photoshop CS6 Extended (Mountain View, California, USA). To ensure assessor blinding, all radiographic and stereomicroscopic images were coded by KM after image acquisition, and the analyses were performed by ES in a blinded manner without access to group allocation.

Subsequently, longitudinal grooves were prepared on the buccal and lingual surfaces of the teeth using a steel separator, and the specimens were split into two halves with a cement spatula. Digital images of the sectioned surfaces were obtained at ×8 magnification using a stereomicroscope (Nikon SMZ25, Tokyo, Japan). These images were analyzed with Adobe Photoshop CS6 Extended (Mountain View, California, USA), and the ratio of the remaining gutta-percha area to the total canal wall area was calculated using the pixel-counting method. The blinded coding procedure described above was applied to these images to maintain assessor blinding during pixel-based measurements.

Statistical Analysis

Normal distribution of the data was confirmed using the Kolmogorov–Smirnov test, and the homogeneity of variances was assessed with the Levene test. Differences in the amount of residual filling material obtained using different root canal sealers and different root canal filling solvents were analyzed by two-way analysis of variance (Two-way ANOVA). Multiple comparisons between groups were performed using the Tukey HSD post hoc test. All statistical analyses were conducted at a 95% confidence level, and a p value of <0.05 was considered statistically significant. The two-way ANOVA and Tukey HSD post hoc tests were applied only to the main canal data. Because of the predominance of zero values in the lateral canal measurements, these data were summarized descriptively without inferential statistical testing.

Results

Descriptive statistics of the residual filling material according to the solvents used with different root canal sealers are presented in Table 1. The type of root canal sealer was found to have no statistically significant effect on the amount of residual filling material remaining in the main canal (F=0.656, p=0.420). In contrast, the type of root canal filling solvent had a statistically significant effect on the amount of residual filling material (F=10.910, p<0.001).

According to the multiple comparisons, the Endosolv group resulted in significantly less residual filling material than the chloroform, eucalyptol, and control groups (p=0.002, p<0.001, and p=0.029, respectively). In addition, the eucalyptol group exhibited a significantly greater amount of residual filling material compared with the control group (p=0.030). No statistically significant differences were observed between the chloroform and control groups (p=0.816) or between the chloroform and eucalyptol groups (p=0.225). The interaction between sealer type and solvent type was not statistically significant (p=0.093) (Table 2).

In the evaluation of the lateral canals, no change was observed in many specimens in either the solvent or the control groups. In the AH Plus groups, 95.6% of all lateral canals created on the mesial and distal surfaces of the coronal, middle, and apical root regions in the control group, 66.6% in the chloroform group, 60.0% in the Endosolv group, and 73.3% in the eucalyptol group showed no removal of root canal filling and were recorded as 0% removal. Similarly, in the MTA-Fillapex groups, 95.5%, 57.8%, 95.5%, and 91.1% of the lateral canals, respectively, exhibited 0% removal, indicating that no filling material could be eliminated from these lateral canals. Because of the lack of measurable removal from the lateral canals and the consequent predominance of zero values in the dataset, no statistically demonstrable differences could be evaluated; therefore, no inferential statistical analysis was performed for these data.

Discussion

In studies in which artificial lateral canals have been created, both extracted permanent teeth (17) and transparent resin blocks or plastic teeth have been used as experimental models (18-20). Although resin blocks have been reported to be advantageous in terms of providing specimen standardization and eliminating the influence of canal preparation procedures (20), it has also been reported that the acrylic surface characteristics, compared with dentin, may affect the flow properties of gutta-percha and root canal sealers (18,20). Therefore, in the present study, extracted human teeth were used to obtain results closer to clinical conditions, and single-rooted premolar teeth with straight canals and similar root lengths were preferred to ensure standardization.

It has been reported that either 0.1-mm cylindrical burs or #15 K-reamers are used to create artificial lateral canals in extracted natural teeth (19,21). The diameter of natural lateral canals has been reported to range between 26 and 200 μm, with most commonly observed values between 60 and 80 μm (22). In another study, it was observed that 80% of lateral canals corresponded to or were narrower

Table 1. Descriptive statistics of residual filling material in the main canal (%) according to solvent and sealer

Solvent	AH Plus (n=15)	MTA-Fillapex (n=15)	Total (n=30)
Control	20.03±10.48	21.74±7.32	20.89
Chloroform	20.46±12.26	25.81±11.75	23.13
Endosolv	16.78±9.38	10.59±7.36	13.69
Eucalyptol	25.56±10.25	30.52±9.19	28.04

Values are presented as mean ± standard deviation (SD).

Table 2. Estimated marginal means of residual filling material in the main canal (%) according to solvent type and Tukey HSD comparison

Solvent	n	Adjusted Mean ± SE	95% Confidence Interval
Control	20.03±10.48	21.74±7.32	20.89
Chloroform	20.46±12.26	25.8	28.04

Values are presented as adjusted (estimated marginal) means ± standard error (SE) derived from the two-way ANOVA model. Different letters indicate statistically significant differences among solvent groups according to the Tukey HSD test (p<0.05).

than the diameter of a #10 K-reamer, 10% corresponded to a #15 K-reamer, and 7% had diameters equivalent to #20–40 K-reamers, while only 3% were wider than a #40 K-reamer tip (23). In the present study, lateral canals were created on the mesial and distal surfaces of premolar teeth at 3, 6, and 9 mm from the apex using a #15 K-reamer, thereby simulating dimensions comparable to those of natural lateral canals (22,23).

It was confirmed that the type of root canal sealer had no statistically significant effect on the amount of residual filling material remaining in the main canal, and thus the first null hypothesis of the study was accepted. Omidi et al. (24) similarly reported no statistically significant difference in residual sealer volume between AH Plus and MTA-Fillapex after retreatment, in agreement with the findings of the present study. In contrast, another study using cone-beam computed tomography reported significantly less residual filling material in the MTA-Fillapex group compared with AH Plus (25). These discrepancies in the literature may be attributed to differences in the imaging methods used (CBCT vs. radiography), measurement techniques (volumetric analysis vs. pixel analysis), obturation protocols, and variations in root canal anatomy.

In the present study, Endosolv was found to be more effective than chloroform. In contrast, another study evaluating the effects of different solvents on MTA-Fillapex in terms of re-establishing apical patency reported that chloroform and Endosolv E were more effective, whereas Endosolv R was insufficient (26). This discrepancy between the findings may be attributed to the fact that, in the present study, the amount of residual filling material was directly evaluated using macroscopic measurements, whereas in the aforementioned study, solvent efficacy was indirectly assessed based on the re-establishment of apical patency. In addition, while the cited study used two different formulations—Endosolv R for resin-based sealers and Endosolv E for zinc oxide–eugenol–based sealers—the present study employed a single-bottle Endosolv formulation claimed to be effective on both types of sealers. This methodological difference may also account for the divergence in results.

In previous studies, Endosolv R, consists of a formamide- and phenethyl alcohol–based formulation developed for resin-based sealers, and Endosolv E, which consists of a tetrachloroethylene-based formulation, intended for zinc oxide–eugenol–based sealers, were evaluated separately, and Endosolv R was reported to exhibit limited efficacy, particularly in terms of main canal wall cleanliness (26-28,29). In contrast, the Endosolv used in the present study, which consists of an ethyl acetate and pentyl acetate formulation, represents a newer single-bottle formulation that has been proposed for use with both resin- and eugenol-based sealers (29), and it demonstrated superior retreatment efficacy compared with the other solvents tested. Therefore, it is plausible that the lack of effectiveness reported for Endosolv in earlier studies, which were conducted using older formulations with different chemical compositions (Endosolv E/R) (26-28.), may account for the discrepancies with the present findings. Furthermore, while previous studies assessed efficacy mainly in terms of apical patency and at a microscopic level, the present study quantified the residual filling material radiographically and stereomicroscopically, representing another important methodological difference that may have influenced the outcomes.

Schäfer et al. (30), in their study evaluating the solubility of root canal sealers with different compositions in organic solvents, reported that epoxy resin–based sealers exhibited greater solubility in chloroform than in eucalyptol oil. Similarly, Alzraikat et al. (31), who compared the solubility of AH Plus and MTA-Fillapex in chloroform and eucalyptol, demonstrated that chloroform was a more effective solvent than eucalyptol for all root canal sealers tested. In the same study, AH Plus was reported to exhibit greater solubility than MTA-Fillapex. Overall, eucalyptol was found to have weak dissolving efficacy, and particularly low solubility of MTA-Fillapex in eucalyptol was reported. In contrast, in the present study, no statistically significant difference was observed between AH Plus and MTA-Fillapex in terms of solubility-related removal efficacy. Considering that the aforementioned studies evaluated the solubility of sealers in their pure form within solvents, whereas the present study investigated the removal efficacy of obturated materials adapted to dentin walls under simulated clinical conditions, this discrepancy is likely to be methodological in origin. It can be stated that the solubility of a material in its pure form does not directly correspond to its intracanal removal efficacy under clinical simulation, and that the clinical performance of solvents cannot be reliably predicted solely on the basis of solubility tests.

Scelza et al. (12) reported that chloroform, orange oil, and eucalyptol exhibited statistically similar cleaning efficacy within dentinal tubules. In contrast, the present study demonstrated statistically significant macroscopic differences, particularly in favor of Endosolv. This inconsistency is likely attributable to the methodological difference in the evaluation scale (microscopic dentinal tubule level vs. macroscopic canal lumen level).

Campello et al. (5) evaluated the effect of solvent use on the removal of filling material from the isthmus region using micro-CT and reported that eucalyptol did not significantly reduce the residual filling volume at either the main canal or isthmus level. Similarly, in the present study, due to the narrow anatomical configuration of the lateral canals, no sufficiently measurable removal was achieved in either the solvent or control groups. Natural lateral canal diameters have been reported to range from 26 to 200 µm, most commonly around 60–80 µm (22). In the present study, simulated lateral canals were created using a #15 K-reamer, resulting in relatively wide artificial canals (≥150 µm). Notably, even under these conditions, solvent-assisted removal from lateral canals remained minimal, suggesting that the effectiveness of solvents in narrower natural lateral canals is likely to be even more limited. This finding indicates that lateral canals represent one of the most resistant microanatomical regions with respect to endodontic retreatment. From a clinical perspective, it should be considered that filling material largely remaining within lateral canals may serve as a potential reservoir for infection and may contribute to the persistence of periapical lesions.

In the present study, since the type of root canal sealer (AH Plus vs. MTA-Fillapex) had no significant effect on the amount of residual filling material in the main canal, the first null hypothesis (H_{01}) was accepted. In contrast, because the type of root canal filling solvent used had a statistically significant effect on the amount of residual filling material in the main canal, the second null hypothesis (H_{02}) was rejected. Regarding the third null hypothesis (H_{03}), none of the solvents produced a measurable or clinically relevant degree of filling removal from the lateral canals. Because of the predominance of zero values, no meaningful statistical comparison could be carried out, and H_{03} was interpreted in the context of these anatomical and methodological limitations rather than being formally rejected. These findings support the notion that lateral canals represent one of the most resistant microanatomical regions during retreatment, largely retaining their filling material regardless of the solvent used.

This study was conducted under in vitro conditions and therefore does not fully reflect the clinical situation. To ensure standardization, a single retreatment system and needle irrigation were used; thus, the findings may not be generalizable to other retreatment approaches or irrigation activation techniques, and future studies should evaluate their effects on lateral canal removal. In addition, only two sealers (AH Plus and MTA-Fillapex) were tested, although numerous root canal sealers with different chemical compositions are currently available; including a broader range of materials may provide a more comprehensive understanding of solvent performance. In the evaluation of lateral canals, the use of a sectioning method may damage the tooth and root structures and may lead to errors in visual assessment. For this reason, the lateral canals could not be evaluated by sectioning and were assessed only using two-dimensional radiography. However, overlap, superimposition, and limited image resolution may have influenced the accuracy of these measurements. Accordingly, further studies employing advanced three-dimensional imaging techniques such as micro-computed tomography and confocal microscopy are required to minimize these limitations and to enable a more detailed evaluation of lateral canals. Finally, as with many in vitro models, the lateral canals were simulated; although 3D printing can generate standardized canal geometries, currently available resin materials do not fully replicate the physical and chemical characteristics of dental tissues. Further methodological innovations that better approximate clinical conditions are therefore warranted.

Conclusion

In this study, the type of root canal sealer had no effect on the amount of residual filling material remaining in the main canal, whereas the type of solvent significantly influenced retreatment efficacy. Endosolv resulted in significantly less residual filling material compared with chloroform, eucalyptol, and the control group. However, in the lateral canals, no group achieved a sufficient level of filling material removal, indicating that these regions are highly resistant to endodontic retreatment and may act as potential reservoirs for persistent infection. Therefore, periapical lesions should be periodically evaluated after retreatment, and if the lesion persists, additional advanced treatment protocols, such as surgical approaches, may need to be considered.

Authorship Contributions: Concept: E.S., K.M.; Design: E.S., K.M.; Supervision: E.S.; Fundings: E.S.; Materials: K.M.; Data: K.M.; Analysis: E.S., K.M.; Literature Search: K.M.; Writing: E.S., K.M.; Critical Revision: E.S.

Use of AI for Writing Assistance: Not declared

Source of Funding: No funding was granted for this study.

Conflict of Interest: The authors deny any conflicts of interest related to this study.

Ethical Approval: Ethical approval for this study was obtained from the Ordu University Clinical Research Ethics Committee (Decision No: 2020-07, Date: 16/01/2020)

Informed consent: Not applicable

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ORIGINAL ARTICLE

Turk Endod J 2026;11(1):93–101
doi: 10.14744/TEJ.2025.85856

Quality and reliability of Youtube videos as a source of patient information about root canal treatment: An analysis of Turkish content

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Purpose: The aim of this study was to examine the quality and reliability of Turkish videos shared on the YouTube video sharing site regarding root canal treatment.

Methods: A total of 360 videos were listed using three different keywords, and 99 of these were included in this study. The quality and reliability of the videos were assessed using the Quality Criteria for Consumer Health (DISCERN) and the Global Quality Scale (GQS).

Results: Quality assessment results demonstrated that the mean DISCERN score was 27.95±6.93, and the mean GQS score was 1.83±0.77. According to the DISCERN scores, the quality and reliability of the videos were mostly 'inadequate,' while the GQS score categorized the average video quality as 'poor.' A positive correlation was found between DISCERN and GQS scores (p<0.001; r=0.917).

Conclusion: There is a growing need for high-quality video content that delivers comprehensive and accurate information regarding the indications, clinical procedures, and postoperative prognosis of root canal treatment, ideally developed by endodontic specialists. After assessing the quality of these videos using internationally accepted criteria, it is believed that sharing only high-quality videos will provide more informative content for patients.

Keywords: Internet and health; root canal treatment, YouTube videos.

Introduction

Whereas in the past the primary source of information about health problems was consultation with a physician or dentist, today, the widespread global use of the internet has led to a paradigm shift in information access (1). In the United States and Europe, approximately 80% of individuals use the internet to obtain health and medical information (2). Similarly, in a study conducted in Türkiye, more than 75% of participants reported that they consult the internet when seeking health-related information (3).

YouTube is one of the most frequently visited websites by patients seeking information about medical problems (4) and ranks as the second most widely used social media platform worldwide (5). Although numerous video-sharing platforms have been developed, none have matched YouTube's level of success (6). Nevertheless, the absence of peer review and the lack of authoritative oversight in content creation raise serious concerns regarding the reliability of medical and dental information on YouTube and

Cite this article as: Kurt EEE, Taşdemir T. Quality and reliability of Youtube videos as a source of patient information about root canal treatment: An analysis of Turkish content. Turk Endod J 2026;11:93-101.

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Submitted: September 29, 2025 Revised: November 23, 2025 Accepted: November 24, 2025 Published: April 27, 2026

similar platforms (7). Recognizing YouTube's growing impact as a source of patient information, several studies have evaluated the accuracy and quality of the health-related content available on this platform (7-10).

Root canal treatment (RCT) is among the most frequently performed procedures in dentistry, with approximately 15 million people worldwide undergoing this treatment annually (11). Consequently, it is not surprising that many individuals turn to YouTube for information about RCT (7).

A review of the literature indicates that, although several studies have examined the quality of RCT-related videos published in other languages on YouTube (7,9,10), no studies have evaluated the quality and reliability of Turkish-language videos. In healthcare research, various metrics have been employed to assess the quality and reliability of YouTube content, with the DISCERN and GQS scales being among the most commonly applied tools (9,12,13). The aim of the present study is to evaluate the quality and reliability of Turkish RCT videos available on YouTube using these two scales. This research is conducted for patients, not professionals. The null hypothesis of this study is that RCT videos demonstrate optimal quality.

Materials and Methods

Google Trends is an online tool that identifies search query trends over specific time periods and geographic locations (14). In the present study, the keywords used for the Google Trends search were 'canal treatment,' 'root canal treatment,' and 'endodontic treatment.' On December 15, 2023, a YouTube search simulation was conducted from a patient's perspective. To minimize bias, user history was cleared, and new accounts were created for each keyword. The only search filter applied was 'relevance' in the ranking criteria. Previous research indicates that more than 90% of individuals searching on YouTube view only the first 60 videos (the first three pages) (15). In contrast, this study examined the first 120 videos for each keyword to maximize sample size, resulting in a total of 360 videos (Fig. 1).

Of the 360 videos, 99 met the inclusion criteria outlined below.

Inclusion criteria:

1. Shared on YouTube.
2. Presented in Turkish.
3. Ranked among the top 120 videos for each keyword.

Exclusion criteria:

1. Content irrelevant to the study topic.
2. Videos containing only animation or music.
3. Poor audio or video quality.
4. Not in Turkish.
5. Duration exceeding 15 minutes.
6. Containing only advertisements or commercial content.
7. Duplicate or repetitive videos.
8. Videos describing patient experiences.
9. Academic content aimed at dentists or dental students (e.g., lectures, conferences, seminars).

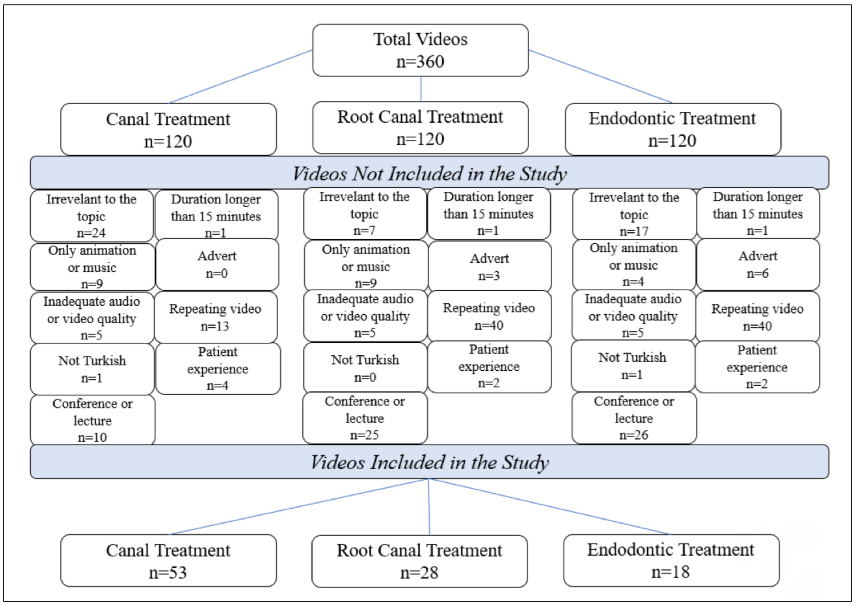

Fig. 1. Flowchart illustrating the identification, screening, exclusion criteria, and final analysis stages of the YouTube videos reviewed.

For each video incorporated into the analysis, a comprehensive set of metadata was extracted and documented. The recorded parameters included the video title, uniform resource locator (URL), year of upload, the elapsed time in days since the upload date, video duration, speaker profile, uploader source, and quantitative engagement metrics (i.e., view count, like count, and comment count).

The academic or professional profiles of the speakers featured in the videos were classified into one of the following categories: Endodontists, dentists specializing in other disciplines, general dentists, or 'other' (encompassing speakers with unclear or unidentifiable profiles). Similarly, the origin of each video was categorized based on the uploader's channel type: Individual dentist channels, clinic or hospital channels, university hospital channels, or 'other' (which included channels operated by dental supply companies, television networks, or general social media platforms).

To evaluate the quality and reliability of the video content, two validated instruments were employed: The DISCERN instrument and the Global Quality Scale (GQS). Each video was independently assessed using the DISCERN scale and assigned a score based on the criteria outlined in Table 1. Subsequently, the total score for each video was used to classify it into one of five quality tiers: Very poor (16-26 points), inadequate (27-38 points), fair (39-50 points), good (51-62 points), or excellent (63-75 points) (16,17). Furthermore, the quality of the videos was evaluated using the GQS index. Based on the scoring protocol detailed in Table 2, each video was categorized as low quality (a score of ≤2), medium quality (a score of 3), or high quality (a score of ≥4) (18). A single researcher assessed and scored all the videos (EEEK), and repeated the assessment process for both scales two months later. An internal reliability assessment was conducted for the evaluator, and the correlation coefficient was calculated as 1.

All statistical analyses were performed using SPSS for Windows, Version 17.0. Descriptive statistics are presented as

Table 1. Evaluation of YouTube videos based on DISCERN scores

1	Are the objectives clear?	1	2	3	4	5
2	Does it achieve the objectives?	1	2	3	4	5
3	Is the information relevant to the topic?	1	2	3	4	5
4	Are the sources of information used clearly identified?	1	2	3	4	5
5	Is the date of the information used clearly stated?	1	2	3	4	5
6	Is the information balanced and unbiased?	1	2	3	4	5
7	Does it provide details about additional sources of information?	1	2	3	4	5
8	Does it address areas of uncertainty?	1	2	3	4	5
9	Does it explain how each treatment is administered?	1	2	3	4	5
10	Does it explain the benefits of each treatment?	1	2	3	4	5
11	Does it explain the risks of each treatment?	1	2	3	4	5
12	Does it explain what might happen if no treatment is used?	1	2	3	4	5
13	Does it explain how treatment choices affect overall quality of life?	1	2	3	4	5
14	Does it clearly state that multiple treatment options are available?	1	2	3	4	5
15	Does it support shared decision-making?	1	2	3	4	5
16	Based on the answers to all the questions above, evaluate the overall quality of the information source	1	2	3	4	5

Table 2. Evaluation of YouTube videos based on GQS scores

Score	Description
1	Poor quality and flow, most information missing, Not at all useful to patients.
2	Generally poor quality and flow, some information listed but many important topics missing. Very limited use for patients.
3	Moderate quality and substandard flow; some important information is adequately covered, but other information is missing. Partially useful for patients.
4	High quality and generally well-flowed; most information is presented but some topics are left out. Useful for patients.
5	Excellent quality and flow, very beneficial for patients.

Table 3. Chronological analysis of YouTube videos related to root canal treatment

Loading Year	Frequency (n)	%
2013	1	1
2014	3	3
2016	3	3
2017	1	1
2018	5	5.1
2019	12	12.1
2020	12	12.1
2021	19	19.2
2022	24	24.2
2023	19	19.2
	99	100

frequencies and percentages for categorical variables. For quantitative variables, data are expressed as mean ± standard deviation along with median and range (minimum-maximum) values. The normality of data distribution for all variables was assessed using the Shapiro-Wilk test. As the data deviated from a normal distribution, non-parametric tests were employed. Inter-group comparisons were conducted using the Kruskal-Wallis test. The strength and direction of the relationship between quantitative variables were evaluated using the Spearman's rank correlation coefficient. A p-value of less than 0.05 was defined as the threshold for statistical significance.

Results

The distribution of videos by upload year revealed that the highest proportion were uploaded in 2022 (24.2%), followed equally by 2021 and 2023 (19.2% each). The lowest frequencies of uploads were observed in 2013 and 2017 (1% each) (Table 3).

Table 4. Quality assessment of root canal treatment-related videos: Descriptive statistics for DISCERN and GQS Scores

	Mean ± SD	Median (min-max)
DISCERN	27.95±6.93	27 (16-46)
GQS	1.83±0.77	2 (1-4)

Regarding the academic profile of the speakers, general dentists constituted the largest group (44.4%), followed by endodontists (39.4%) (Fig. 2). An analysis of upload sources indicated that channels associated with private clinics or hospitals accounted for the majority of the videos (49.2%), whereas university hospital channels contributed only 6.1% of the total (Fig. 3).

Quality assessment results demonstrated that the mean DISCERN score was 27.95±6.93, and the mean GQS score was 1.83±0.77 (Table 4). A positive correlation was found between DISCERN and GQS scores ($p<0.001$; $r=0.917$).

Correlational analyses identified several significant associations. A significant positive correlation was found between the number of days since upload and the cumulative view, like, and comment counts ($p<0.01$). Video duration was significantly correlated with both DISCERN and GQS scores ($p<0.001$). Furthermore, a strong positive correlation was observed between the view count and the number of likes and comments ($p<0.001$). Conversely, no significant correlations were detected between the DISCERN and GQS scores and metrics such as days since upload, view count, interaction index, or viewing rate (Table 5).

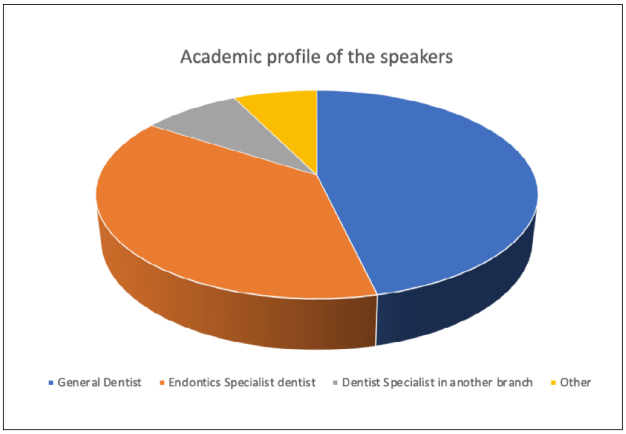

Fig. 2. Academic profile of the speakers in the videos.

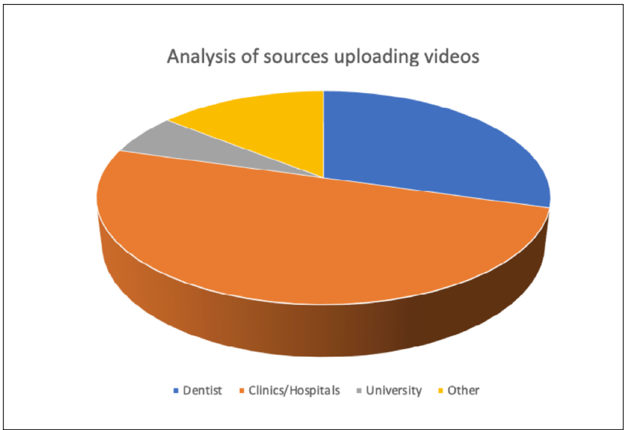

Fig. 3. Analysis of sources uploading videos related to root canal treatment.

Table 5. Correlation analysis between all quantitative variables ıncluded in the study

	DISCERN	GQS	NUMBER OF DAYS PAST	DURATION OF VIDEO	NUMBER OF VIEWS	NUMBER OF LIKES	NUMBER OF COMMENTS
DISCERN							
R	1.000	0.917	-0.096	0.515	0.098	0.209	0.212
P	.	<0.001	0.343	<0.001	0.332	<0.05	<0.05
N	99	99	99	99	99	99	99
GQS							
R	0.917	1.000	-0.125	0.499	0.059	0.197	0.212
P	<0.001	.	0.216	<0.001	0.564	≤0.05	<0.05
N	99	99	99	99	99	99	99
NUMBER OF DAYS PAST							
R	-0.096	-0.125	1.000	0.055	0.512	0.414	0.314
P	0.343	0.216	.	0.586	<0.001	<0.001	<0.01
N	99	99	99	99	99	99	99
DURATION OF VIDEO							
R	0.515	0.499	0.055	1.000	0.360	0.323	0.330
P	<0.001	<0.001	0.586	.	<0.001	<0.01	<0.01
N	99	99	99	99	99	99	99
NUMBER OF VIEWS							
R	0.098	0.059	0.512	0.360	1.000	0.766	0.681
P	0.332	0.564	<0.001	<0.001	.	<0.001	<0.001
N	99	99	99	99	99	99	99
NUMBER OF LIKES							
R	0.209	0.197	0.414	0.323	0.766	1.000	0.796
P	<0.05	≤0.05	<0.001	<0.01	<0.001	.	<0.001
N	99	99	99	99	99	99	99
NUMBER OF COMMENTS							
R	0.212	0.212	0.314	0.330	0.681	0.796	1.000
P	<0.05	<0.05	<0.01	<0.01	<0.001	<0.001	.
N	99	99	99	99	99	99	99

Discussion

The proliferation of the internet has established it as a primary source for health-related information globally (19). Among digital platforms, YouTube has emerged as a particularly prominent channel for the dissemination and consumption of such information (6). This study evaluated the quality of root canal treatment (RCT)-related content on YouTube, revealing significant concerns pertaining to the accuracy, reliability, and educational utility of the available videos.

While YouTube is frequently utilized by individuals seeking information about RCT, our findings indicate a critical gap in content quality. The platform's inherent structure, which lacks mandatory peer-review processes and evidence-based standards, coupled with an absence of formal quality control beyond viewer discretion, fundamentally compromises the reliability of health information it hosts. This environment elevates the risk of patient exposure to inaccurate or misleading information, which can adversely shape their perceptions and understanding of RCT.

Although alternative video-sharing platforms are gaining traction, YouTube maintains a dominant market position due to its extensive user base and unparalleled reach (6). Key attributes such as free access, ease of use, and the capacity for rapid information dissemination make it a preferred choice for patients seeking immediate answers (20). This widespread use underscores YouTube's significant influence in public health communication, justifying its selection as the platform of analysis for this study on RCT-related patient information.

The literature indicates that YouTube serves as a common medium for disseminating information on a wide range of dental topics, including cleft lip and palate, smile design, and traumatic dental injuries (21–23). While several studies have evaluated the quality of RCT-related videos in other languages (7,9,10), to the best of our knowledge, this is the first study to specifically assess the quality of Turkish-language RCT content on YouTube. Consequently, the findings of this study are poised to serve as a valuable reference for Turkish-speaking healthcare professionals and content creators aiming to develop evidence-based patient information on this platform.

The selection of assessment tools was guided by established practices in the field. Previous research has demonstrated the DISCERN instrument and the Global Quality Scale (GQS) to be reliable and widely adopted indices for evaluating the quality and reliability of health-related video content (9,12,13,24). In line with this precedent, our study utilized these validated instruments to ensure a standardized and comparable assessment.

The videos analyzed in this study spanned a ten-year period from 2013 to 2023. A notable concentration of uploads was observed in the most recent three years (2021–2023), with 2022 having the highest frequency. This temporal trend is likely attributable to a confluence of factors, including the sustained global growth in internet penetration, increased user engagement with online platforms, the capacity of video content to rapidly reach broad audiences, the rising number of content creators on YouTube, and possibly growing public interest in dental health procedures such as RCT.

The distribution of uploaders in our sample revealed a notable predominance of general dentists (44.4%), a finding that aligns with previous international studies. For instance, Jung et al. reported comparable figures, with general dentists accounting for 44% and 42% of videos retrieved using the search terms "root canal treatment" and "endodontic treatment," respectively (10). This consistency across different linguistic contexts suggests a broader trend of general dentists being primary contributors to RCT-related content on YouTube.

A concerning finding was the minimal involvement of authoritative sources. University hospitals demonstrated the lowest participation rate as uploaders, and no videos were identified from endodontic associations or other professional organizations. This scarcity of content from accredited institutions represents a significant gap in the information ecosystem. Our results corroborate the findings of McLean et al., whose study also noted a near absence of content from university-based healthcare institutions and found only a single video from the American Association of Endodontists (9). This collective evidence underscores an urgent need for universities and professional societies to enhance their digital footprint. By actively disseminating evidence-based content, these trusted entities can play a pivotal role in mitigating the spread of misinformation.

The primary objective of this study was to evaluate the quality and reliability of RCT-related videos on YouTube. The results, however, are alarming. The mean DISCERN score was 27.95±6.93, and the mean GQS score was 1.83±0.77, categorizing the overall quality of the content as "inadequate" and "low," respectively. This indicates that the information available to users is generally of poor quality and insufficient to support informed patient decision-making. These findings are consistent with quality assessments of RCT-related videos in other languages (7,9,10), pointing to a pervasive, platform-wide issue. The null hypothesis of this study has been rejected.

This widespread low quality stands in stark contrast to the perceptions of a considerable portion of internet users. Several studies indicate that many individuals perceive online health information as reliable. For example, one study found that 86% of users considered such information trustworthy (25), while another reported a figure of approximately 33% (26). The discrepancy between the objectively low quality of available content and relatively high user trust highlights a critical public health challenge and underscores the importance of initiatives aimed at improving both the quality of information and public digital health literacy.

The generally low quality of health information on YouTube observed in our study is consistent with a substantial body of research across diverse medical and dental fields, including Alzheimer's disease, prostate cancer, orthodontic treatment, and dental implants (11, 21, 27-36). However, it is important to acknowledge that some studies have reported moderate to high quality of health-related videos (12,37-40). These discrepant findings can likely be attributed to methodological variations, such as the number of videos assessed, the specific conditions examined, the inclusion of distinct video genres (e.g., conference recordings or academic lectures), and an inherent degree of subjectivity in the quality appraisal process (41). For instance, Demirci et al. highlighted that conference videos ranked highest for the emergency treatment of traumatic dental injuries (23), suggesting that the inclusion of such academic content can skew overall quality assessments upwards.

Another factor potentially influencing quality is video duration. The mean duration of videos in our sample was 142 seconds, which is notably shorter than averages reported in several other studies (27,34,37,42-44). We observed a prevalence of brief, question-answer format videos, which by nature of their brevity, may sacrifice critical details and comprehensive explanations. This observation aligns with literature suggesting that longer videos, which allow for a more thorough discussion, tend to achieve higher DISCERN and GQS scores (23,45,46). It has been proposed that a duration of approximately seven minutes is optimal for explaining a health topic effectively without losing viewer engagement (23).

Finally, a critical finding of our study, consistent with previous research (37,44,47), was the lack of a significant correlation between video quality (as measured by DISCERN and GQS) and view count. This underscores a significant public health concern: High view counts, often interpreted as a marker of popularity or reliability, are not a valid indicator of educational quality. This discrepancy suggests that individuals searching for health information may lack the tools to critically evaluate content, making them vulnerable to widely viewed but poor-quality information. To mitigate this risk and enhance the public's dental health literacy, a multi-faceted approach is recommended. Primarily, authoritative bodies such as endodontic associations and dental schools should take a more active role in creating and disseminating evidence-based, high-quality video content. Furthermore, healthcare professionals are encouraged to produce comprehensive, longer-format videos that address the topic in sufficient detail, moving beyond brief question-and-answer snippets. Finally, the implementation of a pre-publication quality assessment process using validated instruments like the DISCERN and GQS scales is strongly advised. Such a practice would help ensure that only high-quality, reliable information reaches the public, ultimately empowering patients to make better-informed healthcare decisions.

This study is subject to several limitations inherent to its design and the dynamic nature of the platform under investigation. First, the search results on YouTube are influenced by algorithms that personalize content based on factors such as the user's geographical location and search history. Consequently, the sample captured for this study may not be fully representative of all Turkish-language videos available globally. Second, the content on YouTube is in a constant state of flux, with new videos being uploaded and existing ones being removed or modified daily. This temporal variability means that the findings provide a snapshot in time and may not reflect the current state of available content.

A further limitation is the exclusive focus on videos in the Turkish language, which, while providing valuable insights for a specific linguistic group, limits the generalizability of the results to other languages or cultural contexts. Additionally, videos hosted on alternative platforms (e.g., Vimeo, Dailymotion) were not included. Another limitation is that the video scanning and data collection process must be completed by the end of 2023.

Conclusion

This study demonstrates that the overall quality and reliability of Turkish-language YouTube videos pertaining to root canal treatment are inadequate. The prevalence of such low-quality information poses a significant risk, as it may negatively influence patient perceptions and informed decision-making regarding this essential dental procedure.

Authorship Contributions: Concept: E.E.E.K., T.T.; Design: E.E.E.K., T.T.; Supervision: E.E.E.K., T.T.; Data: E.E.E.K., T.T.; Analysis: E.E.E.K., T.T.; Literature search: E.E.E.K., T.T.; Writing: E.E.E.K., T.T.; Critical revision: E.E.E.K., T.T.

Use of AI for Writing Assistance: Not declared

Source of Funding: None declared.

Conflict of Interest: None declared.

Ethical Approval: Not applicable.

Informed consent: None declared.

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ORIGINAL ARTICLE

Turk Endod J 2026;11(1):102–111
doi: 10.14744/TEJ.2025.60783

Evaluation of the effect of different minimally invasive access cavity preparations on discoloration in maxillary and mandibular first molars: An in vitro spectrophotometric study

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Purpose: This study evaluated the effect of different minimally invasive access cavity designs on the discoloration of maxillary and mandibular first molars using spectrophotometric analysis.

Methods: Eighty first molars (maxillary n=40; mandibular n=40), free of caries and restorations, were randomly allocated—stratified by arch—to eight groups (n=10 per group) according to access cavity design (traditional, conservative, ultraconservative, truss; four groups per arch). Using a dental operating microscope, access cavities were prepared, working lengths determined, and canals instrumented with Reciproc R25. Irrigation activation was performed with a #20 Irrisafe ultrasonic tip, followed by single-cone obturation with R25 gutta-percha and A2 composite restorations. Color measurements were recorded using a Vita Easyshade V spectrophotometer at baseline, immediately after treatment, and at 1, 7, 30, and 60 d. L*a*b values were converted to Commission International de l'Eclairage (CIELAB) ΔE values. Data were analyzed with appropriate statistical tests.

Results: Clinically perceptible discoloration ($\Delta E \geq 3.3$) was observed in all groups at various time points. In the maxillary molars, traditional access cavities showed significantly greater discoloration at one month compared at baseline ($p<0.05$). No significant differences were found among the other groups ($p>0.05$).

Conclusion: Traditional access cavities in maxillary molars produced greater discoloration than minimally invasive access cavities. Minimally invasive access cavity designs may help maintain tooth color by preserving dentin and reducing restorative material volume.

Keywords: Conservative access cavity; minimally invasive endodontics; tooth discoloration; traditional access cavity; truss access cavity; ultraconservative access cavity.

Introduction

Endodontic treatment includes pulpotomy, pulp capping, pulpectomy, and both surgical and nonsurgical treatments of the root canals and surrounding periapical tissues (1). One of the most crucial steps for successful endodontic treatment is preparation of the access cavity (2). Access cavity preparation is one of the most challenging aspects of endodontic treatment; however, it is key to its success (3).

Cite this article as: Ozyaman AG, Ateş MO. Evaluation of the effect of different minimally invasive access cavity preparations on discoloration in maxillary and mandibular first molars: An in vitro spectrophotometric study. Turk Endod J 2026;11:102-111.
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Submitted: September 16, 2025 Revised: November 11, 2025 Accepted: November 11, 2025 Published: April 27, 2026

To date, the general outlines of endodontic access cavities have been standardized for each tooth type, with their design following the principles of "proper form" and "extension for prevention" (2). The main aim of this endodontic approach is to ensure complete removal of the pulp chamber roof for adequate access and visibility of the root canal orifices, while minimizing the risk of procedural errors. However, little emphasis has been placed on preserving the tooth structure (4,5).

Minimally invasive endodontics focuses on disease management while preserving as much natural tooth structure as possible. With advances in magnification and imaging technologies, such conservative approaches have become more widely applied in endodontic practice, particularly through access cavity designs that preserve pericervical dentin.

Pericervical dentin functions as a stress distributor and preserving it can potentially increase fracture resistance (5). This approach was suggested by Clark and Khademi (5) based on the hypothesis that the removal of pericervical dentin, oblique ridges, and thinning of marginal ridges could potentially increase the likelihood of tooth fracture (6).

Reducing the size of the access cavity can jeopardize the subsequent stages of canal treatment by preventing and/or complicating procedures such as cleaning, shaping, and filling canal orifices. Furthermore, it can increase the potential for iatrogenic complications such as missed canals, canal transportation, and/or instrument breakage (7-10). Residual pulp chamber roof structures may support microbial growth, which could contribute to tooth discoloration, although evidence remains limited. A small access cavity may limit the effective removal of pulp remnants, dentin debris, filling materials, and other restorative materials, potentially compromising canal disinfection and contributing to discoloration (11).

The proposal for different designs of access cavity preparation is a relatively new trend in endodontics, and specific terminology has not yet been established (12). Silva et al. (9) proposed a new classification of access cavity geometries to provide common language and self-explanatory abbreviations: Traditional, conservative, ultraconservative, truss, caries-oriented, and restoration-oriented access cavities.

Although the effectiveness of different access cavity designs in terms of remaining coronal tooth tissue removal, fracture resistance, and pulp tissue removal has been extensively studied (13,14), there is limited research evaluating their effect on discoloration, particularly in the anterior teeth (15). To date, no study has been found in the comprehensive literature review that investigates the impact of access cavity design on the discoloration of molar teeth.

Preserving intact tooth structure during endodontic access not only supports the mechanical integrity of the tooth but also plays an important role in maintaining esthetic outcomes. Minimally invasive access designs may help prevent post-treatment discoloration, which is of clinical significance particularly in visible posterior teeth. The aim of this study was to evaluate the effect of different access cavity designs on the discoloration of molar teeth during endodontic treatment. The null hypothesis of the study was that there would be no difference in the effect of different access cavity preparations on tooth discoloration.

Materials and Methods

Sample Selection and Preparation

The manuscript of this in vitro laboratory study was prepared in accordance with the Preferred Reporting Items for Laboratory Studies in Endodontology (PRILE) 2021 guidelines (16).

The study protocol was approved by the Bolu Abant İzzet Baysal University Ethics Committee. (No: 2023/109; Date: 25/04/2023). This study was conducted in accordance with the principles of the Declaration of Helsinki. Informed consent was obtained from all participants and/or their legal guardians. The sample size was calculated using the G* Power software 3.1.9.7 (Heinrich Heine University, Düsseldorf, Germany) by taking a study with a similar methodological design as a reference (17). With 95% confidence (1-α), 95% test power (1-β), and f=0.625 effect size, the total number of cases included in the study was 64, with eight cases in each group. However, in this study, the total number of cases was 80, with 10 cases in each group.

Eighty intact human first molars (maxillary n=40; mandibular n=40), extracted within 30 days prior to testing for prosthodontic or periodontal indications, were included. The teeth were selected after rigorous visual inspection under a dental operating microscope (DOM) (Prima DNT, California, ABD) and radiographic examination. Exclusion criteria were the presence of caries, coronal staining, observable structural defects, restoration, calcification, resorption, or root canal treatment. After extraction, the teeth were stored in 1% chloramine-T solution (Merck, Darmstadt, Germany) until further use. Each tooth was stored individually in capped transparent plastic containers in phosphate-buffered saline (Lp Italiana Spa, Milan, Italy) at 37 ±1°C and 100% humidity throughout the study.

Preparation for Color Measurement

The position of the spectrophotometer tip in contact with the tooth was standardized using a silicone-based impression material (Zetaplus, Zhermack, Badia Polesine, Italy).

Subsequently, the impression was filled with chemically cured acrylic resin to create a model. This model was placed on the cemento-enamel junction (CEJ) of the vestibular surface of the teeth, and a fixed frame was prepared around it using a flowable composite (Filtek Z250, 3M ESPE, Germany). Thus, a standardized area for placing the spectrophotometer tip was created on the buccal surfaces of all the teeth (18).

Randomization was stratified by arch: The 40 maxillary and 40 mandibular molars were independently randomized into the experimental groups using a computer-generated sequence (random.org).

Access Cavity Preparation

The teeth were divided into 8 groups for access cavity preparation. All cavities were prepared under a dental operating microscope (DOM; Prima DNT, California, USA).

Group A (Traditional Access Cavities in Maxillary First Molars): For maxillary first molars, traditional access cavities were initiated using a diamond round bur (Meisinger, Neuss, Germany) under water cooling at a perpendicular angle from the deepest point of the occlusal surface. The cavity boundaries included the oblique ridge and the mesiobuccal, distobuccal, and mesiopalatal cusps. As previously described (13), removal of the pulp chamber roof facilitated direct access to the coronal third of the root canals. After completely removing the pulp chamber roof, the cavity walls were made parallel using a diamond fissure bur (Meisinger, Neuss, Germany) to ensure straight-line access to all canal orifices.

Group B (Conservative Access Cavities in Maxillary First Molars): Conservative access cavities in the maxillary first molars were initiated with a diamond round bur under water cooling at a perpendicular angle from the deepest point of the occlusal surface. Only minimal enlargement of the canal orifices was performed to preserve the oblique ridge, pericervical dentin, and the remaining roof structures of the pulp chamber, ensuring the maintenance of coronal integrity (19). The buccal wall of the cavity was parallel to the buccal wall of the tooth using a diamond fissure bur.

Group C (Ultraconservative Access Cavities in Maxillary First Molars): Ultraconservative access cavities were initiated from the central fossa or the deepest point of the occlusal surface with a diamond round bur under water cooling. The cavity was minimally enlarged to allow visualization of all canal orifices and was extended apically. The pulp chamber roof and pericervical dentin were preserved to a significant extent (20). The cavity walls were beveled at 45-degree angle using a diamond fissure bur to create divergence.

Group D (Truss Access Cavities in Maxillary First Molars): Truss access cavities in maxillary first molars involved the preparation of two separate cavities for canal access using a diamond round bur under water cooling. One cavity included the mesiobuccal and distobuccal canals, whereas the other included the palatal canal. The oblique ridge was preserved. The roof of the pulp chamber was maintained between the prepared cavities (21). Buccal and palatal cavity were prepared with approximate dimensions of 2.5 mm in width, 4.0 mm in depth, and 4.0 mm in length, leaving about 2 mm of intervening dentin intact between them, adapted from the methodology described by Abou-Elnaga et al. (22). The first cavity was widened mesiodistally on the buccal side of the central fossa, whereas the second cavity was round and located buccally to the palatal canal. The cavity walls were diverged using a diamond fissure bur.

Group E (Traditional Access Cavities in Mandibular First Molars): Following the traditional access cavity protocol for the maxillary molar, the only alteration involved extending the cavity margins to encompass half of each cusp.

Group F (Conservative Access Cavities in Mandibular First Molars): Following the approach used for a conservative access cavity in the maxillary molar, enlargement was restricted to that required for identifying the canal orifices while conserving the pericervical dentin and a portion of the pulp chamber roof.

Group G (Ultraconservative Access Cavities in Mandibular First Molars): In mandibular molars, the ultraconservative access cavity was initiated slightly mesial to the central fossa to enhance visibility of the mesiolingual canal. A diamond round bur was used under water cooling at a shallow mesial angle directed toward the mesial root. The cavity was minimally extended to expose all canal orifices, while preserving the pericervical dentin and the roof of the pulp chamber. The cavity walls were refined and beveled at approximately 45° using a fine diamond fissure bur to create divergence and facilitate access.

Group H (Truss Access Cavities in Mandibular First Molars): Truss access cavities in mandibular first molars involved the preparation of two separate cavities for canal access using a diamond bur under water cooling. One cavity included the mesiobuccal and mesiolingual canals, whereas the other included the distal canals. The central fossa was preserved. The first cavity was widened buccolingually on the mesial side of the central fossa, whereas the second cavity was oval and buccolingually widened on the distal side of the central fossa. Each proximal box in the mandibular truss access cavity was prepared according to the methodology described by Abou-Elnaga et al. (22). The cavity walls were diverged using a diamond fissure bur.

Shaping, Filling, and Restoration of Teeth

After the preparation of the access cavities, the apical patency was confirmed using a #10 K-file (VDW, Munich, Germany), and the working length was determined to be 1 mm short of the apex. Rotary instruments were operated in reciprocation mode using an endomotor (X-Smart Plus, Dentsply Sirona, Ballaigues, Switzerland) in accordance with the manufacturer's instructions. Canals were prepared using Reciproc R25 (VDW, Munich, Germany). As an irrigation solution, 2.5 ml 5% NaOCl (Coltene, Whaledent, Switzerland) was used as the irrigation solution. For the final irrigation, 3 ml 5% NaOCl, 3 ml 17% EDTA (Cerkamed, Poland), and 3 ml 5% NaOCl were sequentially applied. The final irrigation activation procedure was performed using a #20 Irrisafe ultrasonic tip (Acteon, Marignac, France) and Satelec P5 Newtron XS ultrasonic device (Satelec Acteon, Merignac, France). A total of 3 ml of each solution was activated for 1 min in each canal, with 1 ml of the solution activated for 20 s, repeated three times. After canal shaping, all canals were dried using R25 paper points (VDW, Munich, Germany). The canals were filled using the single-cone technique with R25 gutta-percha (VDW, Munich, Germany), compatible with a rotary instrument. AH Plus (Dentsply Maillefer, Ballaigues, Switzerland), mixed according to the manufacturer's instructions, was used as a root canal sealer according to the manufacturer's instructions. Residual filling materials were eliminated with heated condensers and an endodontic explorer. Pulp chamber walls were scrubbed using cotton pellets moistened with 70% alcohol under microscopic magnification. The composite restoration (Filtek Z250) was applied in increments of up to 2 mm, with each being cured for 20 s. A2 shade composite was selected because it represents a clinically common intermediate color that offers a neutral reference for assessing discoloration. A uniform 2-mm thickness was maintained to standardize light transmission and optical properties across all samples.

Color Measurement

A spectrophotometer (Vita Easyshade V, Zahnfabrik H. Rauter GmbH & Co. KG, Germany) was used for color measurements. The spectrophotometer was calibrated before each measurement in the same location under standardized white light conditions. Measurements were repeated thrice on the buccal surface of each tooth, and the mean value was recorded. All measurements were conducted by the same operator at all time intervals for all teeth. The L* values represent lightness, ranging from 0 (black) to 100 (white), whereas the a* values indicate the chromatic axis extending from green (−80) to red (+80), and the b* values denote the axis ranging from blue (−80) to yellow (+80), collectively characterizing color variations (23).

In this study, color measurements were taken six times for each sample to investigate the effect of different minimally invasive access cavities on the color change.

- T0: Before any procedure
- T1: Immediately after the procedure
- T2: 1 day after the procedure
- T3: 1 week after the procedure
- T4: 1 month after the procedure
- T5: 2 months after the procedure

Color changes were recorded using the CIELAB color space. The color difference for each sample was calculated using the following formula:

$\Delta E^* = ((\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2)^{½}$.

$\Delta L^* = L1^* - L0^*$; $\Delta a^* = a1^* - a0^*$; $\Delta b^* = b1^* - b0^*$

Statistical Analysis

All data were analyzed using the R statistical software (version 4.4.1). The normality of the distribution was evaluated using the Shapiro-Wilk test. For pairwise comparisons of normally distributed data, an independent two-sample t-test was used, whereas the Mann-Whitney U test was applied for non-normally distributed data. For comparisons of three or more groups, one-way ANOVA was used for normally distributed data, followed by Tamhane's T2 test for multiple comparisons. The Kruskal-Wallis test was used for non-normally distributed data, followed by Dunn's test for multiple comparisons. Within-group comparisons over three or more time points were analyzed using repeated-measures ANOVA for normally distributed data, followed by the Bonferroni test for multiple comparisons. Friedman's test was used for non-normally distributed data, followed by Dunn's test for multiple comparisons. The results are presented as mean ± standard deviation or median (minimum – maximum) for quantitative data. The statistical significance level was determined as 5%.

Results

In the tested groups, clinically perceptible color changes ($\Delta E \geq 3.3$) were observed at various time intervals compared to baseline. When ΔE changes over time for the groups of maxillary molars were compared, a statistically significant difference was found in the median ΔE values T0-T4 time interval between the groups ($p<0.05$) (Fig. 1). The ΔE value was significantly higher in the traditional access cavity than in the conservative and truss access cavities, while the remaining groups exhibited comparable outcomes (Table 1).

Table 1. Comparison of ΔE values among groups A, B, C, and D

	Group A	Group B	Group C	Group D	Test Statistic	p
ΔE T0-T1	3.009 (1.616-8.271)	3.5 (1.896-8.919)	3.811 (2.481-7.607)	4.477 (1.671-5.997)	1.803	0.614[x]
ΔE T0-T2	4.877±1.94	3.368±1.355	4.91±2.239	3.243±2.066	2.267	0.097[y]
ΔE T0-T3	4.722±2.453	3.652±2.846	3.64±1.791	4.515±2.062	0.598	0.621[y]
ΔE T0-T4	5.86±2.506[a]	2.656±1.178[b]	4.717±2.991[ab]	2.74±0.975[b]	5.542	0.007[y]
ΔE T0-T5	4.487 (0.983-6.786)	2.356 (0.77-4.878)	3.396 (1.429-11.077)	2.901 (1.126-7.11)	3.683	0.298[x]

[x]Kruskall Wallis H Test; [y]One Way Anova; [(a-b)] Groups with the same superscript letter are not significantly different; Data are presented as mean ± standard deviation or median (minimum–maximum).

Table 2. Comparison of ΔE values among groups E, F, G, and H

	Group E	Group F	Group G	Group H	Test Statistic	p
ΔE T0-T1	2.634 (1.426-11.889)	3.789 (1.609-5.889)	4.593 (2.701-6.558)	2.807 (0.435-4.999)	4.930	0.177[x]
ΔE T0-T2	3.342 (0.953-6.751)	3.283 (1.632-4.272)	4.167 (1.339-10.105)	3.349 (0.779-8.782)	0.581	0.901[x]
ΔE T0-T3	3.666±1.792	4.894±3.532	4.949±2.693	4.199±1.983	0.639	0.599[z]
ΔE T0-T4	4.274 (1.54-6.788)	3.867 (1.448-10.485)	2.02 (0.291-7.979)	2.874 (1.04-4.554)	7.384	0.061[x]
ΔE T0-T5	3.959 (1.835-8.085)	2.52 (0.732-5.892)	3.407 (1.11-8.377)	3.004 (0.836-8.413)	7.965	0.047[x]

[x]Kruskall Wallis H Test; [z] One Way Anova; Data are presented as mean ± standard deviation or median (minimum–maximum).

For mandibular molars, a statistically significant difference in ΔE values was noted in the T0-T5 time interval (p=0.047) (Table 2); however, no significant differences were observed in multiple comparisons. (p>0.05) (Fig. 2).

When the ΔE changes over time were compared between traditional access cavities in the maxillary and mandibular molars, the differences among groups were not statistically meaningful (p>0.05) (Fig. 3A). Likewise, the conservative, ultraconservative, and truss access cavity groups in maxillary and mandibular molars exhibited comparable ΔE variations over time (p>0.05) (Fig. 3B, 3C, 3D).

In the present study, within-group comparisons of ΔE values over time revealed statistically significant differences between traditional access cavities in maxillary molars (p=0.026) and ultraconservative access cavities in mandibular molars (p=0.049). Nevertheless, no significant variations were observed in multiple comparisons, indicating overall comparable results across all groups. No statistically significant differences were found in the within-group comparisons of the ΔE values over time (p>0.05) (Table 3).

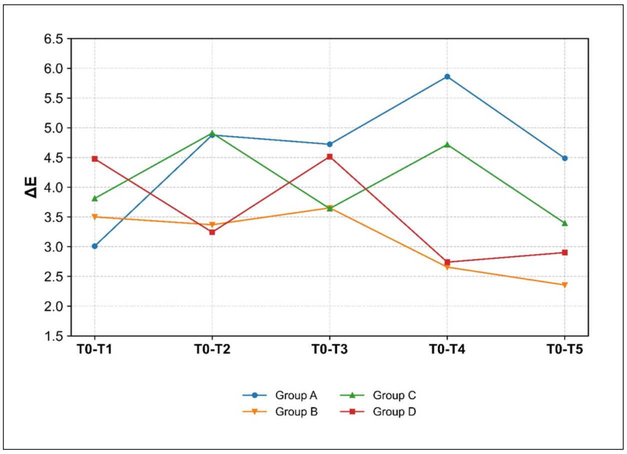

Fig. 1. Comparison of ΔE values according to groups A, B, C and D.

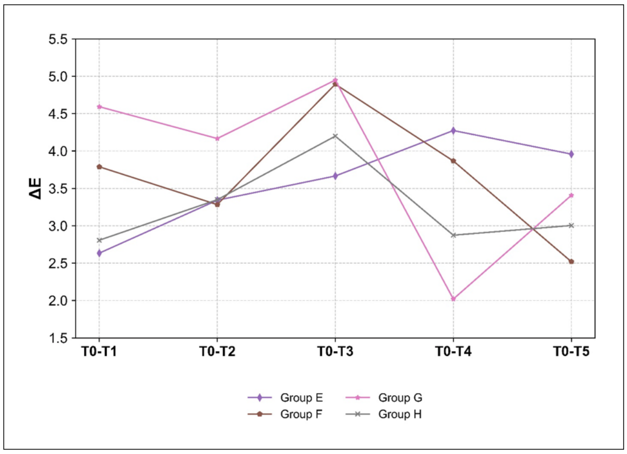

Fig. 2. Comparison of ΔE values according to groups E, F, G and H.

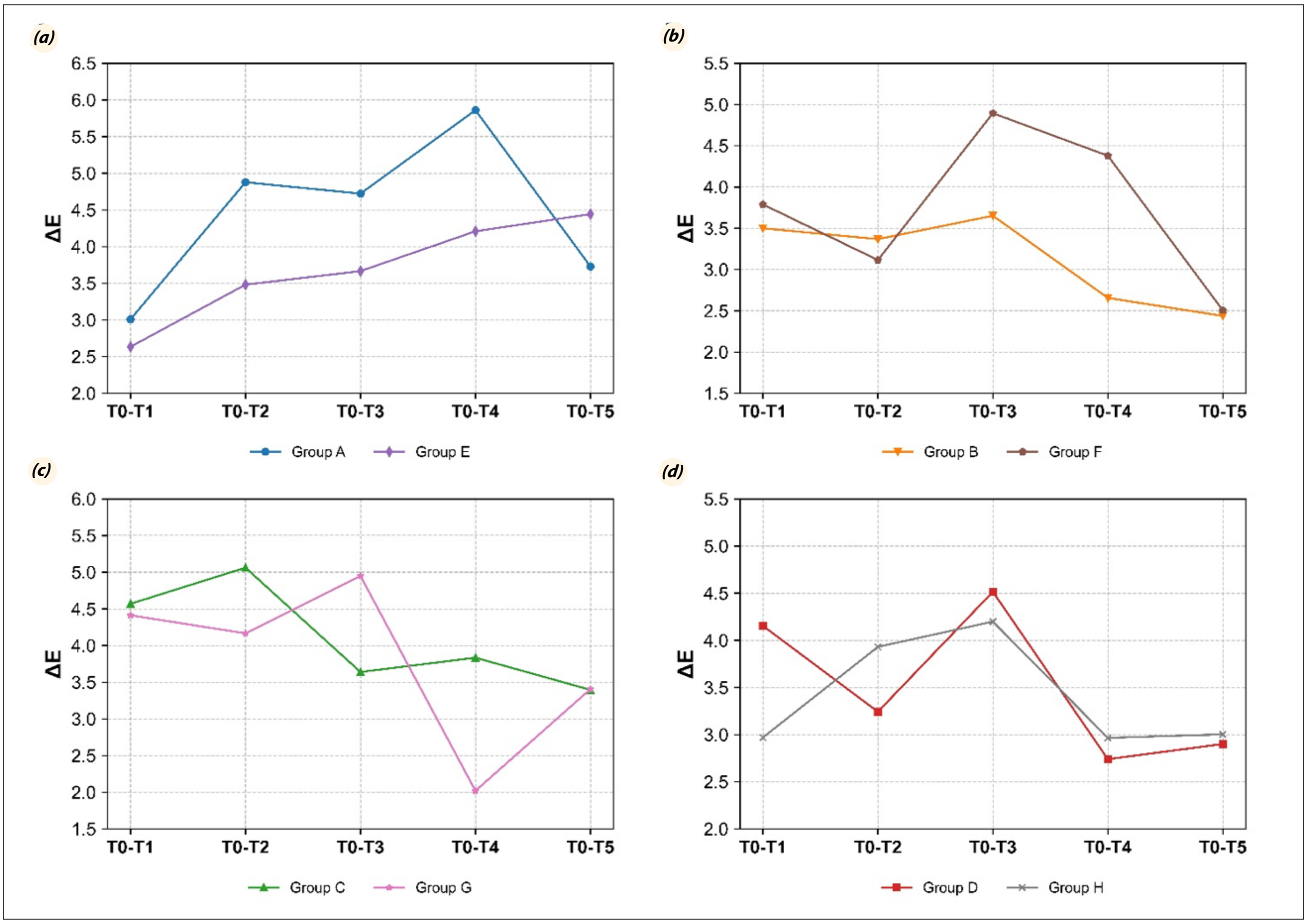

Fig. 3. **(a)** Comparative analysis of ΔE values between group A and group E. **(b)** Comparative analysis of ΔE values between group B and group F. **(c)** Comparative analysis of ΔE values between group C and group G. **(d)** Comparative analysis of ΔE values between group D and group H.

Table 3. Comparison of ΔE values over time within each group

Group	T0-T1	T0-T2	T0-T3	T0-T4	T0-T5	Test Statistic	p
Group A	3.897±2.014	4.877±1.94	4.722±2.453	5.86±2.506	3.729±1.902	3.147	0.026^x
Group B	3.5 (1.896-8.919)	3.331 (1.404-5.482)	3.439 (0.552-10.145)	3.002 (0.834-4.238)	2.356 (0.77-4.878)	7.760	0.101^y
Group C	3.811 (2.481-7.607)	5.062 (1.146-9.086)	3.56 (1.527-6.502)	3.835 (1.471-10.222)	3.396 (1.429-11.077)	2.560	0.634^y
Group D	4.154±1.382	3.243±2.066	4.515±2.062	2.74±0.975	3.423±2.125	1.757	0.159^x
Group E	2.634 (1.426-11.889)	3.342 (0.953-6.751)	3.489 (1.271-6.904)	4.274 (1.54-6.788)	3.959 (1.835-8.085)	1.040	0.904^y
Group F	3.677±1.415	3.115±0.856	4.894±3.532	4.379±2.723	2.505±1.625	1.705	0.170^x
Group G	4.593 (2.701-6.558)	4.167 (1.339-10.105)	4.368 (1.765-8.976)	2.02 (0.291-7.979)	3.407 (1.11-8.377)	9.520	0.049^y
Group H	2.807 (0.435-4.999)	3.349 (0.779-8.782)	3.622 (0.852-7.855)	2.874 (1.04-4.554)	3.004 (0.836-8.413)	3.280	0.512^y

^{x}Repeated Measures Anova; ^{y}Friedman Test; Data are presented as mean ± standard deviation or median (minimum–maximum).

Discussion

Minimally invasive access cavities are used in dentistry to treat carious or damaged areas with minimal loss of tooth structure. The impact of such cavity preparations on tooth color is critically important for preserving esthetic outcomes and maintaining the natural appearance of teeth (12). A comprehensive review of the literature revealed no studies evaluating the effect of access cavities on discoloration.

Known causes of discoloration in endodontically treated teeth include endodontic medicaments and various filling materials (24). Root canal materials containing bismuth trioxide as a filler and radiopacifier may cause discoloration (25). AH Plus, which includes zirconium oxide as a radiopacifier, demonstrates good color stability (25). Therefore, AH Plus was used as the canal filling material in this study to minimize the risk of color change. Studies have shown that the cervical margin of the root filling is associated with coronal discoloration in endodontically treated teeth (26). An insufficient endodontic procedure to define the cervical margin of the endodontic material may allow direct contact with the axial dentin walls, and interactions between chemical components over time may lead to tooth darkening (27). In such cases, trimming the filling material below the CEJ is recommended (26).

Research indicates that color changes are more prominent in the cervical one-third of the crown compared to the occlusal one-third (28,29). In the present study, a composite frame was constructed on the buccal surface of the teeth, including the cervical third, to position the spectrophotometer head in the same location at each time interval. To ensure standardization of repeated measurements, all assessments were recorded under the same conditions, with the same lighting, and by the same operator. The device was calibrated according to the manufacturer's instructions prior to each measurement. Each measurement was repeated thrice, and the average of these values was calculated.

Clinically perceptible color changes ($\Delta E \geq 3.3$) compared with baseline were observed at various time intervals in the tested groups in the present study. Among the different access cavities created in maxillary molars, greater discoloration was observed 1 month after the preparation of the traditional access cavity than at baseline. According to literature, the intrinsic color of a tooth is related to the light scattering and absorption properties of enamel and dentin (30). Tooth color is determined by a combination of the optical properties of the tooth. Vaarkamp et al. (31) supported the idea that hydroxyapatite crystals significantly contribute to light scattering in enamel, whereas dentinal tubules are the dominant cause in dentin. An in vitro study concluded that enamel removal does not significantly alter tooth color, confirming that dentin primarily determines tooth color, with enamel playing a minor role (30). Traditional access cavity designs involve wide cavity preparations that may result in excessive dentin loss to fully remove the pulp chamber roof and provide straight-line access to root canals (32). Ribeiro et al. (33) proposed minimally invasive cavity designs aiming to preserve as much pericervical dentin as possible. Research has shown that preserving pericervical dentin is crucial for maintaining the normal function, esthetics, and durability of treated teeth (34).

Traditional access cavities remove more cervical dentin than minimally invasive cavities, leading to greater loss of translucency and increased reflection of the restorative material. Isufi et al. (35) reported that the amount of coronal tooth structure removed was less than 15% in conservative access cavities, whereas it exceeded 15% in traditional access cavities. Lin et al. (36) observed the greatest loss of tooth structure in the cervical region of traditional access cavities when evaluating material loss in maxillary molars. Additionally, the thickness of the restorative material used to replace the lost dentin is greater in traditional cavities than in minimally invasive cavities. A study evaluating the translucency parameters of light-cured composite resins at different thicknesses revealed that increased thickness reduces translucency (34), making the material appear opaque (37). Consistent with our findings, Kamishima et al. (38) demonstrated that an increased composite thickness resulted in higher L* and b* values.

Minimally invasive cavity designs help maintain the natural color of the tooth by preserving enamel and dentin. Structural preservation supports the tooth's original translucency and enhances color harmony between the restorative material and the surrounding tissue (39). Restorations performed using minimally invasive methods affect the long-term color stability of the composite filling materials. Such restorations cause less damage to the esthetic structure of the tooth, prevent discoloration over time, and maintain the natural appearance of the restoration for an extended period (39,40). Traditional access cavities, compared with minimally invasive cavities, result in the removal of more dentin, making the cavities wider. A literature review reported that polymerization shrinkage can lead to discoloration issues due to failure at the composite-tooth interface (41). One possible reason for the greater discoloration in conventional access cavities compared to minimally invasive cavities may be the higher polymerization shrinkage.

In the present study, clinically perceptible color changes ($\Delta E \geq 3.3$) were observed in mandibular molars over time compared with baseline. A significant difference was detected at the T0–T5 interval; however, multiple comparison tests revealed no statistically meaningful variation among the groups. Although statistically significant ΔE differences were observed in mandibular molars, most values were near the clinically perceptible threshold ($\Delta E = 3.3$), suggesting limited clinical relevance of these color changes. Although some groups exhibited an increase in ΔE values over time, these differences did not reach statistical significance, possibly due to high variability among samples and the proximity of most values to the perceptibility threshold. Biologically, these findings indicate that the observed color changes, while measurable, are unlikely to be clinically perceptible or meaningful. The absence of statistically significant differences in mandibular molars may be attributed to anatomical and optical factors. Compared with maxillary molars, mandibular molars have thinner enamel and higher dentin dominance, which may reduce light transmission and mask subtle internal color changes (42).

Pereira et al. (43) reported that the presence of voids at the tooth-restoration interface could compromise the marginal integrity of coronal restorations, leading to microleakage and ultimately causing discoloration over time. Silva et al. (44) investigated the effect of different access cavity designs on the formation of voids between the composite and the tooth structure in extracted teeth. Their study concluded that minimally invasive access cavity design was associated with a significantly greater number of voids within the restorations. This information may explain the observation of clinically perceptible color changes at various time intervals compared with the initial level in the minimally invasive cavity groups.

When the traditional, conservative, ultraconservative, and truss access cavities were compared between the mandibular and maxillary molar teeth regarding their discoloration potentials, no statistically significant difference was found. Previous studies have shown that residual root canal filling material left within the cavity after endodontic treatment and gutta-percha that does not extend below the CEJ can lead to discoloration. Depending on the chemical composition of the root canal sealers, coronal discoloration can be mild, moderate, or severe (45). Rover et al. (14) compared different cavity designs in mandibular teeth and examined the remnants of the root canal filling material left in the pulp chamber after cleaning. Similar to our findings, their study found no significant difference among different access cavities in the percentage of root canal filling remnants in the pulp chamber. Barbosa et al. (13) also examined the effects of different access cavity designs on the remnants of root canal fillings in the pulp chamber. Consistent with our results, their study demonstrated statistically comparable outcomes between the conservative and traditional access cavity designs.

In the present study, within-group comparisons of time-dependent ΔE values revealed significant differences for the traditional access cavity in maxillary molars and the ultraconservative access cavity in mandibular molars. However, multiple comparison tests showed that these differences were not statistically meaningful. A review of the literature revealed that incomplete removal of pulp tissue leads to the breakdown of residual pulp tissue, allowing blood components to penetrate the dentinal tubules. This demonstrates that residual pulp tissue in the pulp chamber after treatment is one of the primary causes of discoloration (45).

Neelakantan et al. (21) compared the effects of different minimally invasive access cavity designs on pulp chamber cleanliness with traditional access cavities in mandibular molars. Similar to our findings, their study reported no significant differences among traditional, conservative, and truss access cavity types regarding the remaining pulp tissue. Studies have indicated that long-term discoloration can occur owing to the inability to detect extra canals because of inadequate cavity preparation (46). Among the three studies evaluating the effect of access cavity design on detecting extra canals, two studies focused on detecting MB2 canals in maxillary first molars (14,47), and one examined the detection of the middle mesial canal in mandibular first molars (19). Without magnification or the use of DOM, more MB2 (second mesiobuccal) canals were detected in traditional access cavities than in conservative ones (8). The present study was conducted using DOM, and similar to the findings of our study, studies using DOM reported no significant difference between these two cavity designs in detecting MB2 or middle mesial canals (46). Furthermore, Mendes et al. (19) reported in a recent study that the type of access cavity did not affect the detection of the middle mesial canals in mandibular molars when performed by an experienced endodontist under DOM.

Despite the standardized conditions maintained in our study, the current in vitro study model has limitations in fully mimicking clinical scenarios. The lack of biological factors, such as natural tooth discoloration in human teeth, distance from the actual clinical environment, diet, oral hygiene, and saliva, limits its applicability. More randomized controlled clinical trials with longer durations are needed to evaluate the effects of access cavities on discoloration.

Conclusion

Clinically perceptible color changes were detected in the tested groups at various time intervals compared with baseline. When different access cavities prepared in maxillary molar teeth were compared, more discoloration was observed in traditional access cavities. No significant differences in discoloration were observed among the other tested groups. Minimally invasive access cavity designs may help maintain tooth color by preserving dentin and reducing restorative material volume.

Acknowledgments: This article is derived from Ayşe Gamze Özyaman's specialty thesis in Endodontics (Bolu Abant Izzet Baysal University, 2024).

Authorship Contributions: Concept: A.G.O., M.O.A.; Design: A.G.O., M.O.A.; Supervision: M.O.A.; Fundings: A.G.O., M.O.A.; Materials: A.G.O., M.O.A.; Data: A.G.O.; Analysis: A.G.O., M.O.A.; Literature Search: A.G.O., M.O.A.; Writing: A.G.O., M.O.A.; Critical Revision: A.G.O., M.O.A.

Use of AI for Writing Assistance: Not declared

Source of Funding: This study was supported by Scientific and Technological Research Council of Turkey (TUBITAK) under the Grant Number 223S491.

Conflict of Interest: The authors did not report a conflict of interest.

Ethical Approval: The study protocol was approved by the Bolu Abant İzzet Baysal University Ethics Committee. (No: 2023/109; Date: 25/04/2023)

Informed consent: Written informed consent was obtained from patients who participated in this study.

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ORIGINAL ARTICLE

Turk Endod J 2026;11(1):112–117
doi: 10.14744/TEJ.2025.87699

Comparative analysis of torsional resistance among single-file nickel-titanium systems

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Purpose: To evaluate the torsional fatigue resistance of One Curve Mini (OCM), HyFlex EDM (HEDM), WaveOne Gold Primary (WOG), and Reciproc Blue R25 (RPB) rotary and reciprocating nickel-titanium (NiTi) single-file systems.

Methods: Eighty NiTi instruments were tested: OCM (25/.06), HEDM (25/.08), WOG (25/.07), and RPB (25/.08) (n=20 per group). The instruments were fixed at apical 3 mm along their long axis and constant rotation of 2 rpm were applied until fracture occured. Ultimate strength at maximum torque and distortional angle for each file were measured using torsiometer. Statistical analysis was performed with one-way analysis of variance followed by Tukey's post-hoc test, using a 5% significance level ($p<0.05$). All the fractured instruments were scanned using scanning electron microscope to confirm that the instruments were fractured due to torsional fatigue.

Results: Maximum torque values were observed in HEDM and RPB ($p<0.05$) and the minimum values were in OCM ($p<0.05$) files. The torque values of WOG were not statistically different from the other three files ($p>0.05$). The distortion angle was highest in OCM and HEDM and the lowest values were in WOG files ($p<0.05$). RPB files have a similar distortion angle with the other three files ($p>0.05$).

Conclusion: HEDM and RPB were highest and OCM was the least resistant to torsional stress among the tested NiTi file systems.

Keywords: Instrument fracture; nickel-titanium; resiprocating file; rotary file; torsional resistance.

Introduction

Nickel–Titanium (NiTi) files, owing to their elasticity and flexibility, allow for rapid and reliable preparation of curved root canals (1). However, they are prone to fracture under torsional and cyclic fatigue stresses during use, which may adversely affect the treatment prognosis (2). Cyclic fatigue arises from alternating tensile and compressive stresses acting on files in curved root canals. Torsional fatigue is

Cite this article as: Odabaşı Tezer E, Keskin NB, Uslu G, Ozyurek T, Gundoğar M, Bölük A. Comparative analysis of torsional resistance among single-file nickel-titanium systems. Turk Endod J 2026;11:112-117.
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Submitted: October 17, 2025 Revised: November 24, 2025 Accepted: November 28, 2025 Published: April 27, 2026

induced when the file tip becomes engaged in the canal (3,4). The alloy composition, size, cross-sectional design, and kinematics of NiTi files significantly influence their clinical performance and resistance to fatigue (5,6).

Reciprocating motion of NiTi files, either clockwise or counterclockwise, was introduced to reduce torsional and cyclic fatigue, thereby simplifying root canal shaping and enabling a single-file approach. The single-use recommendation for these systems primarily aims to minimise the risk of cross-contamination, including prion transmission (7). In reciprocating motion, the smaller counterclockwise angle allows NiTi files to operate within their elastic limit, thus reducing the risk of fracture in curved canals (8). The first reciprocating NiTi file systems introduced were Reciproc (RPC; VDW GmbH, Munich, Germany) and WaveOne (WO; Dentsply Sirona, Ballaigues, Switzerland). These systems were later updated to Reciproc Blue (RPC Blue; VDW GmbH, Munich, Germany) and WaveOne Gold (WOG; Dentsply Sirona, Ballaigues, Switzerland), respectively.

RPC Blue files are reciprocating NiTi instruments with similar dimensions and an S-shaped cross-section to the original RPC files. They undergo a proprietary heat treatment that produces a blue titanium oxide layer on the surface, imparting shape memory properties to the instrument. This heat treatment has been shown to significantly increase the cyclic fatigue resistance and flexibility of RPC Blue compared with RPC (9,10). WOG files employ the same kinematics as the WO system, but their dimensions and cross-sectional geometry have been modified. Specifically, the WOG cross-section has been redesigned into a parallelogram with two cutting edges (11), and the instruments undergo a post-manufacturing Gold heat treatment, which enhances flexibility (12). The slow heating–cooling process applied during Gold treatment leads to Ti_3Ni_4 precipitation on the NiTi surface (13), and the martensitic transformation occurs in two steps, thereby increasing file flexibility (11,14).

Hyflex EDM (HEDM; Coltene/Whaledent AG, Altstätten, Switzerland) is a NiTi system that operate in continuous rotation and permit complete root canal preparation with a single instrument. Manufactured from controlled memory (CM) wire using electro-discharge machining (EDM) technology, these files have been reported to exhibit superior mechanical properties (15). The design of HEDM changes along its working length, being quadratic in the apical third, trapezoidal in the middle third, and triangular in the coronal third.

One Curve Mini (OCM; Micro-Mega, Besançon, France) is made from heat-treated C Wire NiTi alloy, which is purported to enhance flexibility and fatigue resistance. Developed as a rotary single-file system, it is intended to shape root canals to the full working length while minimising dentine removal (16).

Preparation of the entire root canal system with a single instrument generates substantial torsional stress (17). Heat-treated single-use files with improved flexibility are less prone to fracture from cyclic fatigue (18,19). Nevertheless, most NiTi file separations occur due to torsional loading (17). Therefore, evaluating the torsional fatigue resistance of single-file systems is critical for ensuring safe clinical use. Accordingly, this study aimed to assess the torsional fatigue resistance of the single-file systems OCM, HEDM, WOG, and RPC Blue. The null hypothesis was that no significant differences would exist among the tested systems regarding resistance to torsional fatigue–related fracture.

Materials and Methods

Sample Selection

Power analysis was performed with G*Power v3.1.9.4 (Heinrich Heine University of Düsseldorf, Düsseldorf, Germany) based on the effect size reported in a previous study (20). A one-way ANOVA (fixed effects, omnibus) from the F-test family was selected, with an alpha error of 0.05 and a beta power of 0.95. The calculation indicated that at least 15 samples per group were required to detect the same effect. Accordingly, 20 NiTi files per group were allocated for torsional resistance testing.

Torsional Resistance Test

A total of 80 files—OCM (25/.06), HEDM OneFile (25/.08), WOG Primary (25/.07), and RPC Blue R25 (25/.08)—were examined under a dental operating microscope (OMS 3200, Zumax Medical, Suzhou, China) at 20× magnification for possible defects. As no deformation was observed, all instruments were included in the torsional resistance test. The tests were conducted in accordance with ISO 3630-1 standards (1992) using a custom-made torsion device, as described in previous studies (17,20).

Before testing, the handles of the files were removed at the shaft junction and secured in a mandrel connected to a geared motor. To prevent slippage during rotation, the apical 3 mm of each file was clamped in another brass mandrel. OCM and HEDM files were rotated clockwise, while WOG and RPC Blue were rotated counterclockwise, all at a constant speed of 2 rpm until fracture occurred. For each file, the maximum torque (N·cm) and angle of rotation (°) at fracture were recorded.

Scanning Electron Microscopic Analysis

All instruments were cleaned in an ultrasonic bath containing ethyl alcohol for 5 minutes prior to scanning electron microscope (SEM) analysis. To examine the topographic features of the fractured instrument surfaces, photomicrographs at different magnifications (x600, x800, x3000) were obtained using a SEM device (FEI Quanta 400 FEG, Hillsboro, OR, USA).

Statistical Analysis

Normality of the data was first assessed using the Shapiro–Wilk test. Subsequently, one-way ANOVA followed by Tukey's post-hoc test was performed. All statistical analyses were conducted with SPSS version 21.0 (IBM-SPSS Inc., Chicago, IL, USA), and the significance level was set at 5% ($p<0.05$).

Results

Figure 1 presents representative SEM micrographs of the fractured surfaces of the tested instruments. The mean and standard deviation values of maximum torque (N·cm) and distortion angle (°) are presented in Table 1. The highest maximum torque values were observed in HEDM and RPC Blue instruments ($p<0.05$), with no significant difference between these two groups ($p>0.05$). The lowest torque values were recorded for OCM instruments ($p<0.05$). The maximum torque of WOG instruments did not differ significantly from those of the other systems ($p>0.05$).

The greatest distortion angles were found in OCM and HEDM instruments, whereas the lowest values were observed in the WOG group ($p<0.05$). The distortion angles of RPC Blue instruments did not differ significantly from those of the other groups ($p>0.05$).

SEM images obtained from the cross-sections of the fractured instrument surfaces revealed typical features of torsional failure. At low magnification, smooth flat areas and concentric abrasion marks were observed, while at higher magnification, centrally located dimpled depressions were evident.

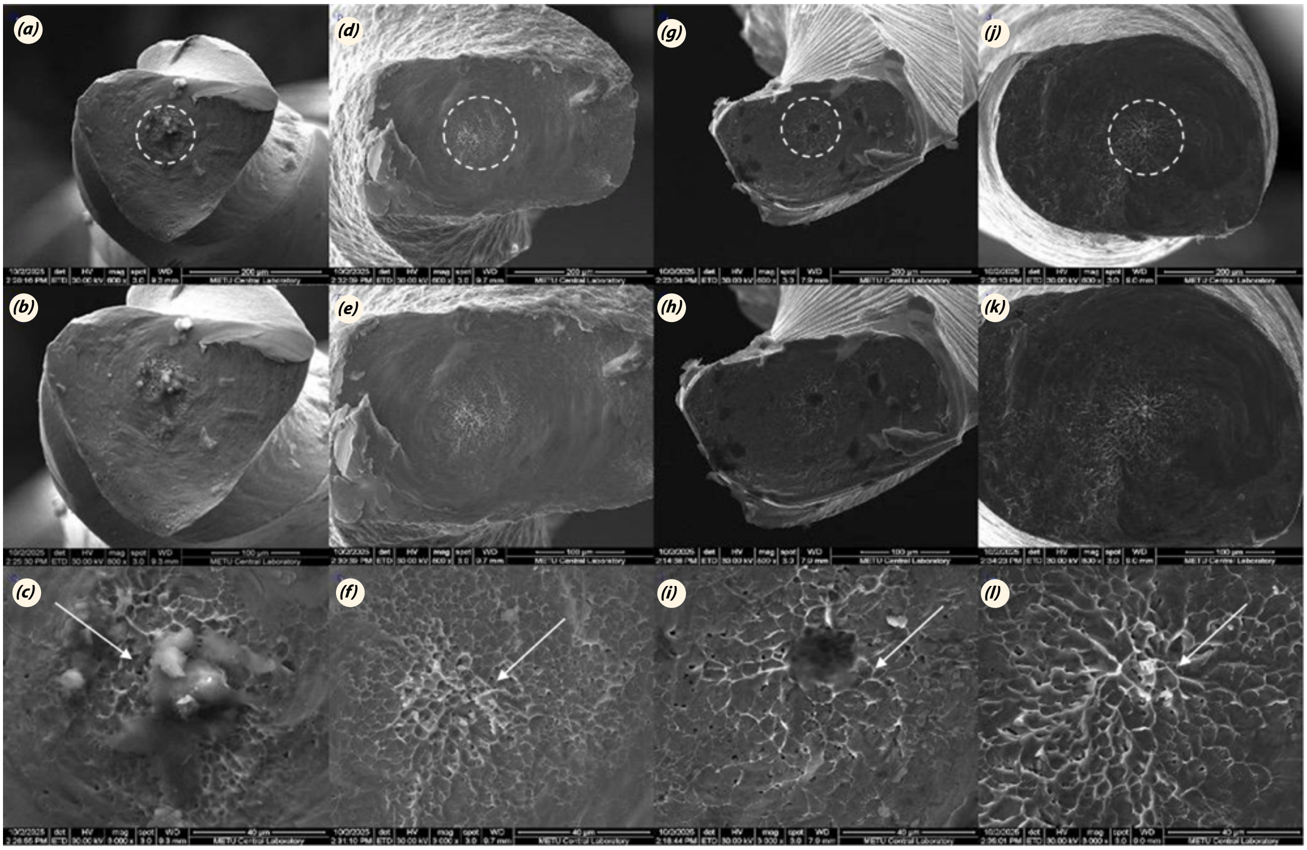

Fig. 1. Scanning electron micrographs of the cross-sections of fractured instrument surfaces. The columns, from left to right, correspond to One Curve Mini **(a, b, c)**, HEDM **(d, e, f)**, WaveOne Gold Primary **(g, h, i)**, and Reciproc Blue **(j, k, l)**, respectively. The rows, from top to bottom, display images captured at ×600, ×800, and ×3000 magnifications, respectively. Scanning electron micrographs of the cross-sections of the fractured instrument surfaces revealed typical characteristics of torsional failure. At lower magnification, smooth flat areas and concentric abrasion marks (indicated by white circles) were observed, whereas at higher magnification, centrally located dimpled depressions (indicated by white arrows) were evident.

Table 1. Ultimate strength at maximum torque (N.cm) and Distortional angle (°) of the tested NiTi file systems (Mean ± Standard Deviation).

NiTi File System	Ultimate strength at maximum torque (N.cm)	Distortion angle (°)
One Curve Mini	1.335±0.16[a]	543.96±70.71[a]
HEDM OneFile	2.195±0.32[b]	559.68±61.56[a]
WaveOne Gold Primary	1.725±0.24[ab]	294.72±44.02[b]
Reciproc Blue R25	2.425±0.31[b]	413.22±67.90[ab]
p-value	<0.05	<0.05

*Different superscript letters indicate statistically significant difference at 5% level (p<0.05).

Discussion

The torsional strength of NiTi instruments reflects their ability to withstand twisting before fracture, which is particularly important in narrow or calcified canals where torsional stresses are high (4). Single-file systems used for root canal preparation are subjected to considerable torsional loads; therefore, adequate resistance is essential to minimise the risk of instrument separation (21). Various NiTi systems employing either reciprocating or continuous rotation kinematics currently allow canal shaping with a single file. The present study evaluated the torsional fatigue resistance of OCM, HEDM, WOG, and RPC Blue instruments.

Based on the results, significant differences were observed among the tested systems in resistance to torsional stress, leading to rejection of the null hypothesis. Maximum torque and distortion angle reflect the instruments' fracture resistance and ductility. Instruments with higher ultimate strength also demonstrate greater resistance to torsional fatigue (22). Among the systems evaluated, HEDM and RPC Blue showed the greatest torsional fatigue resistance. Several factors may influence torsional resistance and stress distribution, including cross-sectional design, instrument size, alloy composition, and thermomechanical heat treatments (5,22,23).

The relative dimensions of instruments within root canals strongly affect the torsional stresses generated during use (24). In this study, although the instruments tested differed in design and taper, they all had the same apical tip diameter. However, the larger tapers of RPC Blue and HEDM instruments (.08) compared with WOG (.07) and OCM (.06) may have resulted in a greater metal mass, which could explain their higher resistance to torsional stress (5).

The torsional fatigue resistance of NiTi instruments is also influenced by alloy type and manufacturing method (25). Each system tested in this study was produced using a different alloy and manufacturing technique. In HEDM, EDM technology is used to shape the surface, creating greater hardness without compromising flexibility (26). This may explain the higher torsional resistance and angular distortion observed in HEDM compared with the other systems. The lowest torsional resistance was found in OCM and WOG instruments. Although WOG has an off-centered parallelogram cross-section and OCM a triangular cross-section, alloy properties appear to play a more decisive role in torsional resistance. The Gold heat treatment applied to WOG instruments increases austenite finish temperature and induces a two-step transformation behavior, which enhances flexibility (11) and may have influenced torsional strength. Consistent with these findings, Silva et al. (27) reported lower torsional resistance for WOG compared with RPC Blue, attributing the difference to the higher taper and greater core mass of RPC Blue instruments.

Careful interpretation of the relationship between maximum torque and distortion angle is essential (4,21). While maximum torque represents the instrument's resistance to fracture when subjected to torsional load, the distortion angle indicates the instrument's capacity to undergo plastic deformation prior to fracture, thereby its ductility (5,25). Typically, the literature suggests that stiffer instruments exhibit higher torque values, whereas their distortion angles tend to be lower (16,23). However, in the present study, no linear correlation was observed between these two parameters across the experimental groups. For instance, the HEDM instrument demonstrated both high torsional resistance and a substantial distortion angle. This absence of a direct correlation can be attributed to the confounding effects of distinct manufacturing processes, such as EDM compared with traditional grinding, and proprietary heat treatments including Blue, Gold, C Wire and CM Wire technologies (15,26,28). These treatments alter the phase transformation temperatures and the martensite-to-austenite ratio within the alloy, effectively decoupling the traditional inverse relationship between strength and ductility (13,17,22). Consequently, a file system can be engineered to be both resistant to torsional stress and sufficiently ductile to provide a safety margin, offering the clinician a visual warning in the form of unwinding (3,18).

In the present study, HEDM (CM Wire) and OCM instruments exhibited the highest distortion angles. Previous reports have shown that NiTi instruments manufactured from CM Wire demonstrate higher distortion angles and lower torsional load capacity compared with Blue and Gold alloys. Moreover, lower transformation temperatures have been associated with greater torsional resistance (22). Further studies are needed to clarify the relationship between transformation behavior and torsional resistance of NiTi instruments.

In this study, torsional resistance was measured as the ultimate torsional strength sustained in the cutting direction until fracture, rather than under reciprocating motion. Elsaka et al. (5) reported that the smaller reverse angles of reciprocation reduce instrument stress, indicating that NiTi files are subjected to greater torsional loads in fatigue testing than under clinical conditions. This contextual difference is important when interpreting the results of torsional fatigue studies on reciprocating systems.

This study has certain limitations that must be acknowledged. Firstly, the torsional resistance was evaluated under static conditions according to ISO 3630-1 standards. While this method provides a standardized baseline for comparison, it does not fully replicate the dynamic stresses of clinical practice, where instruments are subjected to simultaneous torsional and cyclic fatigue. Secondly, the tests were conducted at room temperature (21°C±1°C). Given that phase transformation temperatures of heat-treated NiTi alloys are sensitive to thermal changes future studies should consider simulating body temperature (37°C) to better reflect clinical behavior (29).

Furthermore, the torsional tests were conducted at a constant low speed of 2 rpm in accordance with ISO 3630-1 standards to eliminate the influence of inertia. However, in clinical practice, these instruments operate at significantly higher rotational speeds (ranging from 300 to 500 rpm). While some studies suggest that rotational speed may not significantly alter the ultimate torsional strength of certain NiTi instruments (30), the mechanical response of NiTi alloys is known to be strain-rate dependent. Therefore, the torsional behavior observed at low static speeds might not fully capture the dynamic performance of the specific heat-treated files used in the present study.

Clinically, the findings of this study suggest that instruments with higher torsional resistance, such as HEDM and RPC Blue, may offer a safer option in narrow and calcified canals where the instrument tip is prone to locking. High torsional resistance minimises the risk of plastic deformation and subsequent fracture. However, the clinician must balance this with the need for flexibility, as demonstrated by the high distortion angles of OCM and HEDM, which can provide a warning sign of plastic deformation before separation occurs.

Conclusion

Within the limitations of this study RPC Blue and HEDM instruments demonstrated greater torsional fatigue resistance compared with WOG and OCM, whereas OCM and HEDM exhibited the highest distortion angles.

Authorship Contributions: Concept: E.O.T.; Design: E.O.T.; Supervision: E.O.T.; Materials: A.B.; Data: A.B.; Analysis: N.B.K., G.U., M.G., T.O.; Literature Search: E.O.T., N.B.K., G.U., M.G., T.O.; Writing: E.O.T., N.B.K., G.U., M.G., T.O.; Critical Revision: E.O.T., N.B.K., G.U., M.G., T.O.

Use of AI for Writing Assistance: Not declared.

Source of Funding: No funding was received for this study.

Conflict of Interest: The author declare no potential conflicts of interest with respect to the research, authorship and/or publication of this article.

Ethical Approval: This study did not require ethical approval.

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CASE SERIES

Turk Endod J 2026;11(1):118–124
doi: 10.14744/TEJ.2025.42650

Endodontic retreatment and apexification of a tooth previously treated with a regenerative endodontic procedure: A case report

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In this case report, the treatment procedure and follow-up of a left maxillary central incisor that previously underwent a regenerative endodontic procedure is presented. After a thorough anamnesis, clinical and radiographical examination, a non-surgical endodontic retreatment was applied. Apexification treatment included intensive irrigation, $Ca(OH)_2$ administration and finally, creating an apical plug with MTA. Follow-up radiographic and clinical examination showed healing of the periapical area and reduction of initial symptoms, keeping the tooth in function. As regenerative endodontic procedures can be recognized as the best option for permanent teeth with immature apices, there are always alternatives that can be implemented following failure.

Keywords: Calcium hydroxide; mineral trioxide aggregate; regenerative endodontics; root canal therapy; tooth apex.

Introduction

Regenerative endodontic procedure (REP) is a treatment approach that aims to resume physiological root development and maintain apical closure in immature, necrotic permanent teeth (1). REP procedures are widely accepted treatment strategies, especially by American Association of Endodontics, European Society of Endodontics and European Academy of Paediatric Dentistry. Traumatic dental injuries to the permanent dentition occur frequently in 25% of children and 33% of adults, with most of the injuries taking place before 19 years of age (2). Trauma may induce pulp and periradicular pathosis, and in teeth with immature apices, this may lead to the disruption of the root development. REP contributes to the thickening of the dentin walls and normal maturation of the root, thus maintaining long-term tooth functionality (3). However, the desired outcome may not be achieved in every case, and post-treatment complications such as the development of periapical lesions could occur (4).

According to recent systematic reviews, the clinical success rates of REPs are on par with those of traditional non-surgical endodontic treatments (NSETs). Variability in follow-up periods, however, seems to have an impact on these results. Specifically, short-term results might not accurately represent long-term clinical success, highlighting the significance of proper follow-up in assessing treatment effectiveness (5,6).

Periapical healing is the most commonly attained outcome, and pooled clinical success rates exceeding 90% have been reported in recent quantitative meta-analyses

Cite this article as: Unsal G, Imamoglu D, Rahimi D, Gulsahi G. Endodontic retreatment and apexification of a tooth previously treated with a regenerative endodontic procedure: A case report Turk Endod J 2026;11:118-124.
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Submitted: July 30, 2025 Revised: September 08, 2025 Accepted: September 09, 2025 Published: April 27, 2026

assessing the results of regenerative endodontic therapy (REP). These results support the clinical feasibility of REP, especially when appropriate disinfection is guaranteed and protocols are closely adhered to (7).

In unsuccessful REP cases, retreatment is necessary, and careful planning of the treatment strategy is crucial. In these type of situations, traditional apexification stands out as a safe treatment alternative, especially in teeth with incomplete root development due to failed revitalization (8). The selection between apexification and REPs should be based on the clinical context, root development stage, and patient-related factors. Apexification is a well-established endodontic procedure aimed at inducing a calcified barrier at the apex of an immature permanent tooth with a necrotic pulp. This treatment is especially indicated in teeth that exhibit open apices, which render conventional root canal obturation techniques challenging (9). Prevention of the extrusion of root canal filling material and allowing proper apical sealing is the chief objective of apexification (1).

Calcium hydroxide [$Ca(OH)_2$] has been popularized as the material of choice for this procedure back in 1972 by Cvek et al. (10), due to its ability to stimulate hard tissue formation. Conversely, its application needs multiple visits and periodical monitorization, ranging from 6 to 24 months (11). The hard tissue barrier created by $Ca(OH)_2$ is often porous, increases the risk of root fracture due to long-term $Ca(OH)_2$ exposure and the extended treatment duration may not often be well accepted by the patients (12).

In recent years, Mineral Trioxide Aggregate (MTA) has emerged as a reliable alternative, offering the advantage of a one- or two-visit apexification procedure (13). MTA is a frequently preferred material in endodontics, used in many areas like vital pulp therapy, perforation repair, creating an apical plug, root canal sealer, and has been reported in the literature due to its biocompatibility, antimicrobial effect, and ideal microleakage resistance (14). Studies have reported high success rates with MTA apexification, with healing outcomes exceeding 90% in many cases (15). The clinical protocol typically involves thorough debridement of the root canal system, followed by the placement of MTA at the apical portion to create an artificial apical barrier. Once the material sets, the remainder of the canal can be obturated conventionally. Radiographic follow-up is essential to monitor periapical healing and confirm apical closure over time.

In conclusion, apexification continues to be a valuable treatment modality in contemporary endodontics. With the introduction of bioactive materials such as MTA, the prognosis of necrotic immature teeth has significantly improved. An MTA apexification intervention of a maxillary central incisor that was unsuccessfully treated with REP is presented in this case report.

Case Report

This manuscript has been written according to Preferred Reporting Items for Case reports/or randomized clinical trials/or animal studies in Endodontics.

A 19-year-old systemically healthy female patient presented to the Department of Endodontics at Başkent University, Faculty of Dentistry with complaint of pain on her maxillary left central incisor. According to the anamnesis, the patient had received a REP on right and left maxillary central incisors at an external clinic approximately 10 years ago following a traumatic incident. Her chief complaint involved spontaneous pain as well as pain during mastication.

Clinical examination revealed percussion and palpation sensitivity on the left maxillary central incisor. In addition, pulp vitality tests yielded negative responses. Radiographic evaluation of the periapical area showed incomplete root development of the left maxillary central incisor and a radiolucency consistent with a periapical lesion was observed. Furthermore, structural defects were detected in the MTA material that had been placed during the previous REP (Fig. 1).

The clinician explained the treatment options in detail, repetition of the REP, apexification with MTA or root canal treatment. The patient and the clinician decided to commence with the apexification treatment using MTA. Before proceeding, the patient's written informed consent was taken.

Under local anesthesia and rubber dam isolation, an access cavity was prepared to reach the root canal system. Using a #80 stainless steel K-file, the working length was determined to be 22 mm and the root canal walls were mechanically shaped (Fig. 2). Irrigation was carried out sequentially with 20 ml of 5.25% sodium hypochlorite (NaOCl), 20 ml of 17% EDTA, and finally another 20 ml of 5.25% NaOCl. After drying the root canal with sterile paper points, $Ca(OH)_2$ was placed and a temporary restoration was applied.

At the second appointment given 10 days later, clinical symptoms had subsided, and the same irrigation protocol was repeated. After drying the root canal with sterile paper points, an apical plug was created using Bio MTA (CERKAMED, Stalowa Wola, Poland). The preparation and application of MTA followed the instruction manual provided by the manufacturer. A Schilder plugger (Dentsply Maillefer, Ballaigues, Switzerland) was used to create an apical barrier that was 4 mm thick, to allocate an adequate marginal adaptation and apical sealing (16). To ensure con-

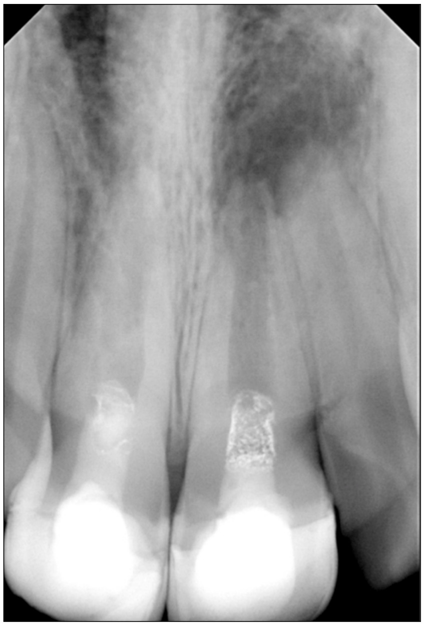

Fig. 1. Initial periapical radiograph.

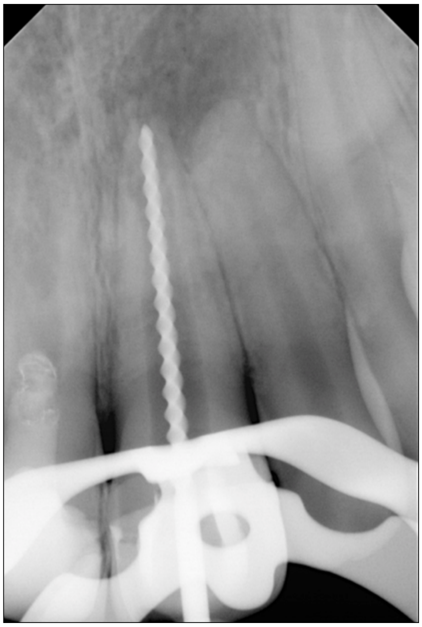

Fig. 2. Working length determination.

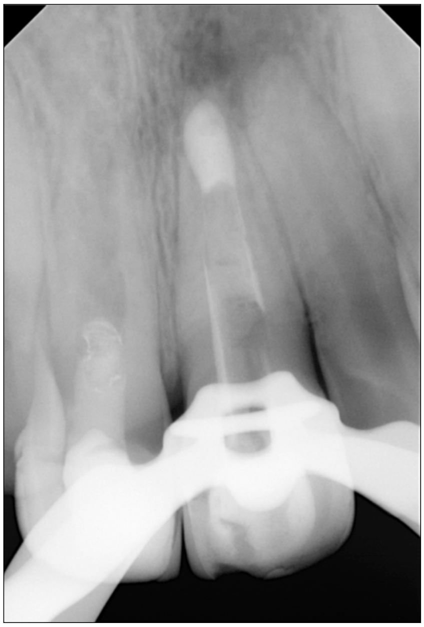

Fig. 3. Forming an apical plug with MTA.

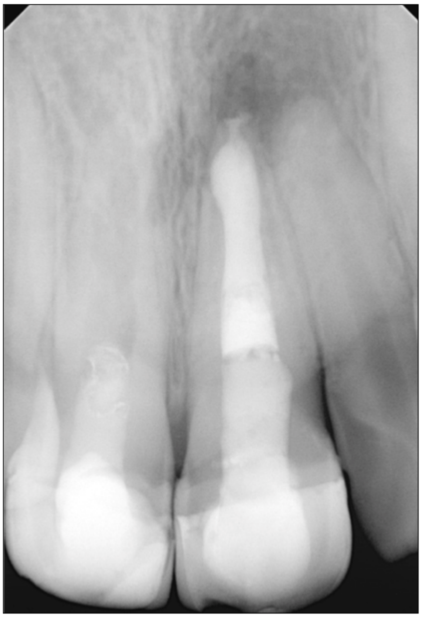

Fig. 4. Root canal obturation.

Fig. 5. 11-month follow-up.

Fig. 6. 21-month follow-up.

trolled placement and compaction of the apical plug, the initial working length was set at 22 mm, and the plugger was gradually shortened by 1 mm per step until a final stop at 18 mm was reached (Fig. 3). The remaining canal space was backfilled with gutta-percha and AH Plus (Dentsply, Germany) sealer using the cold lateral condensation technique. The access cavity was sealed with a composite restoration (Fig. 4).

At the 11-month follow-up, the tooth was found to be asymptomatic and in function (Fig. 5). In the follow-up radiograph taken at 21 months, significant healing of the lesion was observed, and the periradical area appeared to have approached a normal configuration with bone healing (Fig. 6).

Discussion

REP is a cell-based modern therapeutic approach targeted at re-constructing the dentin-pulp complex and promot-ing root development in immature permanent teeth affected by pulp necrosis (1). Although long-term success rates have been reported to exceed 80% in numerous studies (17), REP procedures may fail for various reasons in clinical practice.

The REP protocol generally consists of disinfection, induction of apical bleeding and a hermetically sealed coronal restoration. During the disinfection step, minimal mechanical instrumentation is performed, and irrigants such as 1.5% NaOCl followed by 17% EDTA are used to prepare root canal surfaces. Typically, triple antibiotic paste (TAP) or $Ca(OH)_2$ is placed as an intracanal medicament. At the follow-up appointments, if the tooth is asymptomatic, a traumatic bleeding is induced by using a K-file extended approximately 2 mm beyond the apex to advocate the migration and proliferation of mesenchymal stem cells from the periapical tissues. Once bleeding stabilizes, a collagen sponge is placed over the clot, followed by a biocompatible material, and then the final restoration is completed. This protocol is described in detail in AAE's 2021 clinical guidelines (18).

Reasons for failure include inadequate sterilization, inability to eliminate infection, unfavorable root canal morphology, limited stem cell migration in the apical tissues, and issues related to patient compliance. In a study by Lee and Song (19) involving 111 cases, persistent infection was reported as the primary cause of failure in 81.3% of cases; anatomical factors like canal morphology were also listed as significant contributors to treatment outcomes.

Unsuccessful REP cases are not uncommon in clinical settings and necessitate a reassessment of the treatment protocol. According to the Mahidol Study published in 2024, 10.8% of regenerative procedures were classified as failures, being labeled "diseased" rather than "healed" (20). Additionally, systematic reviews have associated REP failure with persistent symptoms, unchanged periapical radiolucency, and development of internal or external resorption (21).

The choice of irrigation solution and intracanal medicament significantly impacts the canal environment and promotes cellular regeneration, thereby affecting the success of REPs. NaOCl, the most commonly used irrigant, effectively decomposes tissues and has a potent antimicrobial action but can exhibit cytotoxic effects on stem cell viability at high concentrations. Notably, SCAP (stem cells of the apical papilla) viability has been reported to decrease by over 50% after exposure to 5–6% NaOCl (22). Therefore, lower concentrations, such as 1.5% NaOCl are recommended in REP, followed by a final irrigation with 17% EDTA to demineralize the dentin matrix and release growth factors.

Intracanal medicaments are another critical factor in treatment outcomes. Although traditional TAP offers a broad-spectrum antibacterial activity, it may induce tissue toxicity and cause permanent discoloration of dentin at high concentrations. In 2021, an in vitro study on SCAPs showed that TAP had both cytotoxic and genotoxic effects at high concentrations, significantly reducing stem cell viability (23).

As an alternative, $Ca(OH)_2$ has been proposed as another medicament; however, it may be less effective than TAP in eliminating infection. Meta-analyses from 2021 and 2022 reported that TAP exhibited a significantly greater antimicrobial efficacy against resistant microorganisms like Enterococcus than $Ca(OH)_2$. For example, in one systematic review, TAP's effect on E. faecalis biofilm was reported as (SMD=–3.82, 95% CI: –5.44 to –2.21; p<0.001), demonstrating superiority over $Ca(OH)_2$ (24). Conversely, $Ca(OH)_2$ has been shown to exert less tissue toxicity and more favorable effects on stem cell survival compared to TAP (25). Thus, balancing biocompatibility and antimicrobial efficacy with the use of irrigants and medicaments is vital for the long-term success of REP.

After regenerative endodontic therapy (REP) fails, a number of treatment approaches have been suggested, including extraction, nonsurgical root canal therapy, repeated RET, calcium hydroxide apexification, or surgical procedures. However, there is currently inadequate clinical data to support the efficiency and long-term results of these secondary approaches (26).

Both apexification with an MTA apical plug and REPs may be regarded as effective treatment options in cases with advanced root development (stage 4 according to Cvek's classification) (27). However, the viability of stem cells and tissue-forming cells in the periapical area may be compromised by prior infection, making successful revascularization uncertain. Additionally, mechanical instrumentation was intentionally minimized to avoid further weakening of the already thin dentinal walls (28), although limited instrumentation has also raised concerns regarding the completeness of disinfection in REPs (29,30). Considering these biological and technical limitations, apexification was selected as the more predictable and conservative approach in this case.

In cases of failure, apexification is an alternative treatment approach, intending to create an apical barrier in teeth with open apices to enable safe obturation of the canal system. Traditionally, this procedure is done by placing $Ca(OH)_2$ in the root canal over multiple sessions. However, single-visit apexification using MTA has become a faster, tissue-friendly, and clinically reliable alternative (13,31).

MTA is a calcium silicate-based material that sets in moist environments and exhibits biocompatible and tissue-regenerating properties (32). This material exerts antimicrobial effects by creating a high-pH environment parallel to $Ca(OH)_2$ upon direct contact with tissue and enhances apical sealing through a hydroxyapatite-like surface layer (33). A recent systematic review has shown that single-visit MTA apexification procedures yield success rates exceeding 90% and offer comparable or superior clinical outcomes in a shorter timeframe compared to $Ca(OH)_2$ protocols (34). However, appropriate case selection and strict follow-up protocols are crucial for the success of such revision treatments. In this context, unsuccessful REP cases require a comprehensive analysis of clinical, biological, and patient-centered dynamics.

In the presented case, apexification was performed on a previously REP-treated but non-healing central incisor using the single-visit MTA apical plug technique. MTA was carried with a metal spatula and carrier into the root canal, placed with a plugger under controlled conditions, and a moist cotton pellet was inserted to allow proper setting. After 24 hours, the MTA plug was assessed, and the coronal restoration was completed. At 11- and 21-month follow-ups, the tooth remained clinically asymptomatic, and radiographic healing of the periapical area was observed. These results align with findings reported in the literature regarding MTA-based apexification cases (35,36).

Although alternative materials such as Biodentine and EndoSequence Root Repair Material have been developed, many recent studies highlight MTA's superiority in terms of apical sealing, setting depth, and tissue compatibility. For instance, an in vivo experiment found that MTA showed better marginal adaptation and histological response compared to BioDentine (37). Clinically, after drying the root canal with sterile paper points, MTA is inserted using a moist cotton pellet and a carrier instrument, aiming to form a 4–5 mm thick apical barrier (38). According to a study done by Pereira et al. (16), a 4-mm thick apical barrier ensures a significantly suitable seal and marginal adaptation (39) Nonetheless, some laboratory studies report that Biodentine demonstrates lower porosity and faster setting, which may provide better adaptation in in vitro models (38). Clinical and in vivo comparisons largely support the preference for MTA due to its stable tissue integration and long-term performance. Histological analyses have shown that apical barriers formed with MTA support cementum-like mineralization and positively impact periapical healing. For example, a 2024 study using a Wistar albino rat model reported superior calcific barrier formation and minimal inflammation after 28 days using modified MTA formulations (40).

Conclusion

In conclusion, single-visit apexification with MTA emerges as a biologically and clinically reliable option in failed REP cases. However, prevention of such failures hinges upon patient compliance, sterilization, control of irrigation, and strict adherence to protocols. Further clinical studies should be undertaken to compare the treatment options in cases with failed REPs.

Authorship Contributions: Concept: G.U.; Design: K.G.; Supervision: K.G., D.I., G.U..; Fundings: K.G.; Materials: K.G.; Data: D.I., G.U.; Analysis: S.I., G.U.; Literature Search: D.R., D.I., G.U.; Writing: G.U., D.I.; Critical Revision: D.I., G.U., D.R., K.G.

Use of AI for Writing Assistance: Not declared

Source of Funding: The authors declare that this case report received no specific grant from any funding agency, commercial or not-for-profit sectors.

Conflict of Interest: The authors declare that there is no conflict of interest regarding the publication of this article.

Ethical Approval: Ethical approval was not required for this study.

Informed consent: Written informed consent was obtained from patients who participated in this study

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