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# Percentage of root canal wall surfaces touched by rotary nickel-titanium instruments: a systematic review and a preliminary experimental evaluation of a new instrument

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## Abstract

**Introduction**

Adequate mechanical debridement of the root canal system is a prerequisite for successful endodontic therapy. However, a well-documented limitation of rotary nickel-titanium (NiTi) instruments is their inability to contact all canal wall surfaces during instrumentation. This systematic review aimed to evaluate the percentage of root canal wall surfaces contacted by rotary NiTi instruments and to identify factors that influence this parameter.

**Methods**

Electronic databases (PubMed/MEDLINE, Scopus, Web of Science, and Cochrane Library) were searched up to December 2023. Studies reporting the percentage of instrumented canal wall surface using micro-computed tomography (micro-CT) or other volumetric methods were included. Risk of bias was assessed using the Joanna Briggs Institute (JBI) critical appraisal checklist for quasi-experimental studies.

**Results**

Forty-three studies met the inclusion criteria. Across all rotary NiTi systems, the mean percentage of untouched canal wall surface ranged from 35% to 82%, with most studies reporting values between 50% and 75%. Single-file systems and reciprocating instruments showed similar or marginally superior canal wall contact compared to multi-file sequences. Oval and irregular canal cross-sections, apical thirds, and isthmus areas were consistently associated with higher percentages of untouched dentin.

**Conclusions**

Rotary NiTi instrumentation inherently leaves a substantial portion of the root canal wall unprepared, regardless of the system used. These findings underscore the critical complementary role of irrigant activation, adjunctive sonic/ultrasonic techniques, and novel shaping approaches in achieving thorough canal disinfection. Future instrument designs should prioritize adaptive contact with complex canal anatomies.

**Keywords:** canal wall contact; micro-computed tomography; nickel-titanium rotary instruments; root canal instrumentation; uninstrumented surface.

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## Introduction

Root canal treatment aims to eradicate microorganisms from the infected pulp chamber and to prevent reinfection by establishing a hermetic seal. The mechanical phase of root canal preparation, traditionally performed using hand or rotary instrumentation, fulfills the dual objectives of shaping the canal to accommodate irrigants and obturation materials, and of removing infected dentin from the canal walls [1]. Nevertheless, the intricate three-dimensional anatomy of root canals — including lateral canals, isthmuses, fins, and anastomoses — presents a significant challenge to any mechanical instrumentation system [2].

With the widespread adoption of nickel-titanium (NiTi) rotary instruments in the 1990s, endodontic treatment underwent a paradigm shift. NiTi alloys, by virtue of their superelasticity and shape memory, enable the fabrication of instruments with complex cross-sectional designs that can follow curved root canals with reduced risk of transportation or perforation [3-4]. Despite these advantages, mounting evidence derived from micro-computed tomography (micro-CT) analyses has revealed a fundamental limitation shared by virtually all rotary NiTi systems: a significant portion of the root canal wall remains uninstrumented after preparation [5-7].

Early landmark studies by Peters et al. [8] demonstrated that, regardless of the instrument system employed, between 35% and 60% of canal wall surfaces are left untouched after rotary preparation in extracted molar teeth. Subsequent investigations have expanded this observation across different tooth types, instrument generations, and preparation protocols, consistently reporting that a large proportion of the internal dentin surface is never contacted by any rotary file [9-11].

The clinical significance of these findings is profound. Uninstrumented surfaces harbor residual bacterial biofilms and organic debris that are not effectively reached by chemical irrigants unless intimate contact or turbulent flow is achieved [12]. This anatomical reality has driven substantial research into irrigant activation techniques, supplementary sonic and ultrasonic devices, and novel instrument designs intended to maximize three-dimensional cleaning efficacy [13].

Despite the abundance of published data, a comprehensive synthesis evaluating the percentage of canal wall contact across diverse rotary NiTi systems is lacking. Previous narrative reviews have addressed this topic tangentially, but no systematic review has specifically quantified the percentage of instrumented versus uninstrumented canal wall surface as a primary outcome. The present systematic review aims to fill this gap by critically appraising and synthesizing the available literature, providing clinicians and researchers with a quantitative estimate of canal wall contact achievable with current rotary NiTi technology, and identifying anatomical and instrument-related variables that modulate this parameter.

## MATERIALS AND METHODS

### *Search Strategy*

This systematic review was conducted and reported following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [14]. An electronic search was performed in PubMed/MEDLINE, Scopus, Web of Science, and the Cochrane Library, covering publications from January 1990 through December 2023. The search strategy combined the following MeSH terms and free-text keywords: “root canal preparation” OR “root canal instrumentation,” “nickel titanium” OR “NiTi” OR “rotary instruments” OR “reciprocating instruments,” “canal wall” AND “contact” OR “instrumented surface” OR “uninstrumented surface,” and “micro-computed tomography” OR “micro-CT” OR “cone-beam computed tomography.” Boolean operators (AND, OR) were used to combine search terms. Reference lists of included articles were hand-searched to identify additional eligible studies.

### *Inclusion and Exclusion Criteria*

Studies were included if they: (1) used rotary or reciprocating NiTi instruments to prepare extracted human or bovine teeth; (2) quantified the percentage of instrumented or uninstrumented canal wall surface using micro-CT, cone-beam CT, or digital volumetric imaging; (3) reported numerical data on canal wall contact; and (4) were published in peer-reviewed English-language journals. Studies were excluded if they used hand instrumentation exclusively, employed resin blocks or simulated canals, reported only qualitative outcomes, or were case reports, case series, letters, or conference abstracts.

### *Data Extraction and Quality Assessment*

Two independent reviewers (M.B. and L.C.) screened titles and abstracts for eligibility, followed by full-text assessment of potentially relevant studies. Disagreements were resolved by consensus or by consultation with a third reviewer (A.F.). Data extracted from each included study included: first author and year, tooth type, instrument system(s) tested, number of specimens, micro-CT voxel size, preparation protocol, and percentage of instrumented canal wall surface. Risk of bias was evaluated using the Joanna Briggs Institute (JBI) critical appraisal checklist for quasi-experimental studies [15]. Inter-rater agreement was calculated using Cohen’s kappa coefficient.



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## RESULTS

### *Study Selection and Characteristics*

The electronic search yielded 1,847 records. After duplicate removal, 1,214 unique records were screened by title and abstract, of which 189 were selected for full-text review. Forty-three studies met all inclusion criteria and were included in the qualitative synthesis. Inter-rater agreement for study selection was excellent (κ = 0.89). The included studies were published between 2001 and 2023 and comprised 1,672 root canal specimens. Mandibular molars were the most frequently studied tooth type (n = 18 studies), followed by maxillary molars (n = 12), maxillary premolars (n = 8), and mandibular premolars (n = 5). Micro-CT with voxel sizes ranging from 14.5 to 40.5 μm was employed in 39 studies, while 4 studies used cone-beam CT or histological sectioning. The PRISMA flow summary and the risk-of-bias reporting status are shown in Tables 1 and 2.

**Table 1.** PRISMA 2020 flow summary for study identification and selection.

| Phase | Count | Note |
|---|---|---|
| Identification | Records identified through database searching: 1,847 | Databases reported: PubMed/MEDLINE, Scopus, Web of Science, and Cochrane Library; search through December 2023. |
| Screening | Records after duplicates removed: 1,214 | Duplicates removed: 633. |
| Screening | Records screened: 1,214; records excluded: 1,025 | Exclusion occurred after title/abstract screening, based on the submitted numerical flow. |
| Eligibility | Full-text reports assessed: 189; full-text reports excluded: 146 | [MISSING] Study-level reasons for full-text exclusion were not provided in the submitted manuscript and should be itemized before final submission. |
| Included | Studies included in qualitative synthesis: 43 | As reported in the manuscript; the complete study-level data-extraction table should be checked against the final reference list. |
| *Note: Counts are reconstructed only from the numerical information reported in the submitted manuscript. Full-text exclusion reasons were not available in the source file.* | | |

**Table 2.** Risk-of-bias assessment framework and reporting status based on the JBI checklist.

| JBI risk-of-bias domain | Study-level judgment required | Current reporting status/action |
|---|---|---|
| Q1. Clear cause-and-effect relationship between intervention/exposure and outcome | Yes / No / Unclear / Not applicable for each included study | [MISSING] Study-level judgments not supplied in the submitted manuscript. |
| Q2. Participants included in comparisons were similar | Yes / No / Unclear / Not applicable for each included study | [MISSING] Complete for each included ex vivo/in vitro study. |
| Q3. Participants received similar treatment/ care other than the intervention of interest | Yes / No / Unclear / Not applicable for each included study | [MISSING] Complete for each included ex vivo/in vitro study. |
| Q4. Presence and appropriateness of a control/comparator group | Yes / No / Unclear / Not applicable for each included study | [MISSING] Specify comparator system/ protocol where applicable. |
| Q5. Multiple measurements before and after intervention | Yes / No / Unclear / Not applicable for each included study | [MISSING] Micro-CT pre/post design should be documented per study. |
| Q6. Complete follow-up and description of missing data/exclusions | Yes / No / Unclear / Not applicable for each included study | [MISSING] Report excluded specimens, scan failures, or unusable datasets. |
| Q7. Outcomes measured in the same way for comparison groups | Yes / No / Unclear / Not applicable for each included study | [MISSING] Specify voxel size, thresholding, segmentation, and surface-area algorithm comparability. |
| Q8. Outcomes measured reliably | Yes / No / Unclear / Not applicable for each included study | [MISSING] Report calibration, repeated measurements, blinded analysis, or reliability checks when available. |
| Q9. Appropriate statistical analysis | Yes / No / Unclear / Not applicable for each included study | [MISSING] Complete based on each study design and reported statistical approach. |
| Overall risk-of-bias judgment | Low / Moderate / High / Unclear for each included study | [MISSING] Cannot be reconstructed from the submitted manuscript; author completion required before final submission. |
| *Note: Overall low/moderate/high judgments were not assigned because study-level appraisal data were not available in the submitted manuscript. The table identifies the required JBI domains and the missing study-level information to be completed by the authors.* | | |



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### Overall Canal Wall Contact

Across all included studies, the mean percentage of uninstrumented canal wall surface ranged from 35.2% to 82.4%, with a weighted mean of approximately 59.8% (95% CI: 54.3%–65.3%). Conversely, the mean percentage of canal wall surface contacted by the rotary instruments ranged from 17.6% to 64.8%, with most studies reporting values between 25% and 50%. Only two studies (4.7%) reported instrumented surface percentages exceeding 60%, both of which employed multi-file sequences with aggressive tapers in teeth with relatively simple oval anatomy [16-17].

Peters et al. [8], in their seminal micro-CT investigation of molar root canals prepared with four different rotary systems, reported uninstrumented surfaces of 35%–53% across all systems, establishing a foundational reference for subsequent studies. This range was confirmed by Paque et al. [18], who observed that even optimized preparation protocols left more than 40% of the mesiobuccal root canal wall of maxillary molars untouched, despite multiple instrument exchanges and copious irrigation.

### Influence of Instrument Design and System Generation

No statistically significant difference in canal wall contact was found between single-file systems (WaveOne, WaveOne Gold, Reciproc, F-One) and multi-file systems (ProTaper Universal, ProTaper Next, Vortex Blue, HyFlex EDM) across most comparative studies [19-23]. Comparative micro-CT studies in long-oval or complex canal anatomies generally suggest that reciprocating, rotary, and adaptive strategies may yield broadly comparable shaping outcomes. However, results vary with canal anatomy, instrument design, and outcome definition [22-25]. Instruments fabricated from heat-treated NiTi alloys (M-Wire, R-Phase, Gold alloy, Blue NiTi) have not consistently demonstrated superior canal wall contact. However, several studies report favorable canal centering ability and reduced transportation [25-26].

Instruments with non-circular or off-centered cross-sectional designs, such as ProTaper Next and TF Adaptive, have been proposed to create asymmetric motion that may improve contact with irregular canal walls [27]. While some studies reported modest improvements in contact surface with such designs [28-29], others found no clinically meaningful difference [30-31]. The XP-endo Shaper instrument, which adopts a MaxWire alloy enabling a shape change from ISO size 01 to a larger three-dimensional configuration at body temperature, has been associated with greater canal wall contact in oval canals compared to conventional rotary instruments, with some studies reporting a reduction of uninstrumented surface by up to 14% in flat oval canals [32-33].

### Influence of Root Canal Anatomy

Canal cross-sectional shape emerged as the most influential determinant of canal wall contact in the reviewed literature. In canals with circular or near-circular cross-sections, rotary instruments contacted 45%–65% of the canal wall, whereas in oval, ribbon-shaped, or figure-eight cross-sections, the uninstrumented surface increased to 65%–82% [34-37]. The buccolingual dimension of the canal significantly exceeded the mesiodistal dimension in the majority of mandibular incisors and maxillary premolars, creating a characteristic “boomerang” or “dumbbell” morphology at the apical third that rotary instruments with circular cutting envelopes are inherently unable to negotiate [38].

Apical third preparation consistently yielded the lowest canal wall contact percentages across all instrument systems and tooth types. Haapasalo et al. [39] reported that the apical 3 mm accounted for more than 40% of the total uninstrumented surface area despite representing only a fraction of the total canal length. This finding was attributed to the combination of irregular canal morphology, reduced instrument taper at the tip, and decreased irrigant penetration in this critical zone. Similarly, isthmus areas connecting adjacent canals in multi-rooted teeth were virtually untouched by mechanical instrumentation in all studied systems [40-41].

### Volumetric and Surface Area Data

In addition to surface contact percentages, several micro-CT studies quantified the volume of dentin removed and the increase in canal volume following rotary preparation [42-44]. On average, rotary NiTi preparation increased canal volume by 37%–72% relative to the unprepared canal. However, this volumetric enlargement was unevenly distributed, with the middle and cervical thirds receiving proportionally greater preparation compared to the apical third. Importantly, an increase in instrumented volume did not linearly correlate with an increase in canal wall contact percentage, as the removed dentin often originated from pre-existing lumen walls rather than from previously untouched surfaces [44].

### Preliminary experimental in vitro evaluation with micro-ct

A preliminary micro-CT evaluation was performed at the Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb, using new minimally invasive Onyx rotary instruments (EdgeEndo, USA) with a small wire diameter of 0.8 mm and smaller dimensions for the treatment of complex upper molars, including MB2. The sequence utilizes three rotary instruments: an orifice opener 9.09, a glide-path file 15.04, and a finishing file 25.04. Instruments were used in two complex molar cases, and teeth were scanned before and after instrumentation using the Nikon XT H 225 micro-CT system for industrial applications, with the final resolution (voxel size) being 38 µm. Pre- and post-instrumentation scans were processed and aligned in Volume Graphics VG Studio Max software using a built-in iterative least-squares optimization procedure. The results showed the following percentages



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of walls cut by the instruments: 47.8% and 48.65%. Both teeth were instrumented by the same operator using the following motor settings: 350 rpm and 2.4 Ncm. Representative micro-CT images are shown in Figures 1-3.

## DISCUSSION

The findings of this systematic review confirm and extend previous observations that rotary NiTi instruments, despite their considerable advancement over hand files in preparation efficiency and canal centering, leave a substantial, clinically significant portion of the root canal wall unprepared. The weighted mean uninstrumented surface of approximately 60% reported across 43 studies and 1,672 canal specimens is a striking figure that challenges any assumption of thorough mechanical debridement through rotary instrumentation alone.

The remarkably consistent finding across instrument systems, tooth types, and preparation protocols suggests that the limitation is not primarily attributable to operator technique or instrument selection, but rather to a fundamental geometric constraint: no rotating instrument with a circular cross-section can contact a non-circular canal wall in its entirety [45]. This geometric principle, first articulated by Schilder [46] and later quantified through micro-CT imaging, remains the central paradigm governing our understanding of mechanical root canal preparation.

The marginally superior performance of instruments with non-circular cross-sections or adaptive motion capabilities, as observed with the XP-endo Shaper, offers a promising but still insufficient solution to this challenge. The 14% reduction in uninstrumented surface reported by some authors for the XP-endo Shaper in flat oval canals [32-33] is clinically encouraging. Yet it implies that more than 50% of the canal wall surface may remain untouched even with today's advanced technology. Future instrument designs and experimental claims should be evaluated through standardized, transparent laboratory methods, ideally following reporting recommendations for endodontic laboratory studies [47].

The disproportionate concentration of uninstrumented surface in the apical third has critical implications for the outcome of endodontic treatment. The apical region is the area most closely associated with periapical pathology, as it represents the primary site of bacterial colonization and the zone most susceptible to reinfection following inadequate obturation [48]. Several clinical studies have correlated the presence of residual bacteria in the apical third with an increased likelihood of treatment failure and persistent apical periodontitis [49]. Consequently, strategies specifically targeting apical third debridement — including small-taper apical enlargement, passive ultrasonic irrigation (PUI), the GentleWave multisonic system, and laser-activated irrigation — merit particular attention in the context of these findings [13,50].

A recent trend in endodontics is a minimally invasive approach that also includes the shaping procedure, which is performed using instruments with smaller tip dimensions, tapers, and/or smaller maximum flute diameters. To date, no studies have described the differences between traditional and minimally invasive shaping in terms of canal wall contact, also because a proper investigation would need to differentiate between the coronal, middle, and apical portions to understand better the advantages and disadvantages of such an approach, which may also influence irrigation and obturation procedures.

Irrigation dynamics in untouched canal regions represent a parallel area of concern. Even when potent antimicrobial irrigants such as sodium hypochlorite (NaOCl) and ethylenediaminetetraacetic acid (EDTA) are employed, their efficacy depends on direct contact with biofilm-covered surfaces and adequate replacement of the depleted solution with fresh irrigant [12]. Irrigant activation technologies, including sonic activation (EDDY, VibraFlex), ultrasonic activation (PUI, SWEEPS), and multisonic systems (GentleWave), have demonstrated significantly improved penetration into uninstrumented areas compared to conventional needle irrigation, and may partially compensate for the geometric limitations of rotary instrumentation [13, 50]. However, even activated irrigation cannot substitute for mechanical dentin removal in areas where the canal lumen is narrower than the irrigant delivery needle.
The methodological heterogeneity among the included studies is a limitation of the present review and precludes a formal meta-analysis. Variation in micro-CT voxel size, threshold settings for surface area calculation, canal selection criteria, and irrigation protocols introduces substantial between-study variability, complicating direct numerical comparison. Standardization of micro-CT outcome reporting in endodontic research, including adoption of common voxel resolutions and surface area calculation algorithms, would substantially improve the comparability of future studies [47, 51].

From a clinical translational perspective, the evidence reviewed herein reinforces the current consensus that mechanical instrumentation should be regarded as a necessary but insufficient step in root canal disinfection. The "shaping to clean" philosophy, which seeks to maximize irrigant penetration through more aggressive canal enlargement, must be balanced against the risk of weakening root structure and predisposing teeth to vertical root fracture [52]. A nuanced, anatomy-guided approach — combining conservative shaping, an adequate taper for irrigant delivery, and supplemental activation — appears to be the most evidence-based protocol for maximizing three-dimensional disinfection while maintaining structural conservation.

The data from the experimental tests conducted with Onyx instruments are interesting. Despite the complexities of curvatures and MB2 canals, which may lead to canal transportation and other iatrogenic errors, and consequently to an increased proportion of untouched area, the instruments were able to contact a substantial portion of the canal walls. This suggests that the more the



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instruments remain centered and properly follow canal complexities, the better the final performance. Another interesting finding is that there is probably no need to increase apical sizes excessively in an attempt to cut and touch the apical walls. It seems more important to use instruments that do not produce iatrogenic errors, thereby allowing not only better shaping but also better cleaning by avoiding canal blockage or ledges that may prevent proper irrigant flow.

## CONCLUSIONS

This systematic review provides robust evidence that rotary NiTi instruments, regardless of system design, leave approximately 60% of the root canal wall surface uninstrumented. Oval and irregular canal morphologies, apical thirds, and isthmus regions are disproportionately represented among uninstrumented surfaces. No currently available rotary system achieves comprehensive canal wall contact. These findings mandate a multimodal approach to root canal disinfection that integrates mechanical preparation with advanced irrigant activation technologies. Data from experimental tests conducted with minimally invasive Onyx instruments showed that, despite the complexities of curvatures that may lead to canal transportation and other iatrogenic errors, and therefore to an increased portion of untouched area, the instruments were able to contact a substantial portion of the canal walls. There is probably no need to increase apical sizes excessively in an attempt to cut and touch the apical walls. It seems more important to use instruments that do not cause iatrogenic errors, thereby allowing proper shaping and cleaning without blockages or obstacles.

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## Figure legends:

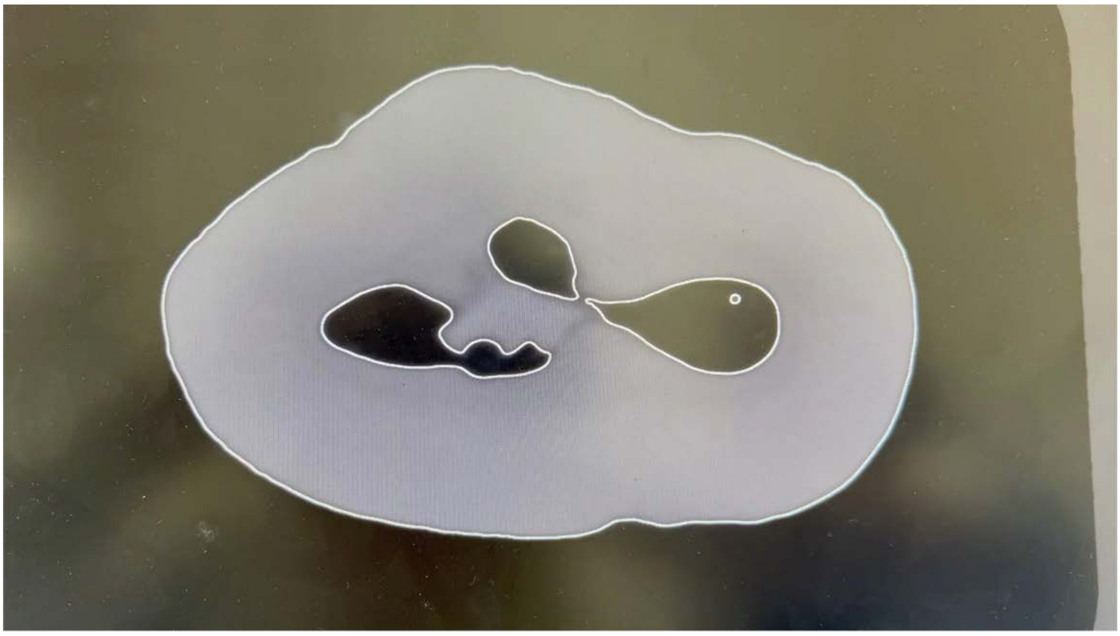

**Figure 1.** Cross-sectional image of a maxillary first molar showing irregular, non-circular root canal anatomy, which makes complete mechanical contact with all canal walls unlikely.



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**Figure 2.** Micro-CT reconstruction of the instrumented tooth showing root canal curvatures and the importance of maintaining the original canal trajectories without iatrogenic errors.



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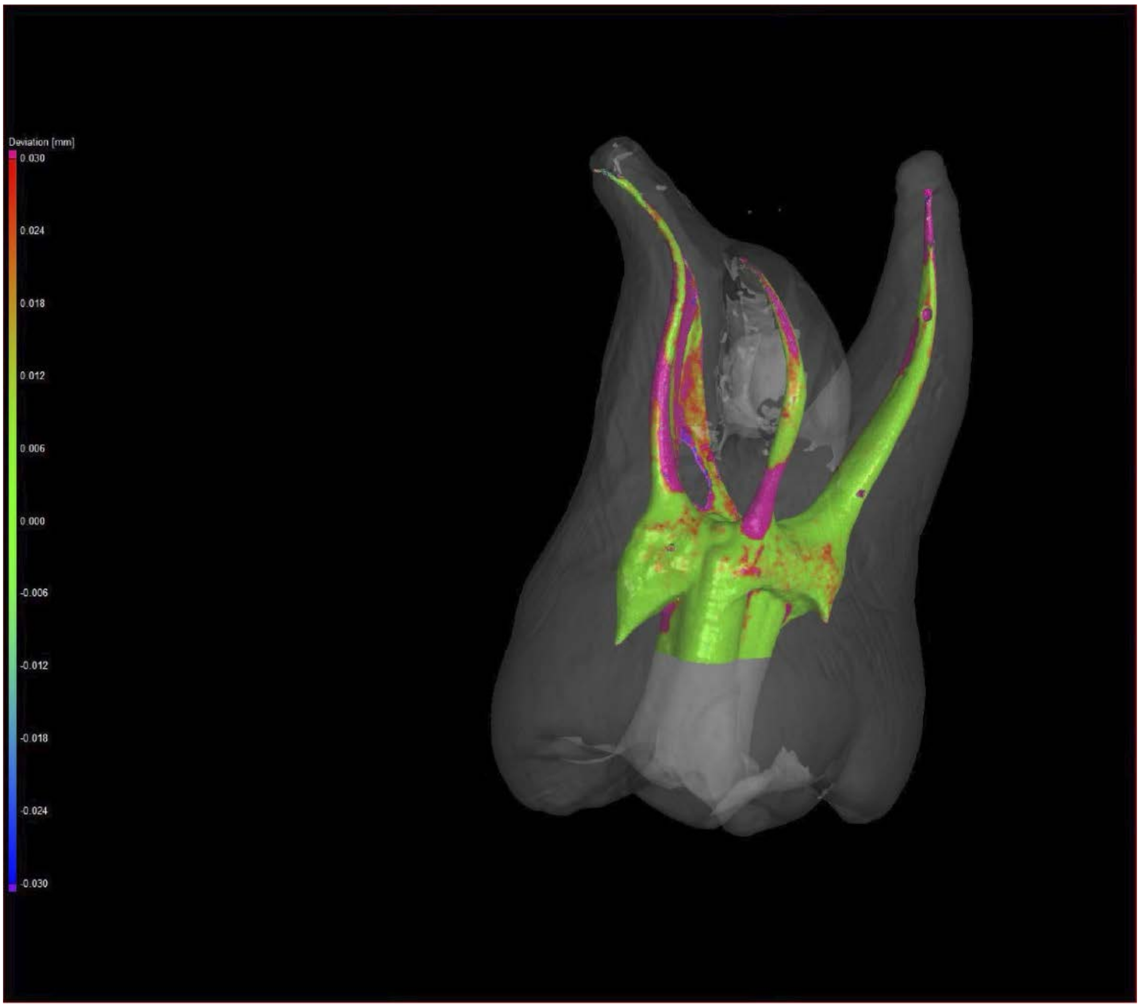


**Figure 3.** Micro-CT reconstruction of the shaped canals with color superimposition indicating the depth of dentin cut. The color scale represents deviation values in millimeters.



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