



UNESP - Universidade Estadual Paulista
“Júlio de Mesquita Filho”
Faculdade de Odontologia de Araraquara



Airton Oliveira Santos Júnior

**Acurácia diagnóstica, planejamento estratégico e segmentação baseada em
inteligência artificial de estruturas da cavidade pulpar por meio de imagens
tridimensionais**

Araraquara
2024



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Tese apresentada à Universidade Estadual Paulista (Unesp), Faculdade de Odontologia de Araraquara, para obtenção do título de Doutor em Odontologia, na Área de Endodontia.

Orientador: Prof. Dr. Mário Tanomaru Filho

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Santos Júnior AO. Acurácia diagnóstica, planejamento estratégico e segmentação baseada em inteligência artificial de estruturas da cavidade pulpar por meio de imagens tridimensionais [tese de doutorado]. Araraquara: Faculdade de Odontologia da UNESP; 2024.

RESUMO

Publicação 1 – Desenvolvimento e validação de um algoritmo de inteligência artificial (IA) baseado em redes neurais convolucionais para a segmentação automática da câmara pulpar e do canal radicular em exames de tomografia computadorizada de feixe cônico (TCFC) de dentes unirradiculares (**Publicação 1**) e birradiculares (**Publicação 2**). A ferramenta de IA demonstrou excelente acurácia na segmentação de dentes unirradiculares (coeficiente de similaridade Dice [CSD]: 89–93%; 95% distância Hausdorff [DH]: 0,10–0,13 mm) e birradiculares (CSD: 88–93%; 95% DH: 0,13–0,16 mm). Além disso, a eficiência de tempo foi significativamente otimizada, com a IA sendo 54 vezes mais rápida para dentes unirradiculares e 75 vezes mais rápida para birradiculares, em comparação ao método manual realizado por especialistas humanos. **Publicação 3** – Avaliação da influência do filtro *Blooming Artifact Reduction* (BAR), integrado ao software e-Vol DX, na detecção de espaços vazios em canais radiculares ovais longos obturados com os cimentos endodônticos AH Plus Jet (AHPJ) e Bio-C Sealer (BCS), utilizando dois aparelhos de TCFC e tendo como referência as imagens de microtomografia computadorizada (micro-CT). No aparelho de TCFC OP300 Maxio, o filtro BAR aumentou significativamente a área sob a curva ROC (AUC) para a detecção de espaços vazios no terço apical em canais obturados com AHPJ e BCS, além de aumentar os valores de especificidade na detecção de espaços vazios no terço apical com AHPJ. No aparelho VeraView X800, os fatores estudados não influenciaram os valores de AUC e sensibilidade, mas o uso do filtro BAR aumentou significativamente a especificidade na detecção de vazios nos terços cervical/médio em canais radiculares obturados com BCS. **Publicação 4** – Investigou a capacidade de preparo e a preservação da dentina pericervical nos canais mesiovestibulares (MV1 e MV2) de molares superiores, utilizando os sistemas de níquel-titânio (NiTi) ProTaper Ultimate (PU) e ProDesign Logic 2 (PDL2). O sistema PU aumentou significativamente o volume no terço cervical do canal MV1 em comparação ao PDL2, que produziu menos debris no terço apical. No geral, ambos os sistemas de NiTi apresentaram uma porcentagem semelhante de superfícies não instrumentadas e mantiveram uma espessura de dentina acima de 0,5 mm. A TCFC subestimou ligeiramente a espessura da dentina em comparação com as medições feitas pela micro-CT. **Publicação 5** – Comparou o desempenho no retratamento endodôntico e a preservação da dentina pericervical dos sistemas de NiTi PDL2, Reciproc Blue (RB) e WaveOne Gold (WOG) nos canais MV1 e MV2 de molares superiores. O sistema RB demonstrou maior eficácia na remoção do material obturador no canal MV1 em comparação ao PDL2, enquanto o PDL2 superou o WOG no terço apical do canal MV2. Todos os sistemas de NiTi apresentaram mínima alteração na trajetória apical. No geral, a remoção de dentina foi semelhante, mas houve uma redução significativa na espessura da dentina na parede distal (zona de perigo) do canal MV2 para valores abaixo de 0,5 mm após o retratamento, independentemente do sistema de NiTi ou da modalidade de imagem utilizada (TCFC ou micro-CT). Exames de TCFC pré-operatórios são importantes para a seleção

adequada dos sistemas de NiTi no retratamento dos canais MV1 e MV2, visando proteger a dentina pericervical na zona de perigo do canal MV2.

Palavras-chave: Endodontia. Inteligência artificial. Microtomografia por Raio-X. Obturação do canal radicular. Retratoamento. Tomografia computadorizada de feixe cônico.

Santos Júnior AO. Diagnostic accuracy, strategic planning, and artificial intelligence-based segmentation of pulp cavity structures using three-dimensional imaging [tese de doutorado]. Araraquara: Faculdade de Odontologia da UNESP; 2024.

ABSTRACT

Publication 1 – Development and validation of an artificial intelligence (AI)-driven algorithm based on convolutional neural networks for the automatic segmentation of the pulp chamber and root canal using cone-beam computed tomography (CBCT) scans of single-rooted (**Publication 1**) and bi-rooted teeth (**Publication 2**). The AI tool demonstrated excellent accuracy in segmenting single-rooted teeth (Dice similarity coefficient [DSC]: 89–93%; 95% Hausdorff distance [HD]: 0.10–0.13 mm) and bi-rooted teeth (DSC: 88–93%; 95% HD: 0.13–0.16 mm). Additionally, the time efficiency was significantly optimized, with the AI being 54 times faster for single-rooted teeth and 75 times faster for bi-rooted teeth compared to the manual method performed by human experts. **Publication 3** – Evaluation of the influence of the Blooming Artifact Reduction (BAR) filter, integrated into the e-Vol DX software, on the detection of voids in long oval root canals filled with the endodontic sealers AH Plus Jet (AHPJ) and Bio-C Sealer (BCS), using two CBCT devices and using micro-computed tomography (micro-CT) images as a reference. In the OP300 Maxio CBCT device, the BAR filter significantly increased the area under the ROC curve (AUC) for detecting voids in the apical third of canals filled with AHPJ and BCS, and also increased specificity values for detecting voids in the apical third with AHPJ. In the VeraView X800 device, the studied factors did not affect AUC and sensitivity values, but the use of the BAR filter significantly increased specificity for detecting voids in the cervical/middle thirds of root canals filled with BCS. **Publication 4** – Investigated the shaping ability and pericervical dentin preservation in the mesiobuccal canals (MB1 and MB2) of maxillary molars using the nickel-titanium (NiTi) systems ProTaper Ultimate (PU) and ProDesign Logic 2 (PDL2). The PU system significantly increased the volume in the cervical third of the MB1 canal compared to PDL2, which produced less debris in the apical third. Overall, both NiTi systems showed a similar percentage of uninstrumented surfaces and maintained a dentin thickness above 0.5 mm. CBCT slightly underestimated dentin thickness compared to micro-CT measurements. **Publication 5** – Compared the performance of NiTi systems PDL2, Reciproc Blue (RB), and WaveOne Gold (WOG) in endodontic retreatment and pericervical dentin preservation in the MB1 and MB2 canals of maxillary molars. The RB system was more effective in removing filling material from the MB1 canal compared to PDL2, while PDL2 outperformed WOG in the apical third of the MB2 canal. All NiTi systems exhibited minimal apical transportation. Overall, dentin removal was similar, but there was a significant reduction in dentin thickness in the distal wall (danger zone) of the MB2 canal to values below 0.5 mm after retreatment, regardless of the NiTi system or imaging modality used (CBCT or micro-CT). Preoperative CBCT scans are important for the proper selection of NiTi systems in the retreatment of MB1 and MB2 canals, aiming to protect pericervical dentin in the danger zone of the MB2 canal.

Keywords: Endodontics. Artificial Intelligence. X-Ray Microtomography. Root Canal Obturation. Retreatment. Cone-Beam Computed Tomography.

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1 INTRODUÇÃO

O sucesso do tratamento endodôntico depende do conhecimento adequado da anatomia do sistema de canais radiculares¹. Além disso, a desinfecção durante o tratamento e a resposta do hospedeiro são fundamentais para eliminar ou reduzir os microrganismos no canal radicular, proporcionando o reparo dos tecidos periapicais². No entanto, a complexidade do sistema de canais radiculares pode dificultar o preparo com instrumentos endodônticos^{3,4}, bem como os processos adequados de limpeza, desinfecção e obturação⁵⁻⁷.

A morfologia dos canais radiculares apresenta variação considerável entre os diferentes grupos dentários⁸. Nos incisivos inferiores, é comum encontrar um único canal, com uma seção transversal oval ou achatada^{8,9}, o que representa desafio para o preparo e obturação adequados¹⁰⁻¹². Molares superiores apresentam maior complexidade morfológica, especialmente devido à presença do segundo canal (MV2) na raiz méso-vestibular¹³. Este canal é altamente prevalente, variando de 48% a 97,6% na população mundial¹⁴, e a persistência da periodontite apical muitas vezes está relacionada à ausência de tratamento endodôntico nos canais MV2¹³. O orifício de entrada do canal MV2 é geralmente menor que o do canal MV1 devido à deposição de dentina secundária¹⁵ e muitas vezes está coberto por uma camada de dentina¹³. Além disso, a espessura de dentina na parede mesial (zona de segurança) e distal (zona de perigo) dos canais MV2 é consideravelmente menor do que a do canal MV1 dos molares superiores¹³. Portanto, o tratamento endodôntico desses canais representa um grande desafio para os clínicos, e o uso de recursos adicionais, como microscópios cirúrgicos operatórios, insertos ultrassônicos e instrumentos de níquel-titânio (NiTi) tratados termicamente, é essencial para garantir uma terapia endodôntica adequada^{13,16-20}.

Embora o tratamento endodôntico possa apresentar altas taxas de sucesso, variando entre 78% e 95,6%, complexidades anatômicas são relacionadas aos casos de insucesso^{21,22,23}. Portanto, o planejamento e o acompanhamento devem orientar a tomada de decisão em casos de insucesso da terapia, evitando extrações dentárias desnecessárias²³. Com os avanços atuais, a tomografia computadorizada de feixe cônico (TCFC) representa uma ferramenta diagnóstica fundamental na endodontia²⁴, sendo capaz de detectar espaços vazios com maior precisão no interior do material

obturador²⁵. Esses avanços, combinados com o histórico do caso clínico podem auxiliar no manejo de situações complexas^{24,25}. Além disso, fornecem informações relevantes para o planejamento do retratamento endodôntico quando necessário, contribuindo para aumentar os índices de sucesso e a possibilidade de manutenção do elemento dentário²⁶.

A TCFC é recomendada na endodontia quando os dados fornecidos pela radiografia periapical são inconclusivos ou incompatíveis com as informações clínicas^{24,27,28}. Essa modalidade de imagem tridimensional (3D) aumenta a confiança dos endodontistas para o diagnóstico e planejamento do tratamento endodôntico, demonstrando ser superior às radiografias periapicais^{24,29}. A TCFC tem diversas aplicações na endodontia, como a visualização detalhada da anatomia interna dos dentes⁸, a detecção de fraturas radiculares^{30,31} e reabsorções³², a localização de canais não tratados^{33,34} e o planejamento de acesso a canais radiculares calcificados^{35,36}. Consequentemente, a TCFC é o principal método de imagem utilizado na endodontia em casos de complexidade moderada a elevada²⁴.

Para análises laboratoriais, a microtomografia computadorizada (micro-CT) é amplamente reconhecida como o padrão-ouro³⁷⁻³⁹. Esse método não invasivo de imagem 3D é comumente utilizado na endodontia para investigar a morfologia dos canais radiculares^{40,41}, avaliar a eficácia das técnicas de preparo^{3,4}, limpeza e irrigação^{42,43}, além de determinar a qualidade do preenchimento^{6,7} e a quantidade de material obturador residual após o retratamento endodôntico^{44,45}. Adicionalmente, a espessura de dentina remanescente após o preparo dos canais radiculares tem sido avaliada por meio de micro-CT^{16,17,18}. Nesse contexto, a inclusão de desenhos experimentais que utilizem exames de TCFC como método de análise, adotando imagens de micro-CT como referência, pode aumentar a robustez dos resultados e a confiabilidade das conclusões obtidas^{37,38}.

Junto com a crescente incorporação da TCFC na endodontia, houve um avanço significativo no desenvolvimento de softwares dedicados para análise das imagens tomográficas²⁵. Um desses softwares é o e-Vol DX (CDT Software, Bauru, São Paulo, Brasil), projetado para tornar a interpretação dos exames de TCFC mais fácil e precisa^{8,25,46}. Ele utiliza filtros de aprimoramento de imagem, como o "*Blooming Artifact Reduction*" (BAR), especialmente útil em situações onde há artefatos de distorção volumétrica que prejudicam a qualidade da imagem para fins

diagnósticos^{25,46,47}. O e-Vol DX tem sido empregado em diversos estudos com objetivos variados, desde auxiliar na localização do forame apical⁴⁸ e medir o diâmetro de estruturas anatômicas^{49,50} até identificar canais radiculares acessórios⁵¹, detectar fraturas radiculares^{47,52} e avaliar a espessura da dentina remanescente após o preparo com instrumentos de NiTi na zona de perigo de molares inferiores⁵³. No entanto, não há evidências sobre o impacto do filtro BAR na precisão diagnóstica para a detecção de espaços vazios em dentes tratados endodonticamente usando imagens de TCFC. Além disso, não existem dados disponíveis sobre a espessura de dentina remanescente medida pelo software e-Vol DX em exames de TCFC após o preparo e retratamento com instrumentos de NiTi nos canais MV1 e MV2 de molares superiores.

Os progressos na ciência da computação impulsionaram o desenvolvimento de algoritmos orientados por inteligência artificial (IA), como as redes neurais convolucionais (RNC), capazes de desempenhar uma ampla gama de tarefas que antes exigiam intervenção humana⁵⁴. Basicamente, as RNC representam as múltiplas camadas de conexões neurais, inspiradas no padrão de conectividade dos neurônios do cérebro humano, que são treinadas para aprendizagem profunda de tarefas específicas^{55,56}. Esses algoritmos apresentam grande potencial para a análise de imagens digitais⁵⁷, podendo simplificar o fluxo de trabalho digital na endodontia⁵⁸⁻⁶². Eles possibilitam um planejamento de tratamento mais personalizado e automatizado, resultando em maior eficiência de tempo e previsibilidade nos resultados do tratamento endodôntico^{57,59}.

No fluxo de trabalho digital, a segunda etapa mais crítica é a segmentação da região de interesse em imagens de TCFC para criar um modelo 3D preciso⁶³. No entanto, os métodos tradicionais de segmentação são prejudicados pela baixa qualidade da imagem, pelos diferentes artefatos causados por materiais de alto número atômico e pelo efeito de volume parcial nas imagens de TCFC^{55,56}. Além disso, esses métodos consomem tempo clínico significativo e são altamente influenciados pela subjetividade e pela habilidade humana⁵⁵⁻⁵⁷. Estudos recentes apontam que a segmentação automatizada de canais radiculares com o uso de ferramentas de IA tem o potencial de revolucionar o fluxo digital na endodontia, trazendo grandes benefícios para a técnica de acesso endodôntico guiado, o processo de ensino e a compreensão por parte dos pacientes⁵⁸⁻⁶². No entanto, existe uma lacuna no conhecimento em relação à aplicação desses modelos computacionais baseados em IA para segmentar

as câmaras pulpares e os canais radiculares em exames de TCFC nos diferentes tipos de dentes.

Portanto, este estudo teve como objetivo desenvolver e validar uma ferramenta de IA para segmentar as estruturas da cavidade pulpar, incluindo a câmara pulpar e o canal radicular, em exames de TCFC. Também foi investigada a influência de um filtro de pós-processamento aplicado a imagens de TCFC na detecção de espaços vazios na obturação de canais radiculares ovais longos. Além disso, foi avaliado o planejamento estratégico do preparo e retratamento endodôntico utilizando diferentes sistemas de NiTi nos canais MV1 e MV2 de molares superiores.

2 PROPOSIÇÃO

Desenvolver e validar um algoritmo de IA para a segmentação automática das estruturas da cavidade pulpar em diferentes tipos de dentes unirradiculares e birradiculares em exames de TCFC. Avaliar a eficácia do filtro BAR na detecção de espaços vazios em canais radiculares ovais longos obturados com diferentes cimentos endodônticos. Além disso, investigar a efetividade e a segurança de diferentes sistemas de NiTi no preparo e retratamento endodôntico dos canais MV1 e MV2 de molares superiores, utilizando imagens de micro-CT e TCFC.

2.1 Objetivos Específicos

Publicação 1 – Desenvolver e validar um algoritmo baseado em IA para a segmentação automática da câmara pulpar e dos canais radiculares em dentes unirradiculares (incisivos, caninos e pré-molares) usando exames de TCFC.

Publicação 2 – Desenvolver e avaliar um algoritmo orientado por IA para a segmentação automatizada da câmara pulpar e dos canais radiculares em dentes pré-molares birradiculares em imagens de TCFC.

Publicação 3 – Avaliar a eficácia do filtro BAR, integrado ao software e-Vol DX, na detecção de espaços vazios em canais radiculares ovais longos obturados com os cimentos endodônticos AH Plus Jet ou Bio-C Sealer, em exames de TCFC adquiridos nos aparelhos VeraView X800 e OP300 Maxio. A eficácia foi determinada utilizando métricas de diagnóstico, incluindo a curva ROC (Receiver Operating Characteristic) (AUC), sensibilidade e especificidade, com as imagens de micro-CT servindo como referência para comparação.

Publicação 4 – Investigar a capacidade de preparo e a preservação da dentina pericervical nos canais MV1 e MV2 de molares superiores, utilizando os sistemas de NiTi ProTaper Ultimate e ProDesign Logic 2.

Publicação 5 – Comparar o desempenho no retratamento endodôntico e a preservação da dentina pericervical dos sistemas de NiTi ProDesign Logic 2, Reciproc Blue e WaveOne Gold nos canais MV1 e MV2 de molares superiores.

3 PUBLICAÇÕES

Esta tese de doutorado resultou nas 5 publicações apresentadas a seguir.

3.1 Publicação 1*

A Novel Artificial Intelligence-Powered Tool for Automated Root Canal Segmentation in Single-Rooted Teeth on Cone-Beam Computed Tomography

ABSTRACT

Aim: To develop and validate an artificial intelligence (AI)-powered tool based on convolutional neural network (CNN) for automatic segmentation of root canals in single-rooted teeth using cone-beam computed tomography (CBCT).

Methodology: A total of sixty-nine CBCT scans were retrospectively recruited from a hospital database and acquired from two devices with varying protocols. These scans were randomly assigned to the training (n=31, 88 teeth), validation (n=8, 15 teeth), and testing (n=30, 120 teeth) sets. For the training and validation datasets, each CBCT scan was imported to the Virtual Patient Creator platform, where manual segmentation of root canals was performed by two operators, establishing the ground truth. Subsequently, the AI model was tested on 30 CBCT scans (120 teeth), and the AI-generated three-dimensional (3D) virtual models were exported in standard triangle language (STL) format. Importantly, the testing dataset encompassed different types of single-rooted teeth. An experienced operator evaluated the automated segmentation, and manual refinements were made to create refined 3D models (R-AI). The AI and R-AI models were compared for performance evaluation. Additionally, 30% of the testing sample was manually segmented at two different times to compare AI-based and human segmentation methods. The time taken by each segmentation method to obtain 3D models was recorded in seconds(s) for further comparison.

Results: The AI-driven tool demonstrated highly accurate segmentation of single-rooted teeth (Dice similarity coefficient [DSC] ranging from 89% to 93%; 95% Hausdorff distance [HD] ranging from 0.10 to 0.13 mm), with no significant impact of tooth type on accuracy metrics ($p>.05$). The AI approach outperformed the manual method

* Artigo escrito nas normas do periódico *International Endodontic Journal*, atualmente em sua primeira revisão (R1) (Anexo C).

($p < .05$), showing higher DSC and lower 95% HD values. In terms of time efficiency, manual segmentation required significantly more time (2262.4 ± 679.1 s) compared to R-AI (94 ± 64.7 s) and AI (41.8 ± 12.2 s) methods ($p < .05$), representing a 54-fold decrease.

Conclusions: The novel AI-based tool exhibited highly accurate and time-efficient performance in the automatic root canal segmentation on CBCT, surpassing the human performance.

Keywords: artificial intelligence, cone-beam computed tomography, convolutional neural network, endodontics, root canal segmentation, single-rooted teeth

INTRODUCTION

The accurate diagnosis and establishment of an appropriate treatment plan are crucial steps for the success of endodontic treatment (Pinto et al., 2023). Thus, the clinician must have a thorough understanding of the complex anatomical configuration of the root canals system to provide satisfactory clinical results for the patient (Mazzi-Chaves et al., 2020). Cone-beam computed tomography (CBCT) represents the main clinic imaging method for assessment of internal tooth anatomy, and it has a positive influence on the endodontic diagnosis and prognosis.

CBCT scans enable the segmentation of anatomical structures to obtain three-dimensional (3D) models, which are essential steps in establishing an effective digital workflow in dentistry (Shujaat et al., 2021; Fontenele et al., 2022, 2023; Lahoud et al., 2021). However, these processes are negatively impacted by poor image quality, partial volume effect, and artefacts generated by high-density materials, such as metallic objects and endodontic sealers with high radiopacity. Additionally, conventional segmentation techniques are time-consuming and can be greatly influenced by human subjectivity (Elgarba et al., 2023; Fontenele et al., 2022, 2023; Shujaat et al., 2021; Lahoud et al., 2021).

Recent advances in computational technology have facilitated the integration of innovative tools guided by artificial intelligence (AI) to overcome limitations associated with classical approaches for segmenting dentomaxillofacial structures on CBCT scans (Elgarba et al., 2023; Fontenele et al., 2022, 2023; Lahoud et al., 2021). In this context, convolutional neural network (CNN), a robust type of deep learning algorithm, have been employed for digital image analysis (Aminoshariae et al., 2021; Fontenele et al., 2022, 2023). Essentially, CNNs consist of multiple layers of neural connections, inspired by the connectivity pattern of neurons in the human brain, and have proven to be an outstanding tool for automatically segmenting various anatomic structures on CBCT scans with high accuracy and time efficiency (Fontenele et al., 2023; Jindanil et al., 2023; Lahoud et al., 2022; Morgan et al., 2022; Nogueira-Reis et al., 2023; Oliveira-Santos et al., 2023; Preda et al., 2022; Shaheen et al., 2021; Verhelst et al., 2021).

CNN-based automated root canal segmentation has the potential to revolutionize the digital workflow in endodontics. This approach offers several advantages for endodontic practice. Firstly, it allows for identification and segmentation

of root canals with anatomical complexities, such as lateral canals, isthmuses, and apical deltas, thereby improving the accuracy and effectiveness of treatments (Duan et al., 2021; Lin et al., 2021; Sherwood et al., 2021; Wang et al., 2023; Zhang et al., 2021). Additionally, the technique enables the measurement of canal volume over time, which is particularly useful in cases of vital pulp treatments for traumatized teeth. It can also be an extremely valuable resource for locating narrow root canals without unnecessary loss of tooth tissue, thus avoiding root perforations (Khanagar et al., 2023). Furthermore, undergraduate dentistry students could significantly benefit from the use of highly accurate 3D models for pre-clinical training during root canal access, optimizing the teaching-learning process (Aminoshariae et al., 2024; Khanagar et al., 2023). Lastly, the application of this technique in epidemiological studies facilitates the analysis of large datasets, providing a better understanding of the prevalence and characteristics of anatomical complexities in root canals across various populations (Khanagar et al., 2023). However, to the best of our knowledge, there is still no study in the literature on CNN-based automatic segmentation of root canals including all groups of single-rooted teeth.

Therefore, the aim of this study was to develop and validate an AI-driven tool for automatic root canal segmentation of single-rooted teeth on CBCT scans. The adopted null hypothesis was that there would be no difference in terms of accuracy and time efficiency between the AI-based method and human performance.

MATERIALS AND METHODS

Ethical criteria

This study underwent review and approval by the local ethics committee before being conducted (reference number: S67798). Additionally, the investigation adhered strictly to the World Medical Association Declaration of Helsinki on medical research and followed the recommendations outlined in the STROBE guidelines. As all patient data were anonymized before analysis, obtaining informed consent was deemed unnecessary.

CBCT data collection

A total of 69 CBCT scans were retrieved from the Dentomaxillofacial Imaging Center database. These scans were initially acquired for different purposes not related to the present research, including endodontic treatment planning, orthognathic surgery, and third molar extraction. The CBCT dataset was acquired using NewTom VGi evo (Cefla, Imola, Italy) and 3D Accuitomo 170 (J Morita, Kyoto, Japan) devices, employing different acquisition parameters to ensure heterogeneous sampling, as described in **Table 1**.

Table 1. Acquisition parameters of the cone-beam computed tomography dataset.

CBCT device	kVp	mA	FOV	Voxel size (mm)
NewTom VGI evo	110	3-20	8×8, 10×10, 12×8, 16×16, 24×19 cm	0.125-0.300
3D Accuitomo 170	90	5	8×8, 10×10, 14×10, 17×12 cm	0.125-0.250

Abbreviations: CBCT, cone-beam computed tomography; kVp, kilovoltage peak; mA, tube current; FOV, field of view; mm, millimeters.

Inclusion criteria consisted of patients aged 18 years or older, as well as CBCT scans with a full permanent dentition and satisfactory image quality, characterized by adequate sharpness, contrast, and noise levels, enabling accurate delineation of pulp chambers and root canals. Additionally, the CBCT scans had to have a field of view (FOV) that covered the maxillary and/or mandibular teeth. It is essential to emphasize the diversity present in the CBCT dataset selected for this study, particularly

concerning the root canal anatomy of single-rooted teeth. The dataset encompassed various clinical scenarios, including single-rooted teeth with either one or two canals, featuring root canals varying from wide to narrow. Additionally, there were cases with root canals of different lengths, ranging from short to long (18 to 26 mm), and roots that exhibited both straight and curved configurations. This diversity accurately represents the natural variation observed in clinical scenarios regarding root canal systems. Any CBCT scans displaying significant expression of artifacts from high-density materials (e.g. presence of multiple dental implants at the same dental arch) and/or movement artefacts were excluded.

The selected CBCT scans were exported in Digital Imaging and Communication in Medicine (DICOM) format and randomly distributed into three steps:

- (1) **Training step** (n=31, 88 teeth): This involved training the AI-driven tool using manual segmentation of root canals;
- (2) **Validation step** (n=8, 15 teeth): Internal validation of the CNN model was performed, optimizing parameters to achieve an ideal model;
- (3) **Test step** (n=30, 120 teeth): This step was dedicated to evaluating the performance of the AI-driven tool by comparing the models obtained from automatic segmentation of the root canals with those from refined automated segmentation (R-AI) performed by an expert.

The study design, along with the dataset distribution, is presented in **Figure 1**. The dataset comprised of all types of single-rooted teeth, encompassing upper central incisors, upper lateral incisors, upper canines, lower incisors, lower canines, and lower premolars. It is important to highlight that the datasets of single-rooted teeth included a wide range of internal teeth anatomies, such as single-rooted teeth with one or two canals, as well as wide, narrow, curved, and straight root canals. This anatomical diversity is summarized in **Table 2**, demonstrating the sample heterogeneity of the sample in the current investigation.

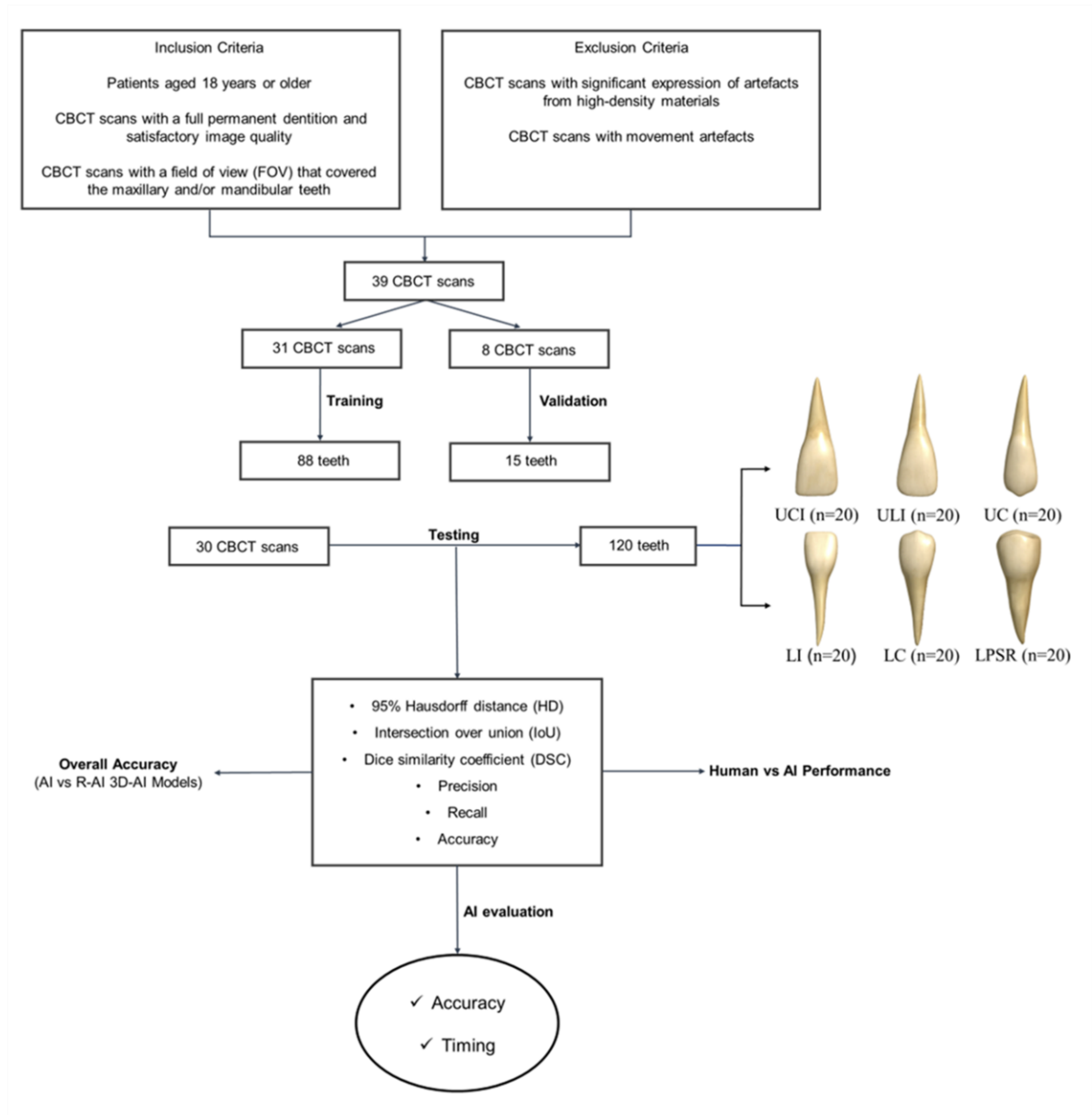


Figure 1. Flowchart showing the overview of the study design including the dataset used for the training, validation, and testing of the CNN model for automated root canal segmentation in single-root teeth.

Abbreviations: CBCT, cone beam computed tomography; AI, artificial intelligence; R-AI, refined artificial intelligence; UCI, upper central incisor; ULI, upper lateral incisor; UC, upper canine; LI, lower incisor; LC, lower canine; LPSR, single-rooted lower premolar.

Table 2. Sample descriptions in the AI tool's test dataset by root canal type

Types of root canals	Number of teeth (n)
Teeth with wide and straight root canals	66
Teeth with wide and curved root canals	25
Teeth with straight root canals and narrowing in at least one of the root thirds	18
Teeth with curved root canals and narrowing in at least one of the root thirds	6
Single-rooted teeth with 2 root canals	5

Abbreviations: n, number of teeth.

Initially, the CBCT scans were imported to the online cloud-based platform “Virtual Patient Creator” (Relu, Leuven, Belgium). This software provides a range of tools for manual segmentation of dentomaxillofacial structures on CBCT scans. These tools, including brush, contour, and interpolation, facilitated delineating the limits of the root canals and pulp chambers in the axial, coronal and sagittal reconstructions.

Two operators (AOSJ and FSN), who had undergone prior training and calibration, independently performed the manual segmentation of the root canals and pulp chamber from the teeth included in the training and validation datasets. Before employing this segmentation dataset for further AI-driven tool development, the operators held a consensus meeting to review all manual segmentations and made refinements as needed. In cases of divergences, a third operator (RCF) was consulted to reach a consensus. Subsequently, the 3D models obtained after manual segmentation were exported in Standard Triangle Language (STL) format, serving as input for the training and validation of the AI networks.

CNN architecture

The AI segmentation pipeline was constructed with two sequential neural networks, utilizing the 3D U-Net architecture, comprising 4 encoder and 3 decoder blocks. Each block featured 2 convolutions with a kernel size of $3 \times 3 \times 3$, followed by rectified linear unit (ReLU) activation and group normalization with 8 feature maps. A $2 \times 2 \times 2$ kernel max pooling with a stride of two was utilized to decrease the resolution by half in all dimensions. Both networks were trained as binary classifiers (0 or 1). All

CBCT scans were standardized to a uniform voxel size. To address GPU memory constraints, each scan was down-sampled to a fixed size. These interconnected networks were essential for the automatic segmentation of endodontic structures, specifically the pulp chamber and root canals. The decision to adopt a two-step approach was strategic, acknowledging the inherent limitations of CNNs when applied to CBCT scans with a large FOV (Fontenele et al., 2023; Fontenele et al., 2022; Preda et al., 2022).

The first neural network performed an initial detection of the structures of interest and propose 3D patches serving as the preliminary segmentation model. Subsequently, these patches were then transferred to the second network to refine the segmentation obtained in the first step, enabling automatic segmentation of endodontic structures at full resolution. These CNN models were implemented using PyTorch, and data augmentation techniques were employed to enrich the training dataset, thereby enhancing the robustness of the developed CNN model. Techniques such as random cropping, scaling, rotation, mirroring, and elastic deformation were utilized for this purpose.

Additionally, the parameters of the CNN model underwent optimization through the ADAM optimization algorithm, initializing with a learning rate of $1.25e^{-4}$, which was halved seven times over 300 epochs. This optimization process involved reducing the learning rate and implementing early stopping based on the validation set to prevent overfitting. A saturation point was identified, indicating that additional training data would lead to overfitting without enhancing the model's generalization. It is important to note that this study used a heterogeneous dataset in the different stages of AI tool development. The dataset was derived from single-rooted teeth with 1 or 2 root canals, which could be wide or narrow, with different root lengths, and presenting either straight or curved roots in different root thirds. This sample diversity allowed the AI tool developed and validated in this study to effectively address the various anatomical complexities frequently observed in root canal systems. Finally, the CNN model was implemented on the online cloud-based AI platform “Virtual Patient Creator”. This platform is specialized in the automated segmentation of dentomaxillofacial structures on CBCT scans, including teeth (Fontenele et al., 2022; Shaheen et al., 2021), mandibular canal (Lahoud et al., 2022; Oliveira-Santos et al., 2023), mandibular incisive canal (Jindanil et al., 2023), and maxillary alveolar bone (Fontenele et al. 2023).

Automated root canal segmentation – Testing step

Each CBCT scan, formatted in DICOM file format, was uploaded to the “Virtual Patient Creator” platform. The platform automatically segmented the endodontic structures using a multi-class approach, segmenting all root canals from the same scan simultaneously. Subsequently, the platform generated the individual 3D models of the pulp chamber and root canal for each single-rooted tooth, exporting in STL format. Additionally, the platform automatically recorded the time required (in seconds) to generate the 3D models.

Refinement of the automated root canal segmentation – Testing step

All automated segmentations were examined by an experienced operator (RCF) to correct potential errors in AI segmentation, which could involve either undersegmentation and/or oversegmentation. This process was carried out using the aforementioned cloud-based platform after a thorough examination of the CBCT scans in the axial, sagittal, and coronal multiplanar reconstructions. It was determined that all segmentation maps required some level of correction, and these corrections were done using the brush tool (removing and adding voxels in the segmentation map) after utilizing the resliceable axes tool. The use of the resliceable axes tool allowed the operator to adjust the axial, sagittal, and coronal planes of CBCT scans to become parallel and perpendicular to each other, considering the areas of interest of the root canal that required corrections. This alignment was crucial for the operator to accurately visualize and assess the root canal morphology. It aided in visualizing the entire length and morphology of the root canal, facilitating manual segmentation and any necessary refinement in the automatic AI-driven segmentation, especially in cases with significant root curvature.

Following these adjustments, the platform generated a new R-AI model for the root canal in STL format. **Figure 2** shows the great diversity of anatomical variations observed in the testing dataset. The time taken for performing the manual refinements was recorded using a digital stopwatch and added to the time required for the initial automatic segmentation provided by the platform.

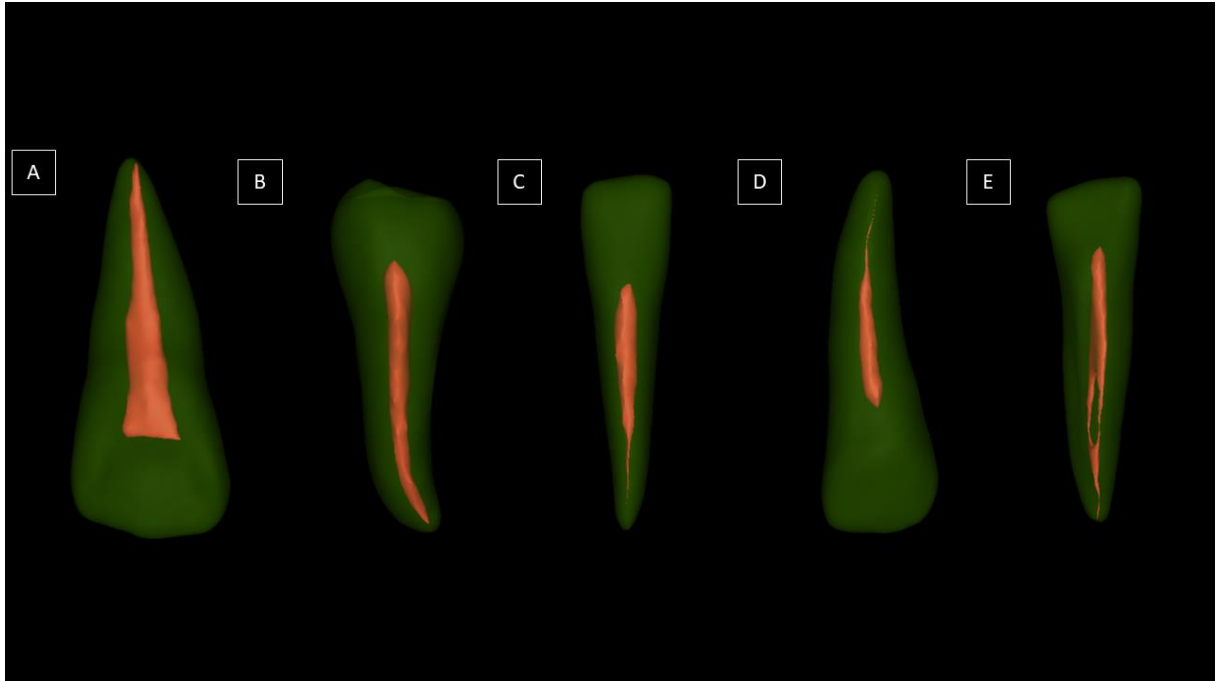


Figure 2. Three-dimensional transparent models of teeth showcasing their internal anatomy and the variability within the testing dataset. (A) Wide and straight root canal; (B) Wide and curved root canal; (C) Straight root canal with narrowing in at least one root third; (D) Curved root canal with narrowing in at least one root third; (E) Single-rooted tooth with two root canals.

Validation metrics

The performance of the developed CNN model was assessed using a confusion matrix at the voxel level, comparing AI and R-AI segmentation maps. From this comparison, the following variables were established:

(1) False positive (FP): Voxels initially included in the automated segmentation but subsequently removed by the operator during the refinement of the root canal segmentation.

(2) False negative (FN): Voxels initially not included in the automated segmentation but later added by the operator during the refinement of the root canal segmentation.

(3) True positive (TP): Voxels that accurately belonged to root canals and were correctly segmented.

(4) True negative (TN): Voxels that did not pertain to root canals and were not correctly excluded from the final segmentation map.

The values of these variables were used to calculate the following accuracy metrics, which were employed to assess the performance of the AI-driven tool:

(a) 95% Hausdorff Distance (HD): Signifies the 95th percentile of the maximum distance between a point on the AI segmentation map and its nearest point on the segmentation map obtained after refinement. This metric provides a measure of spatial accuracy by assessing the maximum distance between the predicted AI segmentation and the refined AI segmentation (R-AI segmentation map).

$$P95 \left(\min_{g \in G} \left(\min_{p \in P} |p - g| \right) \cup \min_{p \in P} \left(\min_{g \in G} |g - p| \right) \right)$$

(b) Intersection over union (IoU): Quantifies the extent of overlap between the AI segmentation map and the R-AI segmentation map (R-AI).

$$IoU = \frac{TP}{TP + FP + FN}$$

(c) Dice similarity coefficient (DSC): Measures the level of intersection between the AI and R-AI segmentation maps. This metric quantifies the overlap between the AI-generated segmentation map and the segmentation map generated after refinements (R-AI segmentation map), providing an indication of how similar they are.

$$DSC = \frac{2 \times IoU}{1 + IoU}$$

(d) Precision: Indicates the ratio of accurately identified voxels to all voxels classified as belonging to the root canal by the AI tool.

$$Precision = \frac{TP}{TP + FP}$$

(e) Recall: Signifies the ratio of voxels that belonged to the root canal and were correctly identified by the AI tool.

$$Recall = \frac{TP}{TP + FN}$$

(f) Accuracy: Indicates the ratio of voxels that were correctly detected among all the observed voxels.

$$Accuracy = \frac{TP + TN}{TP + TN + FP + FN}$$

A 95% HD value of 0 millimeters (mm) and values of 100% for the other metrics signify a perfect segmentation. **Figure 3** illustrates two important accuracy metrics, 95% HD and DSC, by overlapping the contours of the AI-predicted segmentation map (in red) and the refined AI segmentation map (R-AI segmentation map, in green) on the CBCT reconstruction.

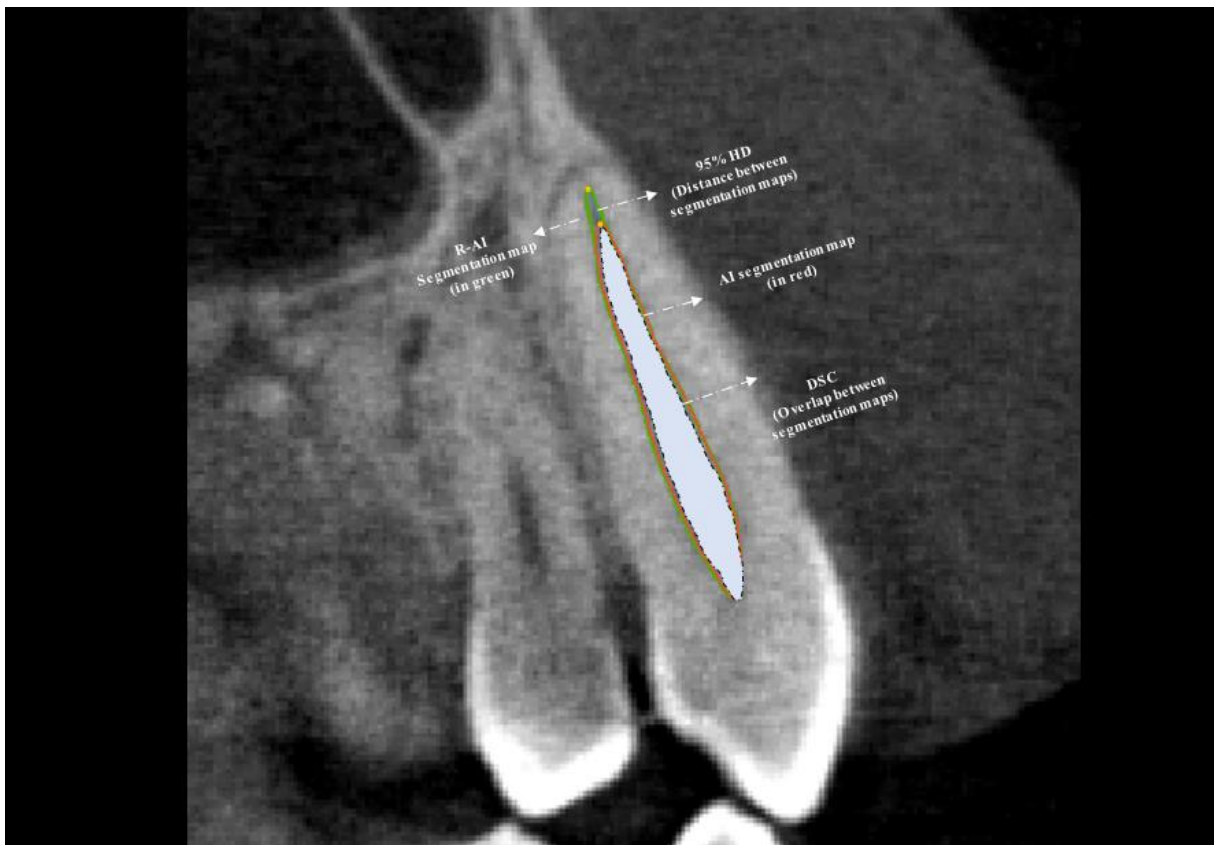


Figure 3. Visual representation of the 95% Hausdorff Distance (HD) and Dice Similarity Coefficient (DSC). The contours of the AI-predicted segmentation map (in red) and the refined AI segmentation map (R-AI segmentation map, in green) are overlapped on the CBCT reconstruction to illustrate these metrics. The 95% HD measures spatial accuracy by evaluating the distance between the segmentation boundaries, while the DSC quantifies the overlap between the segmentation maps.

Comparison between manual and AI-driven segmentation

Manual segmentation performed by a human served as the reference to evaluate the performance of automatic segmentation conducted by the developed CNN model. Thirty percent of the teeth included in the testing step (n=36) were randomly selected, ensuring the inclusion of different single-rooted tooth types. An experienced operator (RCF) conducted manual segmentation of the endodontic structures using the “Virtual Patient Creator” platform.

First, the specialist outlined the pulp chamber and root canal manually using the contour tool on the axial reconstructions of the CBCT scans. Next, the operator activated the resliceable axes tool on that platform, navigating through the sagittal and coronal reconstructions by adding or removing voxels from the segmentation map until achieving a suitable 3D model. This procedure was repeated at two-time points, with a 30-day interval between the segmentation sections, to assess the accuracy of manual segmentation. The accuracy was evaluated by comparing the segmentation maps generated from the first and second segmentation for each single-rooted tooth, using the same accuracy metrics mentioned earlier. Afterwards, these results were compared to those obtained for AI segmentation within each accuracy metric. The time required to carry out the manual segmentation was recorded using a digital stopwatch.

Timing analysis

The average time required to obtain the segmentation maps using manual, AI, and R-AI approaches was investigated. For this task, the same sample used for comparing the manual and automatic approaches was used (i.e. thirty percent of the teeth used in the testing dataset).

(a) Manual method: The time spent to perform manual segmentation from importing the CBCT dataset to generating the 3D model.

(b) AI method: the online platform automatically provided the time spent to perform the automatic segmentation until obtaining the 3D model.

(c) R-AI method: The time required to perform manual refinements was added to the time taken to perform the AI segmentation method.

Statistical analysis

Statistical analysis was performed using SPSS software (version 24.0, IBM Corp., Armonk, NY). Descriptive statistics of the accuracy metrics and time analysis data was carried out using mean and standard deviation (SD) values.

To assess the normality of the data, the Shapiro-Wilk test was utilized, considering the residual values. Since the quantitative parameters showed a normal distribution ($p > .05$), parametric statistical tests were employed depending on the number of groups compared. The mean values of each accuracy metric were compared using a one-way analysis of variance (ANOVA), followed by the Tukey post-hoc test, with the type of tooth as the study factor. Additionally, a paired t-test was employed to compare the performance of manual segmentation and AI segmentation for each accuracy metric. For time analysis, the time spent to generate the 3D root canal models using different segmentation methods (manual, AI, and R-AI) was compared using one-way ANOVA with Tukey post-hoc test. For each statistical test, the power analysis was performed as follows: for ANOVA, it considered the minimum difference between groups, the standard deviation within each group, and the number of teeth in each group. For the paired t-test, it considered the mean difference between paired observations, their standard deviation, and the number of teeth for each accuracy metric. Based on these parameters, a statistical power ranging from 75% to 99% was achieved. Throughout all conducted analyses, the significance level was established at 0.05 ($\alpha = 5\%$).

RESULTS

Table 3 presents the AI-driven tool's performance in generating 3D root canal models within each tooth group based on accuracy metrics. The AI-driven tool demonstrated excellent performance, yielding high values of IoU (ranging from $80\% \pm 14$ to $86\% \pm 7$), DSC (ranging from $89\% \pm 6$ to $93\% \pm 4$), recall (ranging from $84\% \pm 11$ to $93\% \pm 5$), precision (ranging from $90\% \pm 5$ to $94\% \pm 4$), and accuracy (ranging from $98\% \pm 0.8$ to $99\% \pm 0.4$). Furthermore, the tool exhibited low values of 95% HD ranging from 0.10 ± 0.03 mm to 0.13 ± 0.06 mm. These results represent accurate automatic segmentation of root canals with an ideal superposition with the AI and R-AI 3D models, indicating that the AI required only minor refinements (**Figure 4**).

The accuracy metrics were not significantly affected by the tooth type ($p > .05$), except for the recall metric ($p < .05$). The highest recall values were observed for the lower canines ($93\% \pm 4$) and premolars ($93\% \pm 5$), while the lowest value was recorded for the upper lateral incisors ($84\% \pm 11$) (**Table 3**).

Table 4 shows the comparison between manual and AI-driven methods for performing the root canal segmentation. The automated approach exhibited superior performance compared to the manual segmentation method ($p < .05$) (**Figure 5**). This superiority was evidenced by lower 95% HD values (0.13 ± 0.02 mm) and higher values of IoU ($84\% \pm 2$), DSC ($91\% \pm 4$), precision ($94\% \pm 4$), and accuracy ($99\% \pm 0.6$). However, there were similar recall values between the two segmentation methods ($p > .05$). The **Figure 6** illustrates the types of errors (under and/or over segmentation) found in 3D models obtained by automated segmentation of root canals.

Regarding the time analysis (**Figure 7**), the manual method showed the lengthiest consumption of time (2262.4 ± 679.1 s) for conducting the segmentation when compared to the AI-driven approach (41.8 ± 12.2 s) and R-AI (94 ± 64.7 s), which did not differ from each other ($p < .05$).

Table 3. Performance of the AI-driven tool for automated root canal segmentation according to teeth group based on accuracy metrics.

Teeth group	IoU (%) Mean (SD)	DSC (%) Mean (SD)	Recall (%) Mean (SD)	Precision (%) Mean (SD)	Accuracy (%) Mean (SD)	95% HD (mm) Mean (SD)
Upper central incisors (n=20)	83 (8)	90 (5)	88 (7) AB	94 (4)	99 (0.4)	0.13 (0.06)
Upper lateral incisors (n=20)	80 (14)	89 (8)	84 (11) B	92 (6)	99 (0.6)	0.12 (0.04)
Upper canines (n=20)	81 (9)	89 (6)	88 (6) AB	90 (6)	98 (0.8)	0.10 (0.03)
Lower incisors (n=20)	81 (9)	89 (5)	88 (7) AB	90 (5)	99 (0.6)	0.12 (0.04)
Lower canines (n=20)	86 (6)	93 (4)	93 (4) A	92 (4)	99 (0.9)	0.11 (0.08)
Lower premolars (n=20)	86 (7)	93 (4)	93 (5) A	92 (4)	99 (0.5)	0.12 (0.04)
<i>p</i> -value	.11	.09	< .001	.16	.31	.32

Abbreviations: IoU, Intersection over union; DSC, Dice similarity coefficient; HD, Hausdorff distance; n, sample size; SD, Standard deviation.

Statistical power analysis showed a range from 75% (for the 95% HD metric) to 98% (for the recall metric).

Note: Distinct uppercase letters indicate a statistically significant difference between the groups of teeth ($p < .05$).

Table 4. Comparison between the manual and AI segmentation methods for single-rooted canal segmentation.

Metrics	Manual Mean (SD) (n=54)	AI Mean (SD) (n=54)	<i>p</i>-Value
IoU (%) *	74 (10)	84 (2)	.003
DSC (%) *	85 (7)	91 (4)	.004
Recall (%)	87 (11)	89 (7)	.50
Precision (%) *	86 (10)	94 (4)	.01
Accuracy (%) *	98 (0.02)	99 (0.6)	.02
95% HD (mm) *	0.24 (0.06)	0.13 (0.02)	<.001

Abbreviations: AI, Artificial intelligence; IoU, Intersection over union; DSC, Dice similarity coefficient; HD, Hausdorff distance; n, sample size; SD, Standard deviation.

Statistical power analysis showed a range from 78% (for the recall metric) to 93% (for the 95% HD metric).

Note: Asterisk (*) indicates a statistically significant difference between the segmentation methods within each accuracy metric ($p < .05$)

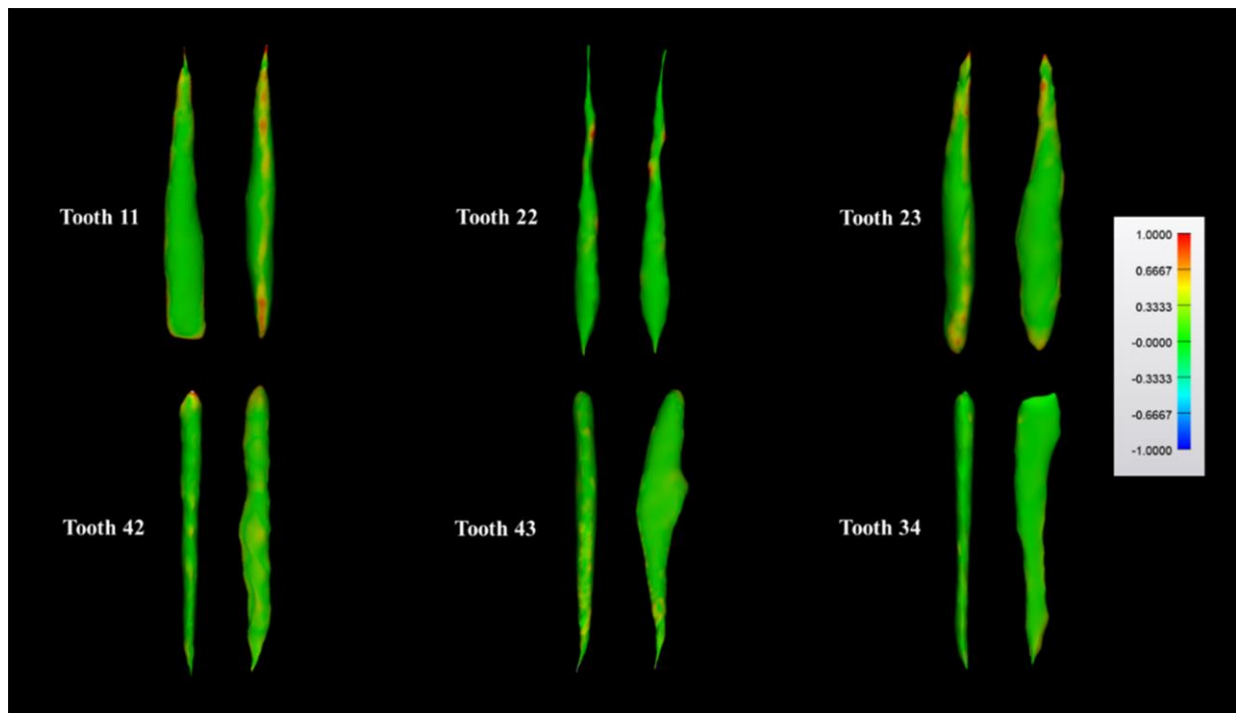


Figure 4. Comparison of AI and R-AI three-dimensional models for different types of single-rooted teeth, employing color mapping in frontal and lateral views.

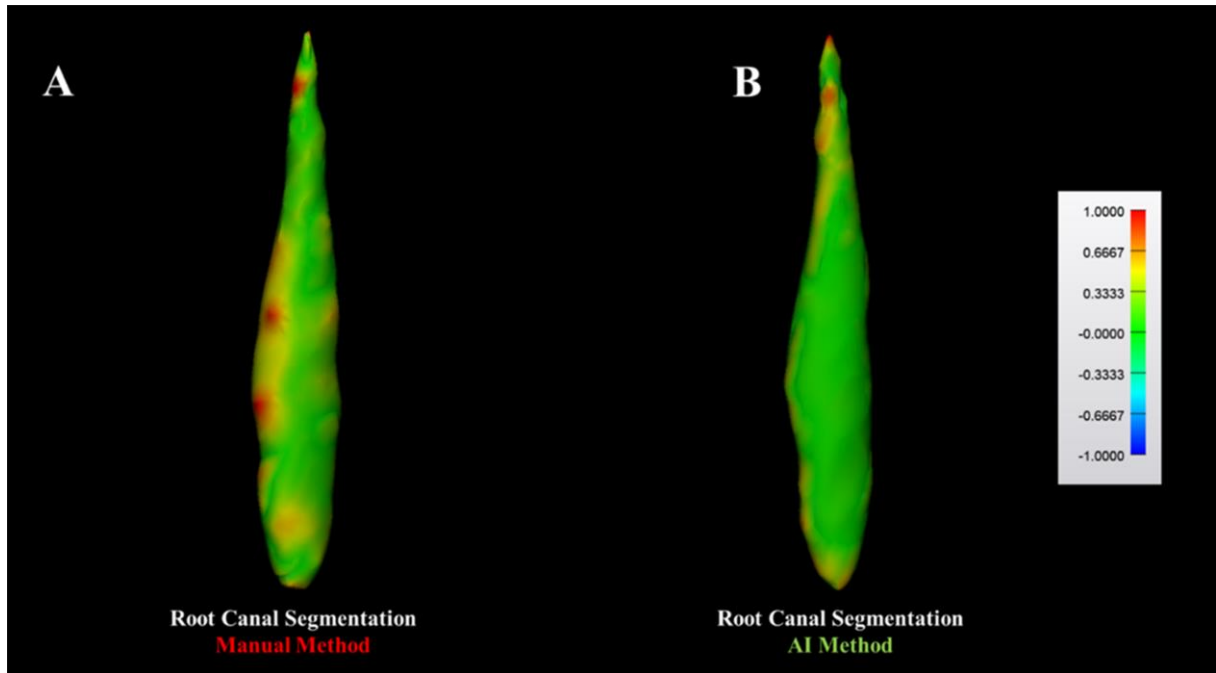


Figure 5. Three-dimensional (3D) models of an upper canine root canal segmentation employing color mapping, comparing (A) the manual method and (B) the AI method. The areas highlighted in red and yellow indicate regions with significant differences, representing discrepancies between the first and second manual segmentation for the manual method and between the AI and R-AI 3D models for the AI method.

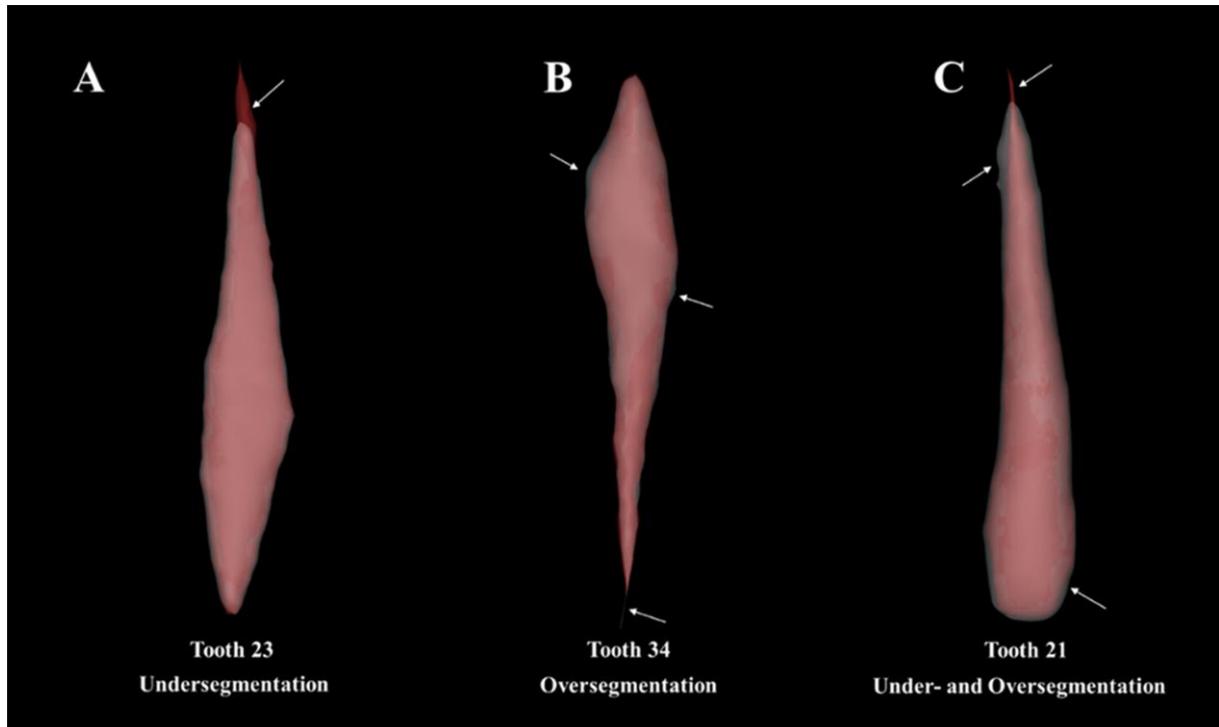


Figure 6. Three-dimensional models illustrating various types of errors found in AI-driven segmentation. The white three-dimensional (3D) models represent AI predictions, while the red ones represent the 3D model after the refinements made by the expert. Errors are indicated by arrows. A, Undersegmentation in the apical third of the root canal for an upper left canine tooth; B, Oversegmentation in the pulp chamber and apical third of a first lower left premolar tooth; and C, Under- and oversegmentation in the pulp chamber and root canal of an upper left central incisor tooth.

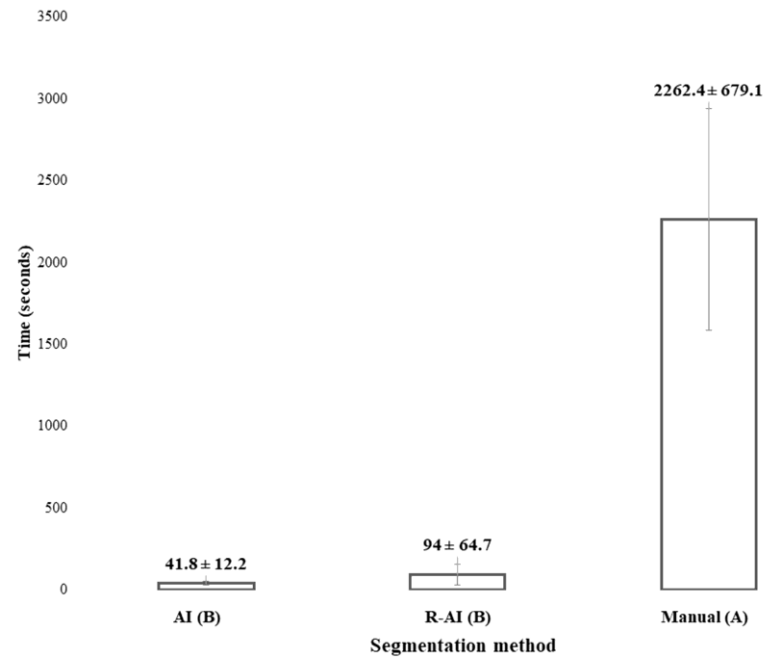


Figure 7. Timing analysis according to the segmentation method. Distinct uppercase letters indicate a statistically significant difference among the segmentation methods ($p < .05$). Statistical power analysis of 99%.

Abbreviations: AI, artificial intelligence; R-AI, refined artificial intelligence.

DISCUSSION

The 3D segmentation of the pulp chamber and root canal is a crucial step in the endodontic digital workflow. However, several limitations are commonly associated with classical segmentation methods (Lin et al., 2021; Wang et al., 2023). To address these challenges, the present investigation aimed to develop and validate a unique AI tool for the automatic segmentation of endodontic structures (i.e. pulp chamber and root canal) in single-rooted teeth on CBCT scans. The current findings revealed that the CNN model could provide highly accurate automated segmentation of these fine anatomical structures with minimal working time, demonstrating significant differences compared to manual segmentation performed by a human. Thereby, the null hypothesis established was rejected.

The performance of the AI-based algorithm was evaluated using accuracy metrics. The high IoU values (ranging from $80\% \pm 14$ to $86\% \pm 7$), DSC (ranging from $89\% \pm 6$ to $93\% \pm 4$), and low values of 95% HD (ranging from 0.10 ± 0.03 mm to 0.13 ± 0.06 mm) evidence the excellent performance attributed to the AI tool developed in this study for obtaining accurate 3D models of root canals in single-rooted teeth. To the best of our knowledge, there are few previous investigations that have explored the effectiveness of AI-driven tools for automatically segmenting root canals on CBCT scans. Duan et al. (2021) reported adequate performance for a CNN model in segmenting teeth and pulp chambers of single and multi-rooted teeth. However, their image dataset was acquired from only one CBCT device using similar acquisition parameters, making comparison challenging with the current investigation. Lin et al. (2021) reported acceptable performance (DSC = 87.49%, 95% HD = 1.99 mm) for AI-based automatic segmentation of root canals in single-rooted premolars. However, the authors stated that the developed CNN model needed optimization, especially for accurate segmentation of root canals in the apical third. Still, these results should be carefully interpreted, as only single-rooted premolars were included in the sample. Another study revealed that it was not possible to perform automatic segmentation of narrow root canals in mandibular molars using a 3D U-Net neural network on CBCT scans (Lin et al., 2022). On the other hand, Zhang et al. (2021) attributed acceptable results (DSC = 0.95) to an AI algorithm for automated segmentation of root canals. However, no information related to the type of tooth included in the dataset was reported. Recently, Wang et al. (2023) proposed a CNN model for the automatic

segmentation of single-rooted teeth and their root canals on CBCT scans. However, due to the limited dataset used during the training (5 CBCT scans, 21 teeth), validation (2 CBCT scans, 8 teeth), and testing (7 CBCT scans, 27 teeth) of the AI networks, and also due to the unknown CBCT device used, generalizations and comparisons with the findings of the present investigation are difficult.

The current findings evidence the excellent performance of the AI algorithm in obtaining highly accurate 3D models of root canals across all types of single-rooted teeth, including incisors, canines, and premolars. This is in contrast to the results of previous studies aforementioned. However, when evaluating the recall metric, slightly lower values were found for the root canals of the upper lateral incisors ($84\% \pm 11$) compared to canines ($93\% \pm 4$) and lower premolars ($93\% \pm 5$). Nevertheless, this statistical difference was relatively minor and might not have a significant impact on the tool's performance in clinical practice. These findings could be attributed to the complex root anatomy of the upper lateral incisors, characterized by the presence of a long and narrow root canal, especially in the apical third, along with a pronounced radicular curvature in the palato-distal direction (Wang et al., 2022).

Automated segmentation of root canals driven by AI exhibited notably superior performance (IoU = $84\% \pm 2$, DSC = $91\% \pm 4$, precision = $94\% \pm 4$, accuracy = $99\% \pm 0.6$, and 95% HD = 0.13 ± 0.02 mm) compared to manual segmentation performed by human. However, no statistical differences were found when considering the recall metric between both segmentation methods. These results further reinforce the premise that the anatomical complexity of the upper lateral incisor root canals presents an intrinsic challenge for segmentation cannot be attributed as a limitation to the AI tool. Consequently, these findings highlight the clinically acceptable results attributed to the CNN model in this study for obtaining accurate 3D models of root canals, even in teeth with challenging root anatomy.

Previous studies have shown that precise segmentation of fine head and neck anatomical structures requires a large training sample size when using deep learning algorithms (Fang et al., 2021). In the present study, a dataset comprising 69 CBCT scans was used to train and validate the AI algorithm, encompassing 103 teeth. To address the challenge of overfitting, several strategies were implemented, including ensuring dataset heterogeneity, partitioning the data for continuous monitoring of model performance, employing data augmentation techniques such as rotations, flips, and zooms, and incorporating early stopping as a regularization technique. While these

measures were crucial in optimizing the training process and ensuring enough dataset size for performing the training, the success of the approach cannot be solely attributed to them. Prior training of the current AI platform for tooth segmentation, involving a robust sample of 175 CBCT scans and 500 teeth, as demonstrated by Shaheen et al. (2021) and Fontenele et al. (2022), played a pivotal role. This pre-existing knowledge provided a foundational understanding and feature extraction capability for the AI network tested. By leveraging insights gained from tooth segmentation, particularly the voxels representing tooth segmentation, acquired through extensive AI algorithm training, it was able to expedite the learning process for endodontic structures segmentation. This accelerated learning, informed by previous training, enabled the research to reach the saturation point in the learning curve with a reduced sample size, thus optimizing the study's outcomes.

The time consumed to perform segmentation is a key point in the digital workflow (Fontenele et al., 2022, 2023). However, existing literature lacks information regarding the time required for root canal segmentation. This investigation pioneers the evaluation and comparison of the time required for the root canal segmentation using manual, AI, and R-AI methods. The AI segmentation showed the fastest performance (41.8 ± 12.2 s), being 54 times faster than manual segmentation performed by human ($2.262.4 \pm 679.1$ s). Additionally, the current findings revealed that the R-AI approach exhibited low working time (94 ± 64.7 s), similar to AI-driven segmentation. These results highlight the high accuracy of the 3D models obtained by the AI method and clearly suggest that in cases where adjustments to the segmentation map are needed, such refinement will be minimal and not require significant working time.

The datasets utilized in this study for training, validation, and testing the AI tool encompassed a diverse range of single-rooted teeth, providing a comprehensive representation of clinical scenarios. These teeth exhibited variations in the number of root canals, ranging from one to two, and displayed diverse widths, lengths, and curvatures, particularly notable in the apical third. This anatomy diversity within the sample set served as a crucial factor for the adaptation of the CNN model to accommodate the myriad anatomical nuances of root canals, ultimately leading to remarkably accurate automatic segmentation results, as evidenced in **Table 3**. Initially, the AI tool underwent training with simpler cases, such as teeth possessing a single, wide, and straight root canal. This strategic approach, focusing on less complex root

canal configurations, facilitated a progressive learning curve for the AI algorithm, akin to a curriculum-based learning strategy (Shan et al., 2021). Consequently, the tool evolved to exhibit enhanced performance in providing highly precise automatic segmentations, even for root canals characterized by complex anatomical features.

To further evaluate the AI tool's robustness, future studies should exclusively test its performance with challenging cases, focusing on teeth with highly complex root canal configurations. This approach allows researchers to clearly assess the tool's ability to accurately segment targeted data samples (e.g., those presenting intricate anatomical features). Additionally, conducting regression model analyses or subgroup analyses in these future studies would help determine the influence of variations in canal number, length, diameter, and the presence of calcifications on the AI tool's performance. Exploring the tool's performance across different patient populations and imaging settings is also recommended to ensure its reliability and applicability in various clinical contexts.

Periapical radiography serves as the primary imaging modality for diagnosis and planning in Endodontics (Hilmi et al., 2023). However, complex clinical cases may necessitate a CBCT scan to aid in establishing a more accurate diagnosis and precise treatment plan (Pinto et al., 2023). In addition, requesting a CBCT scan is a mandatory step in the digital workflow for guided endodontic access planning in challenging cases, such as calcified root canals (Chaves et al., 2023). Nevertheless, it is essential to note that a CBCT scan requires a higher radiation dose than a periapical radiograph (Pauwels R, 2015). Hence, clinicians must bear in mind that a CBCT device should provide an image with effective diagnostic quality while requiring the lowest radiation dose possible, following the ALADAIP principle (as low as diagnostically acceptable being indication-oriented and patient-specific) (Oenning et al., 2018).

The image dataset for this study was acquired from two CBCT devices, which may limit the generalization of the current results to different devices. Thus, future investigations should focus on optimizing the AI tool using data from various CBCT devices. A portion of the sample included in the present study comprises CBCT scans with large FOV, which could be considered a potential limitation. In fact, visualizing small anatomical structures like root canals is challenging in images acquired with a large FOV due to lower spatial resolution (Pinto et al., 2023). However, to achieve greater generalization of AI networks, it is necessary to include CBCT scans with larger FOVs (Fontenele et al., 2022, 2023), a choice that demonstrated no negative impact

given the overall excellent performance of the CNN model in this study for precise and fast automated segmentation of root canals. It is important to acknowledge that the set of CBCT scans used in this investigation was collected from the database of a single hospital, and the demographic characteristics of the patients were unknown. Therefore, multi-center studies are highly recommended, as they can provide an extensive and diverse dataset for training and testing AI algorithms. Additionally, CBCT scans with a high artifact expression from materials with high density were excluded; consequently, our results cannot not be extrapolated to this clinical scenario. However, it is important to emphasize that some CBCT scans included were not entirely artefact-free, considering the presence of some teeth with coronal and root fillings (e.g. metallic restorations, gutta-percha and sealer). Thus, further research is needed to test the CNN model's performance within a clinical setting with a higher expression of artifacts.

The groundbreaking results of this study reveal the remarkable high accuracy and time efficiency achieved by a unique AI-based tool for automatically segmenting single-rooted teeth on CBCT scans, surpassing human performance. These outcomes not only suggest the need for further research in automating segmentation for bi-rooted premolars and molars but also indicate the transformative potential of the developed AI tool in revolutionizing the digital workflow within endodontics. Particularly, beneficial in cases requiring guided endodontic access, this advancement may facilitate fast and precise localization of narrow root canals, thereby reducing the risk of root perforations and preserving the dentin structure. Such technologies ensure greater consistency in endodontic diagnosis and safer treatment planning. Moreover, the tool's potential application in the pre-clinical training of undergraduate and postgraduate students, specifically in accessing root canals, stands as a notable advantage. Lastly, clinicians can leverage the highly accurate 3D models of root canals to improve communication with patients, ultimately enhancing treatment acceptance.

CONCLUSION

The unique AI-based tool demonstrated an exceptional accuracy and fast performance in segmenting pulp chambers and root canals in single-rooted teeth on CBCT images, surpassing the human performance. These outcomes hold significant

for reshaping the digital workflow in Endodontics, fostering greater consistency and predictability in treatments with minimal loss of tooth hard tissue structures.

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CONFLICT OF INTEREST STATEMENT

The authors explicitly state that there are no conflicts of interest in connection with this article.

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3.2 Publicação 2*

Progress in Endodontics: A Unique AI-Based Tool for Automated Segmentation of Pulp Cavity Structures in Maxillary Premolars on CBCT

ABSTRACT

To develop and validate an artificial intelligence (AI)-driven tool for the automatic segmentation of pulp cavity structures in maxillary premolars teeth on cone-beam computed tomography (CBCT). One hundred and eleven CBCT scans were divided into training ($n = 55$), validation ($n = 14$), and testing ($n = 42$) sets, with manual segmentation serving as the ground truth. The AI tool automatically segmented the testing dataset, with errors corrected by an operator to create refined 3D (R-AI) models. The overall AI performance was assessed by comparing AI and R-AI models, and thirty percent of the test sample was manually segmented to compare AI and human performance. Time-efficiency of each method was recorded in seconds (s). Statistical analysis included independent and paired t-tests to evaluate the effect of tooth type on accuracy metrics and AI versus manual segmentation. One-way ANOVA with Tukey's post hoc test was used for time efficiency analysis. A 5% significance level was used for all analyses. The AI tool demonstrated excellent performance with Dice similarity coefficients (DSC) ranging from $88\% \pm 7$ to $93\% \pm 3$ and 95% Hausdorff distances (HD) from 0.13 ± 0.06 to 0.16 ± 0.06 mm. Automated segmentation of maxillary second premolars performed slightly better than that of maxillary first premolars in terms of intersection over union ($p = 0.005$), DSC ($p = 0.008$), recall ($p = 0.008$), precision ($p = 0.02$), and 95% HD ($p = 0.04$). The AI-based approach showed higher recall ($p = 0.04$), accuracy ($p = 0.01$), and lower 95% HD than manual segmentation ($p < 0.001$). AI segmentation (42.8 ± 8.4 s) was 75 times faster than manual segmentation (3218.7 ± 692.2 s) ($p < 0.001$). The AI tool proved highly accurate and time-efficient, surpassing human expert performance.

MeSH keywords: Artificial intelligence, Cone-beam computed tomography, Endodontics, Premolars, 3-D Imaging.

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INTRODUCTION

The integration of a digital workflow in dentistry has revolutionized daily clinical practice, enhancing patient experiences¹⁻³. Key advances in digital dentistry involve technologies, including intraoral scanners (IOS), cone-beam computed tomography (CBCT), three-dimensional (3D) impressions, augmented reality, and dynamic navigation systems^{1,4,5}. In Endodontics, the adoption of a digital workflow has enabled more assertive diagnoses, the formulation of well-suited treatment plans with a notable reduction in working time, and heightened predictability in endodontic treatment outcomes^{2,3,6}.

Among the steps in the digital workflow, the delineation (i.e., segmentation) of dentomaxillofacial hard-tissue structures in CBCT scans is acknowledged as a pivotal factor for generating highly accurate 3D models of the structures of interest. Conventionally, segmentation methods encompass semi- or fully-automated approaches to determine the correct thresholding of the object of study based on the grayscale values of voxels in CBCT scans⁷⁻⁹. However, the segmentation process is considered operator and CBCT device-dependent, often necessitating additional manual corrections that demand significant clinical time and are subject to human subjectivity⁷⁻⁹.

Technological advances in computational engineering have facilitated the development of artificial intelligence (AI)-driven tools based on convolutional neural network (CNN) models to overcome limitations inherent in traditional segmentation methods, simplifying the digital workflow^{1,10,11}. CNN, as a special type of AI algorithm based on an artificial neural network, demonstrates considerable promise in automatically segmenting digital images¹². Previous investigations reported the effective application of highly accurate and time-efficient CNN models in the automated segmentation of various anatomical and non-anatomical structures, including teeth^{10,13-15}, dental implants¹⁶, alveolar bone¹¹, mandibular canal^{17,18}, maxillary sinus¹⁹, pharyngeal airway space²⁰, and mandibular incisive canal²¹, on CBCT scans.

In this context, novel AI-driven tools offer a valuable alternative for automating the segmentation of pulp cavity structures (i.e., pulp chamber and root canal), significantly impacting clinical procedures and endodontic treatment outcomes. These tools are particularly valuable for accurately identifying the morphology of the root canal

system on CBCT scans, including anatomically complex regions such as apical deltas, narrow canals and isthmuses²². Additionally, these tools might enhance pre-clinical training by providing students with more effective access to root canals. Additionally, they can assist in analyzing large datasets for studies on root canal anatomy in different populations, offering a more comprehensive understanding of endodontic anatomical complexities^{7,23,24}. Maxillary premolars present considerable anatomical challenges during preparation, cleaning, and obturation due to their challenging root canal systems, which often include reduced apical diameter and root curvature^{25,26}. Typically, these teeth have two roots, often with multiple canals, isthmuses, and accessory canals²⁷. Canal morphology changes with age, with older patients showing increased calcification. Furthermore, males generally have a higher prevalence of multiple canals, highlighting gender-related morphological differences²⁷. The complexity is further increased by the proximity of the maxillary first and second premolars to vital anatomical structures like the maxillary sinus²⁵.

Generating highly accurate 3D models of pulp chambers and root canals in maxillary premolars can be a highly effective strategy in endodontic treatment, particularly for guided access, as it ensures precise localization of pulp cavity structures, minimizes unnecessary removal of hard dental tissue, and optimizes treatment outcomes. Additionally, these 3D models are invaluable for educational training, helping students better understand complex anatomical structures, and they enhance dentist-patient communication by allowing patients to visualize and comprehend proposed treatment plans more clearly. Despite the importance of accurate segmentation in digital endodontic workflows, there is still a significant shortage of clinically validated tools for automating this process, particularly in maxillary premolars. To address this gap, our study focuses on developing and validating an AI-driven tool specifically designed to improve reliability and efficiency in endodontic practice.

The primary objective of this investigation was to develop and validate a novel AI-based tool for the automatic segmentation of the pulp chamber and root canal in maxillary premolars on CBCT scans. The hypothesis of the study suggests that the novel AI-driven tool would offer pulp cavity segmentation for maxillary premolars with a performance below that of human experts in terms of accuracy and time efficiency.

MATERIAL AND METHODS

Ethical Aspects

The research ethics committee of University Hospitals Leuven granted ethical approval for this investigation before its initiation (protocol number: S67798). The current study adheres to the ICH-GCP principles and the World Medical Association Declaration of Helsinki on medical research. Considering the anonymization of patient data conducted before any analysis, informed consent was not required.

Dataset

Retrospectively, a set of 111 CBCT scans was retrieved from the Dentomaxillofacial Imaging Center database of UZ Leuven University Hospital in Leuven, Belgium. These scans were acquired for different purposes unrelated to the current investigation, such as endodontic treatment planning, implant planning, and oral and maxillofacial surgery procedures. The dataset was acquired using two CBCT devices: 3D Accuitomo 170 (J Morita, Kyoto, Japan) and NewTom VGi evo (Cefla, Imola, Italy). It is important to highlight that heterogeneous acquisition parameters were employed to obtain the CBCT scans: For 3D Accuitomo, 90 kilovoltage-peak (kVp), 5 milliamperere (mA), field of view (FOV) of 8×8 , 10×10 , 14×10 , and 17×12 cm, with a voxel size ranging from 0.125 to 0.250 mm. For the NewTom VGi EVO, the parameters comprised 110 kVp, 3 – 20 mA, FOV sizes of 8×8 , 10×10 , 12×8 , 16×16 , and 24×19 cm, with a voxel size ranging from 0.125 to 0.300 mm. **Figure 1** summarizes the conceptual framework of the current study design.

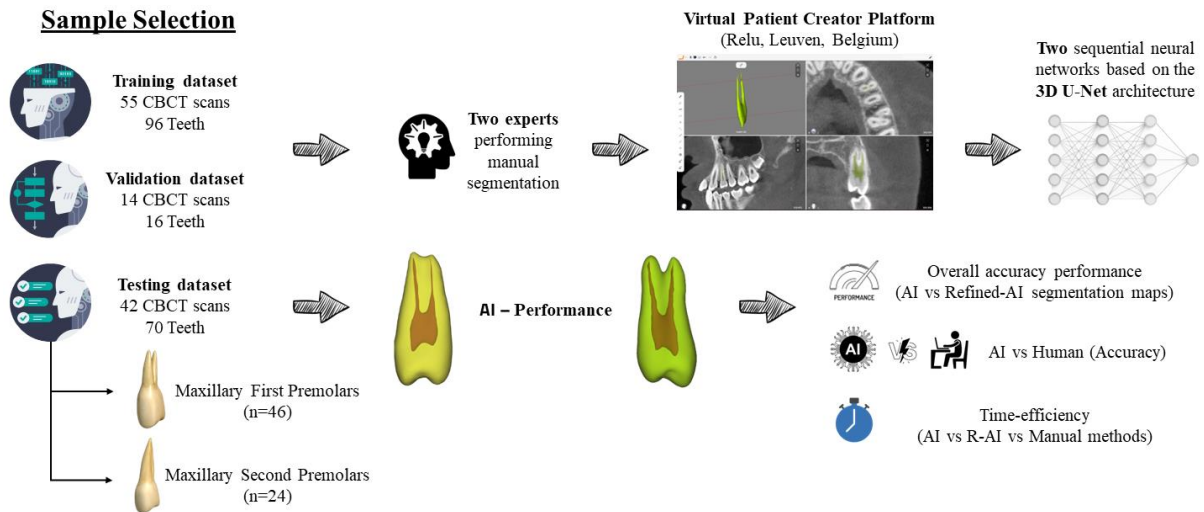


Figure 1. Conceptual framework of the study design for developing and validating an AI-driven tool for the automated segmentation of maxillary premolars.

For the selection of the imaging dataset, inclusion criteria encompassed CBCT scans from patients with a complete permanent dentition and satisfactory image quality, characterized by medium levels of sharpness and contrast, and low noise levels. This approach ensured accurate delineation of pulp chambers and root canals in maxillary premolars. CBCT scans with fields of view (FOV) covering either the maxilla alone or both the maxilla and mandible were included. Although some scans captured both arches, the analysis focused exclusively on maxillary premolars. Including scans with different FOVs aimed to enhance the generalizability of the study findings. Scans with poor image quality, such as those affected by significant artifacts from beam hardening or movement, were excluded.

The selected CBCT scans were exported in Digital Imaging and Communication in Medicine (DICOM) format and randomly distributed into the three steps of the CNN model:

- i) CNN Training (n = 55, 96 teeth): Training the AI model using manual segmentation carried out by operators as the ground truth.
- ii) CNN Validation (n = 14, 16 teeth): Conducting internal validation of the AI model by optimizing parameters until the establishment of an ideal architecture.

iii) CNN Testing (n = 42, 70 teeth): Conducting the performance assessment of the AI model through the comparison of 3D models generated entirely by AI versus those obtained from refined automated segmentation (R-AI) performed by an expert.

The DICOM files were imported into the cloud-based online platform named as “Virtual Patient Creator” (Relu, Leuven, Belgium). This interactive platform offers a set of editing tools (e.g., brush, contour, and interpolation tools) for the manual segmentation of dentomaxillofacial anatomical structures on CBCT scans. Utilizing these tools enabled the precise delineation of the limits of the pulp chambers and root canals of maxillary premolars displayed in the multiplanar reconstructions of CBCT scans.

Each pulp chamber and root canal of the maxillary premolars teeth in the training and validation dataset of the CNN model underwent manual segmentation by two operators (F.S.N., and S.S.A.). Prior to performing manual segmentation on the ground truth sample, all operators underwent training and calibration using different CBCT scans not included in the study dataset. This calibration involved manual segmentation of 10 maxillary premolars on separate CBCT scans by the two operators (F.S.N. and S.S.A.) at two different time points. The segmentation results were compared to assess intra-examiner agreement (same operator at different times) and inter-operator agreement (between the two operators) using two metrics: intersection over union (IoU) and 95% Hausdorff distance (HD). Operators were considered calibrated if the IoU and 95% HD were at least 80% and 0.20 mm, respectively, for both intra- and inter-operator agreements. An oral radiologist with 8 years of experience (R.C.F.) reviewed all manual segmentations before CNN model development and made adjustments when deemed necessary. The final segmentation maps were exported in Standard Triangle Language (STL) format and later used as input for training the CNN model.

CNN Network Architecture

The CNN model developed in this study was built based on two sequential neural networks based on the 3D U-Net architecture. Each network comprised four contracting encoder blocks and three expansive decoder blocks. These blocks included two convolutions with a standard kernel size ($3 \times 3 \times 3$), followed by rectified linear unit (ReLU) activation and group normalization with eight feature maps. The decision to adopt a two-step method stemmed from the challenges encountered when applying CNN to CBCT scans with a large FOV^{10,11}.

The first neural network detected approximate pulp chambers and root canals, generating an initial segmentation model. Subsequently, the second neural network refined the initial segmentation, enabling automatic segmentation of the structures of interest at full resolution. The CNN models were implemented in PyTorch, and increased robustness of the AI algorithm was achieved using data augmentation strategies within the training dataset. These strategies included elastic deformation, rotation, scaling, cropping, and mirroring.

Moreover, the CNN model underwent optimization using the ADAM optimization algorithm. This process included reducing the learning rate and implementing early stopping based on the validation set to prevent overfitting and ensure the effective performance of the CNN model. Subsequently, the finalized CNN model was implemented and made accessible on the online cloud-based AI platform called "Virtual Patient Creator".

CNN model testing

Automated segmentation of pulp chambers and root canals of maxillary premolars teeth was conducted using the aforementioned online platform. Each CBCT scan in DICOM format was uploaded to the platform, which then automatically segmented the pulp cavity structures for each maxillary premolar tooth, generating individual 3D models in STL format. Additionally, the platform automatically recorded the time taken to generate the segmentation map in seconds.

An experienced oral radiologist with 8 years of experience (R.C.F.) evaluated the automated segmentations of the test set to detect and correct any errors, including oversegmentation or undersegmentation, in the AI-generated 3D models. After evaluating each automated segmentation, the operator determined that all segmentation maps required some form of minor correction.

For conducting this assessment, the resliceable axes tool within the "Virtual Patient Creator" platform was employed. By activating this tool, all CBCT multiplanar reconstructions (axial, sagittal, and coronal) were aligned to be parallel to the long axis each root canal. The brush tool was utilized to add or remove voxels in the segmentation maps, using the anatomical contour of the pulp cavity structures displayed on the CBCT reconstructions as reference. Finally, a new R-AI segmentation map of the pulp cavity structures of each maxillary premolar tooth was obtained in STL format. A digital stopwatch was used to record the time taken on manual refinements.

Validation metrics

A voxel-level confusion matrix was applied to evaluate the performance of the developed AI tool. The AI and R-AI 3D models were compared, and four variables were derived:

a) False positive (FP): voxels initially identified as part of the pulp cavity structures by the CNN model but subsequently removed by the operator during the refinement of the AI segmentation.

b) False negative (FN): Voxels not initially recognized as part of the pulp cavity structures by the CNN model but later included by the operator during the refinement of the AI segmentation.

c) True positive (TP): Voxels representing the actual pulp cavity structures that were accurately segmented during the automated segmentation.

d) True negative (TN): Voxels not associated with the pulp cavity structures and correctly excluded from the automated segmentation.

The performance of the developed CNN model was assessed using the following accuracy metrics based on the aforementioned variable values: IoU, Dice similarity coefficient (DSC), Recall, Precision, Accuracy, and 95% HD (**Table 1**).

Table 1. Accuracy metrics used to evaluate the performance of the AI-based tool

Metrics		Definition	Formula
95% distance (HD)	Hausdorff	The 95 th percentile of the maximum distance between a point on the AI segmentation map and its nearest point on the segmentation map is obtained after the expert performs automated segmentation refinement (R-AI). The strategy of using the 95 th percentile is to eliminate a possible subset of outliers. A 95% HD value of 0 millimeters (mm) means perfect segmentation	$P95 \left(\min_{g \in G} \left p - g \right _2 \cup \min_{p \in P} \left g - p \right _2 \right)$
Intersection over union (IoU)		The degree of overlap between the AI and R-AI segmentation maps. An IoU of 1 means perfect segmentation	$IoU = \frac{TP}{TP + FP + FN}$
Dice coefficient (DSC)	similarity	The amount of intersection between the AI and R-AI segmentation maps. A DCS of 1 means a perfect intersection	$DSC = \frac{2 \times IoU}{1 + IoU}$
Precision		The percentage of voxels correctly identified among all voxels considered to belong to the pulp chamber and root canal by the CNN model	$Precision = \frac{TP}{TP + FP}$
Recall		The proportion of voxels belonging to the pulp chamber and root canal that were correctly identified by the CNN model	$Recall = \frac{TP}{TP + FN}$
Accuracy		The proportion of voxels successfully recognized by the CNN model among all observed voxels	$Accuracy = \frac{TP + TN}{TP + TN + FP + FN}$

Comparison between human and AI-driven segmentations

The evaluation of AI-based automated segmentation performance involved a comparison with manual segmentation performed by a human (i.e. manual segmentation). Twenty-one teeth, constituting 30% of the test sample and including both maxillary first and second premolars, were randomly selected. An experienced endodontist with experience in CBCT image analysis (A.O.S.J.) manually performed the segmentation of pulp cavity structures using the aforementioned AI platform. The operator used the contour tool to manually outline the pulp chamber and root canal boundaries for each tooth based on the axial reconstructions of the CBCT scans.

Subsequently, the resliceable axes tool was employed to align each CBCT scan parallel to the long axis of each root canal. This allowed the operator to add or remove voxels while navigating the sagittal and coronal reconstructions of CBCT scans, facilitating the establishment of an ideal 3D model for each tooth. This task was performed twice, with a 30-day interval, to evaluate the accuracy of manual segmentation. The STL files obtained from the initial and subsequent segmentation sessions for each case were compared to calculate the accuracy metrics previously described. Finally, these manual segmentation results were compared with those obtained from automated segmentation by the CNN model for each accuracy metric. A digital stopwatch was used to record the time taken to manually segment the pulp chamber and root canal of each maxillary premolar tooth.

Time-efficiency analysis

The comparison of the time needed for segmenting the pulp cavity structures of maxillary premolar teeth was conducted for the different methods investigated: manual, AI, and R-AI methods. This analysis utilized the same sample ($n = 21$) employed for assessing the accuracy of manual and AI-driven segmentation:

i) Manual segmentation: The time required for the operator to perform the manual segmentation of pulp cavity structures encompassed the duration from importing the DICOM data to the AI platform until obtaining the segmentation map.

ii) AI segmentation: The online platform recorded the time spent for the automated segmentation of pulp cavity structures until obtaining the 3D model.

iii) R-AI segmentation: The duration of manual refinements performed by the operator was recorded and combined with the time taken by the AI method.

Statistical analysis

The analysis of data was conducted using SPSS statistical software (version 24.0, IBM Corp., Armonk, NY). Descriptive data analysis involved summarizing the results with mean and standard deviation (SD) values for accuracy and time-efficiency assessment.

The normal distribution of data was verified through the Shapiro-Wilk test. For the comparison of mean accuracy metric values between the maxillary first and second premolars, the independent t-test was utilized. Similarly, to compare the performance between AI-driven and manual approaches, the paired t-test was applied. Lastly, the one-way analysis of variance (ANOVA) with the Tukey post-hoc test was conducted to compare the time needed for pulp cavity structures segmentation among the segmentation methods investigated. A significance level of 5% was adopted for all analyses.

Using GPower statistical software (version 3.1.9.2, GPower, Düsseldorf, Germany), post hoc power analyses were performed for all statistical tests performed in the study as follows: for the independent t-test, the analysis considered the difference between group means, the standard deviation, and the sample size for each group. For the paired t-test, the mean difference between paired observations, their standard deviation, and the sample size for each accuracy metric were considered. For ANOVA, the power analysis considered the minimum difference between groups, the within-group standard deviation, and the number of observations per group. Based on these parameters, the statistical power achieved ranged from 70% to 99%.

RESULTS

Table 2 presents the performance of the AI-driven segmentation through the accuracy metrics considering each maxillary premolar tooth group. Regardless of the type of maxillary premolar and the accuracy metrics, the automated segmentation based on AI showed an excellent performance with high values of IoU (ranging from $80\% \pm 10$

to $86\% \pm 5$), DSC (ranging from $88\% \pm 7$ to $93\% \pm 3$), recall (ranging from $90\% \pm 8$ to $95\% \pm 3$), precision ($87\% \pm 7$ to $90\% \pm 4$), and accuracy ($99\% \pm 0.6$ to $99\% \pm 1.0$). Additionally, a low value of 95% HD was observed (ranging from 0.13 ± 0.06 mm to 0.16 ± 0.06 mm), confirming the similarity between AI and R-AI 3D models. This indicates a minor level of refinements needed in automated segmentation (**Fig. 2**).

Regarding the effect of the maxillary premolar tooth group, the maxillary first premolars (teeth 14 and 24) demonstrated inferior performance compared to the maxillary second premolars (teeth 15 and 25) regarding IoU ($p = 0.005$), DSC ($p = 0.008$), Recall ($p = 0.02$), and 95% HD ($p < 0.001$). The maxillary first premolars had lower values for IoU ($80\% \pm 10$), DSC ($88\% \pm 7$), recall ($90\% \pm 8$), and precision ($87\% \pm 7$) compared to the maxillary second premolars, which had higher values for IoU ($86\% \pm 5$), DSC ($93\% \pm 3$), recall ($95\% \pm 3$), and precision ($90\% \pm 4$). Additionally, the maxillary first premolars exhibited a higher 95% Hausdorff distance (HD) value (0.16 ± 0.06 mm) compared to the maxillary second premolars (0.13 ± 0.06 mm). In terms of the accuracy metric, there was no statistically significant difference observed among the groups of teeth ($p = 0.87$). An illustration of the types of errors found in the 3D models obtained by the AI-based method can be seen in **Fig. 3**.

Table 3 presents the results comparing accuracy metrics between the manual and AI segmentation approaches. The AI method exhibited higher recall ($91\% \pm 7$, $p = 0.04$), accuracy ($99\% \pm 1$, $p = 0.01$), and lower 95% HD (0.14 ± 0.05 mm, $p < 0.001$) when compared to the manual approach (**Fig. 4**). However, there was no statistically significant difference observed between the segmentation methods tested in terms of IoU ($p = 0.06$), DSC ($p = 0.09$), and precision ($p = 0.33$) metrics.

Fig. 5 depicts the time required for manual, AI, and R-AI segmentation methods. The time taken by AI-driven segmentation (42.8 ± 8.4 s) and R-AI (161.8 ± 67.2 s) showed similar working times ($p = 0.95$), both significantly shorter than the manual method (3218.7 ± 692.2 s), which proved to be the most time-consuming approach ($p < 0.001$).

Table 2. Evaluation of AI-driven automated bi-rooted canal segmentation performance by teeth group using accuracy metrics

Teeth group	IoU (%) *	DSC (%) *	Recall (%) *	Precision (%) *	Accuracy (%)	95% HD (mm) *
	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
Maxillary First Premolar (n = 46, Teeth 14/24)	80 (10)	88 (7)	90 (8)	87 (7)	99 (1)	0.16 (0.06)
Maxillary Second Premolar (n = 24, Teeth 15/25)	86 (5)	93 (3)	95 (3)	90 (4)	99 (0.6)	0.13 (0.06)
<i>p</i> -value	0.005	0.008	0.008	0.02	0.87	0.04

IoU, Intersection over union; DSC, Dice similarity coefficient; HD, Hausdorff distance; n, sample size; SD, Standard deviation. Asterisk (*) indicates a statistically significant difference between the teeth groups ($P < .05$) within each accuracy metric. Statistical power analysis ranging from 70% (accuracy metric) to 98% (DSC metric).

Table 3. Comparison of manual and AI-driven segmentation methods for maxillary premolar canal segmentation, including all types of maxillary premolars (teeth 14, 15, 24, and 25)

Metrics	Manual Mean (SD) (n = 21)	AI Mean (SD) (n = 21)	<i>p</i> -value
IoU (%)	75 (7)	82 (0.9)	0.06
DSC (%)	86 (4)	90 (6)	0.09
Recall (%) *	86 (6)	91 (7)	0.04
Precision (%)	85 (7)	89 (6)	0.33
Accuracy (%) *	97 (1)	99 (1)	0.01
95% HD (mm) *	0.26 (0.06)	0.14 (0.05)	< 0.001

AI, Artificial intelligence; IoU, Intersection over union; DSC, Dice similarity coefficient; HD, Hausdorff distance; n, sample size; SD, Standard deviation. Asterisk (*) indicates a statistically significant difference between the segmentation methods within each accuracy metric ($P < .05$). Statistical power analysis of 99% for all metrics.

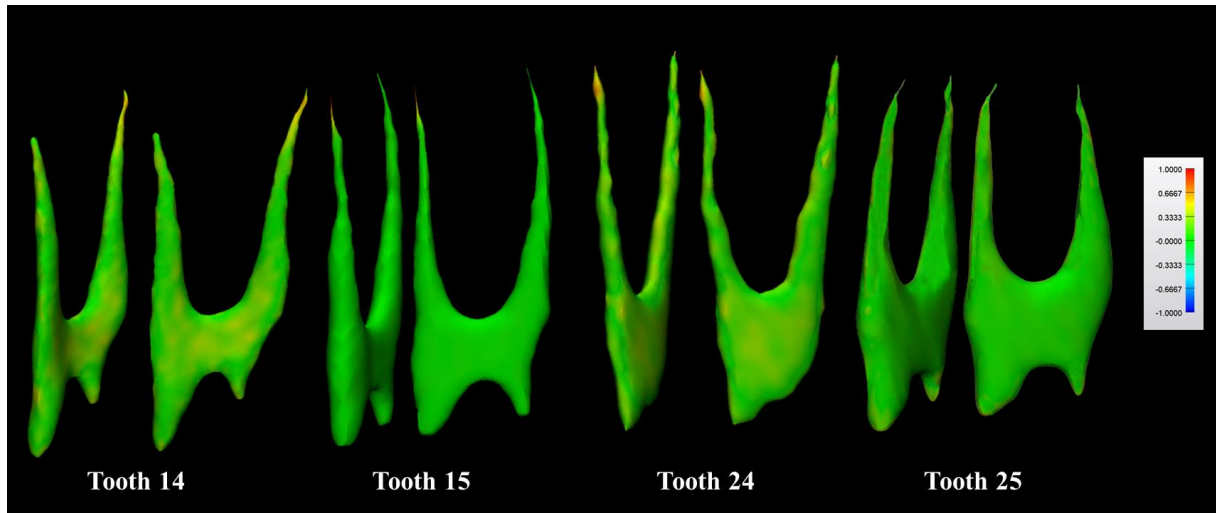


Figure 2. Comparison of STL files between AI and R-AI models for all types of maxillary premolars teeth groups (teeth 14, 15, 24, and 25) using color mapping in frontal and lateral views. The red and yellow areas indicate significant variations, emphasizing discrepancies between the AI and R-AI 3D models.

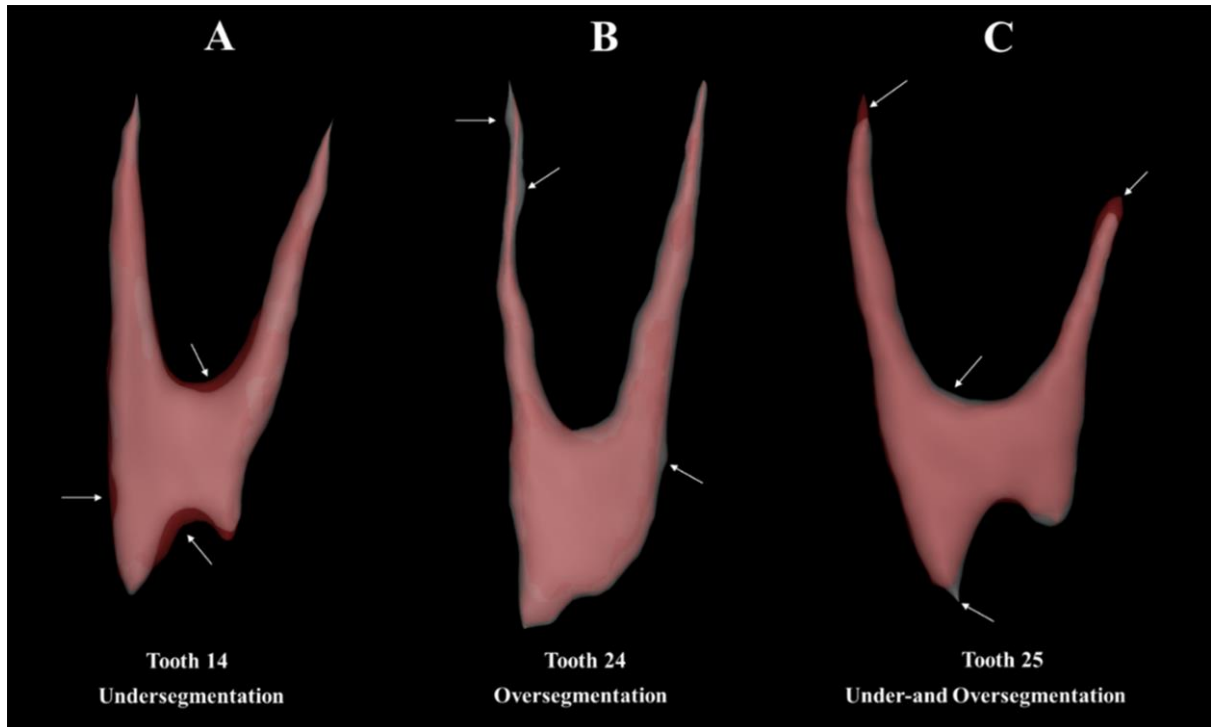


Figure 3. Three-dimensional models generated by AI illustrating errors in the automatic segmentation method. White areas (before refinements) are indicated by arrows alongside red areas (after refinements) in the root canal segmentation maps. A, Undersegmentation in the pulp chamber and root canal of the maxillary first right premolar tooth; B, Oversegmentation in the root canal of the maxillary first left premolar tooth; C, Both under- and oversegmentation in the pulp chamber and apical third of the maxillary second left premolar tooth.

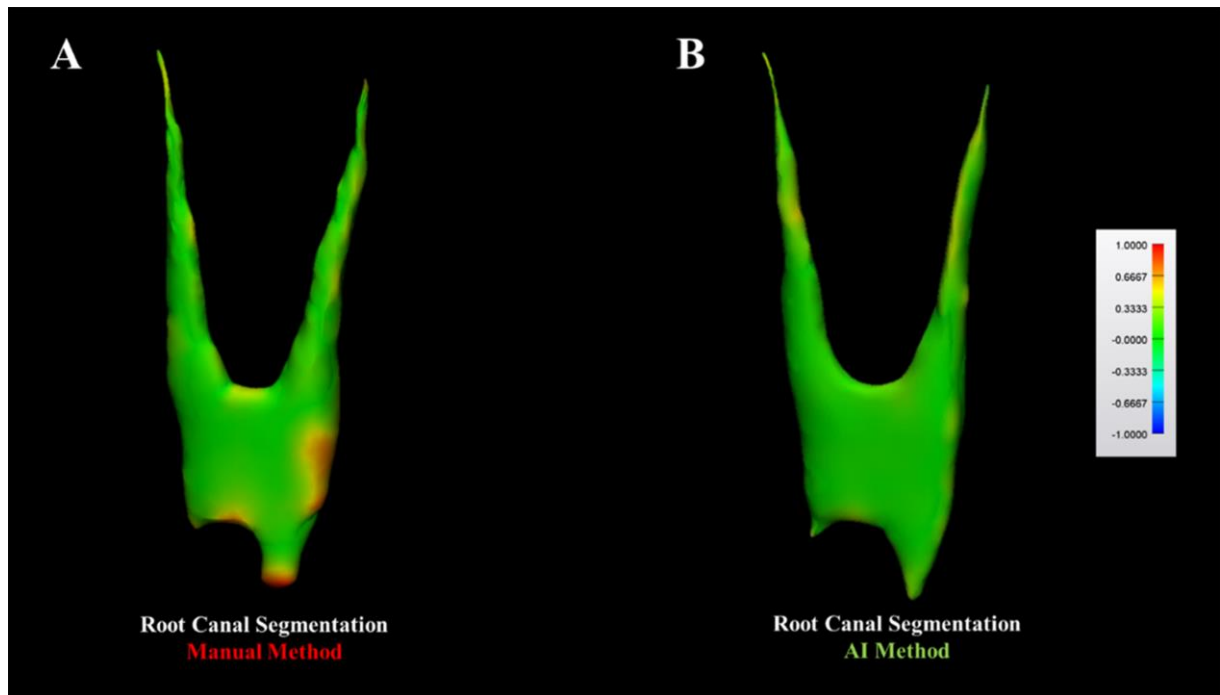


Figure 4. Comparison between manual (A) and AI (B) segmentation methods based on STL comparison using color mapping of a maxillary first right premolar tooth. The areas highlighted in red and yellow indicate significant differences between the first and second manual segmentation for the manual method and between the AI and R-AI 3D models for the AI method.

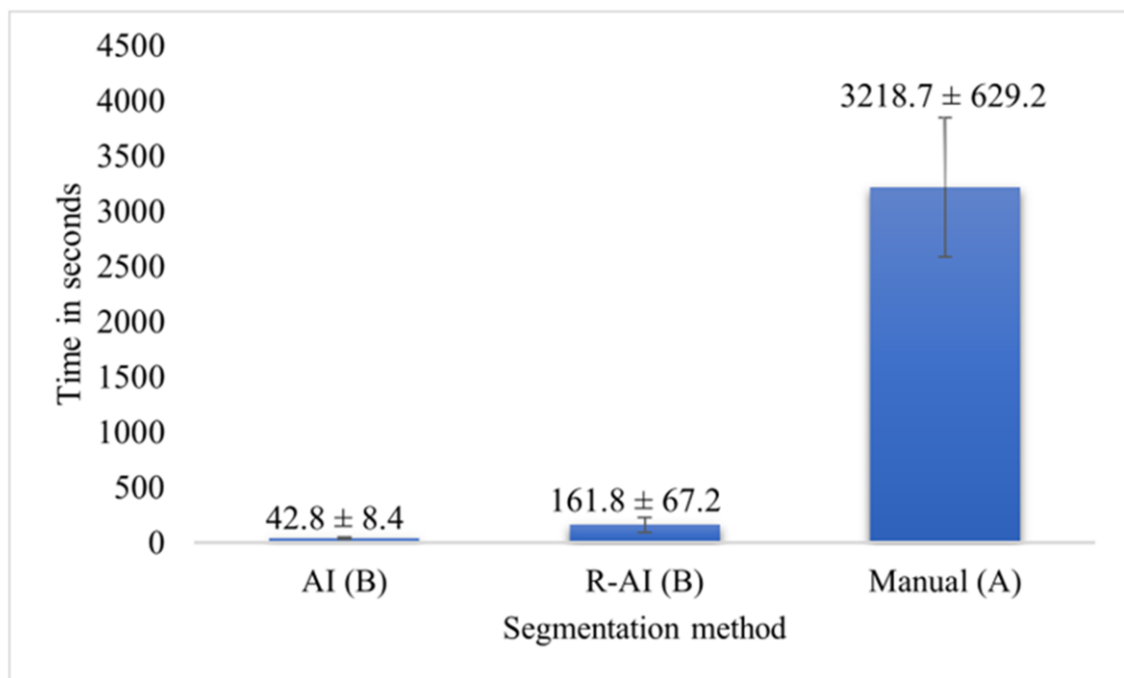


Figure 5. Time-efficiency analysis based on segmentation method. Different uppercase letters indicate statistically significant differences among segmentation methods ($p < .05$). Statistical power analysis of 0.99. AI, Artificial Intelligence; R-AI, Refined Artificial Intelligence.

DISCUSSION

Accurate segmentation of pulp cavity structures is a critical component in the digital workflow in Endodontics^{7,23,24,28}. Obtaining precise 3D models of the pulp chamber and root canal of maxillary premolar teeth could significantly enhance diagnostic efficiency for clinicians, leading to higher success rates in endodontic treatment outcomes. However, the literature has highlighted notable limitations in 3D image segmentation using thresholding-based methods, such as semi-automatic or fully-automated methods^{10,11,13}. Therefore, the present investigation developed and validated an AI-based tool for automated segmentation of the pulp cavity structures of maxillary premolar teeth on CBCT scans. The developed CNN model demonstrated outstanding performance, generating highly accurate 3D models of these fine endodontic structures in a time-efficient manner, surpassing human performance based on manual segmentation.

The innovative and promising results of this research can be attributed to the continuous curriculum learning of the developed AI algorithm²⁹. Initially, the AI-based tool was trained for the automated segmentation of less complex root canals (i.e., teeth with single root canals). Gradually, the CNN model was consistently optimized until it could provide adequate segmentation of the root canals of maxillary premolar teeth, a task considered much more complex. Consequently, the current findings revealed that the developed AI tool was capable of providing highly accurate automated segmentation of the pulp cavity structures of maxillary premolars (IoU: ranging from $80\% \pm 10$ to $86\% \pm 5$; DSC: ranging from $88\% \pm 7$ to $93\% \pm 3$; and 95% HD: ranging from 0.13 ± 0.06 mm to 0.16 ± 0.06 mm).

Based on these findings, it is conceivable that the CNN model developed in this study could serve as a potent tool in clinical practice for the automatic segmentation of pulp chambers and root canals of maxillary first and second premolars, signifying a revolution in the digital workflow in Endodontics. The segmentation of endodontic structures on CBCT scans has consistently posed a challenge in the digital workflow^{7,23,24,28}. A previous investigation proposed the use of two 3D U-Net networks for automated segmentation of the pulp chamber and root canal of single-rooted premolar teeth⁷. Although acceptable performance was reported (DSC = 87.49%, 95% HD = 1.99 mm), the authors employed 3D models obtained from micro-computed tomography data as the ground truth for evaluating the AI tool's performance, limiting

the generalizability of the results. Furthermore, the proposed CNN model struggled to provide accurate automated segmentation of the apical third of the root canals of single-rooted premolar teeth. Other studies assessed the performance of AI-based tools for automatic tooth segmentation¹³, single-rooted teeth and their root canals²³, teeth and pulp chambers of single- and multi-rooted teeth²⁸, and lower molars and their pulp chambers³⁰ on CBCT scans. However, none of these aforementioned studies focused on the development and validation of an accurate and fast CNN model for automatic segmentation of the pulp chamber and root canal of maxillary premolar teeth on CBCT scans. Therefore, direct comparisons of the current findings with previous investigations were not feasible.

Overall, the accuracy metrics in this study indicated slightly superior performance of AI-based automated segmentation for maxillary second premolars compared to first premolars. However, it is crucial to highlight that this statistical difference was relatively low, mainly due to the low values of standard deviation achieved and may not have significant influence on the performance of the CNN model developed in a clinical scenario. These results may be explained by the anatomical complexities of maxillary first premolars, such as the fact that most of the apical foramina do not coincide with the root apex, and also the significant incidence of apical delta canals^{25,31}. Additionally, this group of teeth often presents anatomical challenges on the external surface of the root, including the presence of a pronounced depression on the palatal surface of the buccal root, which can have important clinical implications in endodontic procedures²⁵. Thus, all these factors could contribute to the lower performance observed in the AI-driven segmentation of pulp cavity structures in maxillary first premolars.

Given the anatomical complexities of root canal systems, a thorough understanding of root canal morphology is crucial in digital endodontics, especially for maxillary premolars where such variations are common^{25,26,27,31}. The advent of CBCT scans has significantly improved diagnostic accuracy by providing detailed 3D imaging that surpasses traditional methods^{26,32}. Integrating CBCT scans into the management of challenging clinical cases not only enhances clinician confidence but also enhances success rates in endodontic treatment³². This technology allows for precise navigation of root canal intricacies, leading to better patient outcomes²⁶. By offering a comprehensive view of anatomical complexities, CBCT scans support the careful

selection of instrumentation techniques and optimize obturation processes, both essential for achieving favorable endodontic results³².

Manual segmentation performed by a human was used as a reference to evaluate the results of the automated segmentation provided by the AI tool developed in this study. Remarkably, the AI outperformed human intelligence, akin to a retake of the Turing test, where machines are compared to humans for conducting a specific task^{33,34}. This superiority was evident through the high recall values ($91\% \pm 7$), accuracy ($99\% \pm 1$), and low 95% HD values ($0.14 \text{ mm} \pm 0.05 \text{ mm}$). Such performance likely arises because human decision-making is inherently complex and can vary due to factors like experience level and emotional state³⁴. These human elements can introduce inconsistencies, even among skilled professionals, while AI-driven tools provide consistent and precise outcomes without such variability. It is crucial to emphasize that accuracy metrics are essential for evaluating the performance of the developed CNN model. This study's findings confirm that the AI tool is highly effective at accurately segmenting the pulp chamber and root canal in maxillary premolars, challenging the notion that human-based approaches are superior in this context. In terms of IoU, DSC, and precision metrics, no statistical differences were detected between the AI-driven segmentation and manual segmentation methods. However, even for metrics that did not exhibit a statistically significant difference, it is essential to note that the developed AI algorithm demonstrated excellent performance with significance values approaching the cut-off value determined at $p < 0.05$. Future investigations with a larger sample size are encouraged, as they could provide statistical confirmation of these results.

In this study, the AI algorithm was trained and validated using a dataset of 69 CBCT scans containing 112 teeth. To prevent overfitting, several strategies were employed, including ensuring dataset heterogeneity in terms of CBCT devices and acquisition parameters, partitioning the data for continuous monitoring, and using data augmentation techniques such as rotations, flips, and zooms. Early stopping was also applied as a regularization method to enhance training efficiency. A significant contributor to the results was the AI platform's prior training on a larger dataset of 175 CBCT scans and 500 teeth, as detailed by Shaheen et al. (2021)¹⁴ and Fontenele et al. (2022)¹⁰. This earlier training equipped the AI with strong feature extraction capabilities and a deep understanding of tooth segmentation, which accelerated the learning process for endodontic structures. Consequently, the AI-driven tool was able

to achieve saturation in the learning curve with a smaller sample size, ultimately optimizing the study's outcomes.

Time efficiency is a crucial parameter for implementing new AI-driven tools in the digital workflow in Endodontics¹³. The present study was pioneering in evaluating and comparing the time required to segment the pulp chamber and root canal of maxillary premolar teeth through various segmentation approaches. The analysis of time efficiency revealed a notable increase in speed for AI-driven segmentation (42.8 ± 8.4 s) in contrast to the manual method (3218.7 ± 692.2 s), indicating an impressive 75-fold reduction. The current findings also indicate that the R-AI segmentation method presented a low working time (161.8 ± 67.2 s), demonstrating the minor level of refinements needed. These results underscore the excellent performance of the AI algorithm developed for highly accurate automated segmentation of the endodontic structures investigated. Importantly, they suggested that when some fine-tuning of the segmentation map is necessary in clinical practice, it can be performed quickly and without consuming significant clinical time.

In the methodological design of this study, CBCT scans with varying FOV and voxel sizes were intentionally included to enhance the generalization of the developed AI tool. This approach aimed to ensure that the CNN model could perform well across different acquisition protocols commonly encountered in clinical practice. The dataset, sourced from two different CBCT devices, further contributed to the model's generalization. However, it is important to acknowledge the limitations of this investigation. One significant limitation is the need for future research to optimize the AI algorithm for application across a broader range of CBCT devices, as its performance may vary depending on the specific device used. Additionally, the study did not address the potential impact of artifacts from high-density materials (e.g., orthodontic brackets, metallic crowns, dental implants, gutta-percha, and endodontic sealers with high radiopacity) on the accuracy and efficiency of the CNN model. Moreover, although the current study demonstrated excellent accuracy and time efficiency in segmenting maxillary premolars, these results should not be generalized to multi-rooted teeth (i.e., those with more than two canals). Therefore, future research should focus on developing CNN models specifically tailored to handle these more complex scenarios. The present study is based on the development and testing of an AI-driven tool, with an architecture based on multiple 3D U-Net models. Future studies could explore the performance of other AI techniques to potentially enhance the

segmentation process. Finally, the scope of the study could be extended through multicenter studies, which are highly recommended. Such studies would allow for the collection of a larger and more diverse dataset, including populations with varying demographic characteristics. This broader data collection would significantly improve the generalization and robustness of the CNN model, ensuring its applicability in a wide range of clinical settings.

The clinical applicability of the pioneering results of the current investigation is related to the possibility of precise and fast localization of calcified root canals, preventing unnecessary removal of dental hard tissue, and potentially increasing the success rates of the guided endodontic access technique. Furthermore, clinicians could utilize highly accurate 3D models of pulp cavity structures for planning and monitoring endodontic treatment within routine clinical practice, providing patients with a greater understanding of endodontic therapy. It is crucial to underscore that while CBCT scan is not advisable for routine use in all endodontic cases, it becomes indispensable in instances of moderate to high complexity, where precise diagnosis and prognosis are critical, especially when periapical radiographs are insufficient for accurate diagnosis and treatment planning³². In these challenging scenarios, particularly when dealing with teeth that have complex root canal systems (e.g., maxillary premolars), the AI tool developed in this study provides significant value. By generating highly accurate 3D models, this technology serves as a crucial resource for clinicians, enhancing both treatment planning and execution. Additionally, the developed AI tool could serve as an invaluable resource in the educational field of endodontics. Students could use 3D models to optimize pre-clinical training on accessing root canals, thereby enhancing the teaching-learning process.

CONCLUSION

The AI-driven tool developed and validated in this study achieved highly precise automatic segmentation of pulp cavity structures in maxillary premolars with minimal processing time. It demonstrated slightly better accuracy in segmenting maxillary second premolars compared to first premolars, with both results being clinically satisfactory. Notably, the AI outperformed human experts in manual segmentation, underscoring its potential to revolutionize endodontic procedures. This advancement

is especially significant in clinical scenarios requiring minimally invasive techniques for precise root canal localization, particularly in cases of root canal obliteration where guided endodontic access is crucial.

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CONFLICT OF INTEREST

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

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3.3 Publicação 3*

Enhancing Void Detection in Long-Oval Root Canals: Assessing the Impact of the Blooming Artifact Reduction Filter on CBCT Images

ABSTRACT

Introduction: This study evaluated the effectiveness of the blooming artifact reduction (BAR) filter for detecting voids in root canals filled with various sealers, using two cone-beam computed tomography (CBCT) devices and micro-computed tomography (micro-CT) as a reference. **Methods:** Twenty mandibular central incisors with long-oval root canals were filled with AH Plus Jet (AHPJ) or Bio-C Sealer (BCS). Each tooth was placed in the mandibular alveolar socket of a dry skull, covered with Mix-D material, and scanned with VeraView X800 and OP300 Maxio CBCT devices. Micro-CT images served as a reference. Three examiners assessed the CBCT scans with and without the BAR filter (CDT Software, Bauru, SP, Brazil) for void detection in the cervical/middle thirds and in the apical third of the root canals using a 5-point scale, and diagnostic values were compared using multi-way analysis of variance ($\alpha = 5\%$). **Results:** For the OP300 device, using the BAR filter significantly improved ROC curve values for detecting voids in the apical third with AHPJ and BCS ($P < .05$). It also increased specificity for detecting voids in the apical third with AHPJ ($P < .05$). For the VeraView X800 device, the ROC curve and sensitivity values were unaffected ($P > .05$) but using BAR filter significantly enhanced specificity for detecting voids in the cervical/middle thirds with BCS ($P < .05$). **Conclusions:** The diagnostic performance of the BAR filter is CBCT-device dependent. In OP300 scans, it significantly enhances the detection of voids in the apical third with AHPJ and BCS sealers. In VeraView X800 scans, it markedly improves specificity for detecting voids in the cervical/middle thirds with BCS sealer.

KEY WORDS Blooming artifact; cone-beam computed tomography; micro-computed tomography; root canal obturation; void detection

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INTRODUCTION

Three-dimensional obturation of the root canal system is essential for the success of endodontic treatment¹. However, root canal morphology has a direct influence on the quality of the obturation^{2,3}. Filling of root canals with a long-oval cross-section are more challenging due to their large buccolingual extensions⁴. Consequently, there is a higher possibility of voids in the filling of these root canals^{2,3}. Voids are defined as spaces within the filling material that can harbor microorganisms, allowing bacterial growth and reinfection of the root canal, ultimately leading to the failure of endodontic treatment⁵. In the clinical context, the detection of voids in the obturation of root canals is essential¹⁻⁶. In cases of suspected endodontic treatment failure, it is crucial to examine the obturation in order to plan a retreatment or identify the causes of failure, thus avoiding unnecessary tooth extraction⁶.

Periapical radiography plays a crucial role in the planning and throughout all stages of endodontic treatment⁷. However, its two-dimensional nature presents challenges in detecting voids within root canal fillings⁸. Alternatively, cone-beam computed tomography (CBCT) has gained popularity as the primary three-dimensional (3D) imaging modality in endodontic diagnosis and planning, offering advantages over periapical radiography⁹. Despite these advantages, CBCT scans can be challenging when high-density materials and those with high atomic numbers, such as endodontic sealers, gutta-percha, and intracanal metal posts, produce artifacts that degrade image quality and, consequently, affect diagnostic image evaluation¹⁰⁻¹².

Bio-C Sealer (Angelus, Londrina, PR, Brazil) is a bioceramic endodontic sealer containing zirconium oxide as a radiopacifier, with radiopacity values ranging from 5.5 to 7.12 millimeters of aluminum (mm Al)^{13,14}. On the other hand, AH Plus Jet (Dentsply DeTrey, Konstanz, Germany) is an epoxy resin-based root canal sealer containing zirconium oxide combined with calcium tungstate, which results in high radiopacity (over 9 mm Al)^{13,14}. Such differences in radiopacity values can result in distinct artifacts on CBCT scans¹¹. A notable artifact is volumetric distortion, commonly referred to as blooming. This artifact causes the digitized volume to be overestimated, resulting in compromised image quality and diagnostic accuracy¹⁰⁻¹².

While it may not be feasible to completely eliminate artifacts, various strategies can optimize CBCT image quality. These include pre-processing techniques such as

activating the metal artifact reduction (MAR) tool¹⁵ or applying post-processing filters¹⁶. Among these, the blooming artifact reduction (BAR) filter, integrated into the e-Vol software (CDT Software, Bauru, SP, Brazil), was specifically developed to reduce volumetric distortion artifacts¹⁷. The BAR filter enhances brightness and contrast by leveraging the maximum dynamic range of the Digital Imaging and Communication in Medicine (DICOM) files¹⁸. This improvement makes the BAR filter a promising tool for better detection of voids within filling materials on CBCT scans¹⁹. However, to the best of our knowledge, there is no evidence on how the BAR filter impacts the diagnostic accuracy of void detection in endodontically treated teeth.

Therefore, the aim of this study was to assess the impact of the BAR filter on the detection of voids in long-oval root canals of mandibular incisors filled with AH Plus Jet or Bio-C Sealer on CBCT scans from different CBCT devices using micro-computed tomography (micro-CT) images as reference. The null hypothesis was that the use of the BAR filter would not affect the detection of voids regardless of the CBCT device and sealers.

MATERIAL AND METHODS

Sample Size Calculation

The G* Power software (version 3.1.7 for Windows; Heinrich Heine Universitat Dusseldorf, Dusseldorf, Germany) was used to perform the sample size calculation with an alpha error of 0.05 and beta power of 0.80. A previous study¹¹ was used to determine the specific effect size = 1.39. Consequently, it was determined that a total of 10 specimens per group would be the ideal sample size required.

Ethical Implications and Sample Selection

After approval by the Institutional ethics committee (CAAE #41916720.7.0000.5416), 20 human mandibular central incisors were selected. The selection was performed using a digital radiography system (RVG 6100; Kodak Dental Systems, Rochester, NY) and micro-CT scans with a voxel size of 24.5 µm (SkyScan 1272; Bruker-microCT, Kontich, Belgium). The selected root canals were classified as type I according to Vertucci's classification²⁰, with no previous endodontic treatment, fully formed apices, and were free of root cracks/fractures, calcifications, and internal and external resorptions. All root canals included in the study had a long-oval cross-section, with the buccolingual diameter being 2 to 4 times larger than the mesiodistal diameter²¹ at 9 mm from the radiographic apex²². Exclusion criteria comprised teeth with extensive coronal destruction, previous endodontic treatment, open apices, and external or internal root resorption.

Root Canal Preparation

Conventional access cavities were made with a #1012 diamond bur, followed by initial exploration of the root canals with a #10 K-file (Dentsply Sirona, Ballaigues, Switzerland). The working length (WL) was determined by subtracting 1.0 mm from the measurement obtained when the tip of the #10 K-file was visible at the apical foramen. Root canal preparation was performed with Reciproc Blue R40 instruments (VDW GmbH, Munich, Germany), driven by the X-Smart Plus electric motor (Dentsply Sirona, Ballaigues, Switzerland), set to the "Reciproc All" function according to the manufacturer's instructions. The instrument was gradually introduced into each root canal, with in-and-out movements in the cervical, middle, and apical thirds, up to the

WL. Two brushing movements were then made towards the buccal and lingual walls to reach the flattened areas of the root canal²³. For the irrigation step, 6 mL of 2.5% sodium hypochlorite (NaOCl; Ciclo Farma, Serrana, SP, Brazil) was used, 2 mL for each third (cervical, middle, and apical), using a 30-G NaviTip needle (Ultradent, South Jordan, UT) adapted to a 5 mL syringe (Ultradent), positioned 2 mm short of the WL.

To optimize cleaning after preparation with Reciproc Blue R40, all root canals underwent passive ultrasonic irrigation (PUI) protocol using the Irrisonic ultrasonic tip (Helse Ultrasonic, Santa Rosa de Viterbo, São Paulo, Brazil). According to the manufacturer's instructions, the Irrisonic tip was activated at 10% power and 50 Hz frequency with the Newtron® Booster ultrasonic device (ACTEON, North America, NJ, United States). The tip was positioned 2 mm short of the WL within each root canal and moved gently in-and-out without contacting the root canal walls. Each root canal was subjected to three agitation cycles of 20 seconds each. During the first and third cycles, 2 mL of 2.5% NaOCl was used, while the second cycle involved 2 mL of 17% EDTA. Following the cycles, a final irrigation was performed with 5 mL of distilled water on each sample, following the protocol outlined by Pinto et al²⁴.

Root Canal Filling

After root canal preparation, the specimens were divided into two experimental groups ($n = 10$ each) using simple stratified randomization. This approach ensured that the post-preparation volume (mm^3) of the root canals, measured by the CTAn software (v.1.14.4, Bruker-microCT), was similar across groups to maintain consistency during the obturation phase.

For obturation, all root canals were filled using the single-cone technique with either AH Plus Jet or Bio-C Sealer ($n = 10$ each). R40 gutta-percha principal cones (VDW GmbH) were selected using a profilometer device (Profile Projector Nikon model 6C-2; Nikon, Tokyo, Japan). Digital radiographs were taken in the mesiodistal and buccolingual directions to confirm the adaptation of the gutta-percha cones at the WL. For AH Plus Jet sealer, it was inserted into the root canals using a Lentulo spiral #40, coupled with a low-speed motor (Micromotor N270 and contra angle, Dabi-Atlante, Ribeirão Preto, SP, Brazil), positioned 2 mm short of the WL. In addition, #40 K-files were also used with in-and-out movements up to the WL.

In canals filled with Bio-C Sealer, the sealer was injected using syringes and plastic needles, positioned 4 mm from the WL, following the manufacturer's

recommendations. The syringe plunger was gently pressed until the Bio-C Sealer flowed back to the pulp chamber, indicating complete filling of the root canals. The R40 gutta-percha cones were coated with the respective sealers according to each experimental group and inserted into the canals up to the WL. Excess filling material was then removed and vertically condensed with a #2 heat plugger (Golgran, Sao Caetano do Sul, SP, Brazil). Digital radiographs were taken in the mesiodistal and buccolingual directions to ensure adequate filling of all samples.

Finally, the teeth were restored with Coltosol (Vigodent, Rio de Janeiro, Brazil) and stored in an oven at 37 °C and 95% humidity for 7 days to allow complete setting of the endodontic sealers.

Micro-CT Acquisition

To obtain a gold standard reference for comparisons with CBCT scans, each tooth was individually scanned using a high-resolution micro-CT device (SkyScan 1272; Bruker-microCT). The scanning parameters were set as follows: voxel size of 9 µm, a 1 mm aluminum filter, exposure time of 2500 ms, a 180° rotation around the vertical axis, a 0.5° rotation step, 80 kV and 125 µA.

CBCT Acquisition

An anthropomorphic model, consisting of a dry human skull and a fully dentate mandible, was used to acquire the CBCT scans. The entire phantom was covered with Mix-D, a soft-tissue simulator material designed to replicate the X-ray attenuation of human soft tissue, as previously described²⁵. Additionally, a tongue model made from the same material was attached to the lingual region of the mandible (**Figure 1**). Subsequently, the mandibular left central incisor of the dry mandible was delicately removed, and the teeth with previously selected long-oval root canals were individually placed into the empty socket. For each tooth specimen, the complete phantom was scanned using two CBCT devices: VeraView X800 (J Morita, Tokyo, Japan) and OP300 Maxio (Instrumentarium Dental, Tuusula, Finland). The acquisition protocols for each device are detailed in **Table 1**. Subsequently, the CBCT scans were exported in DICOM format.

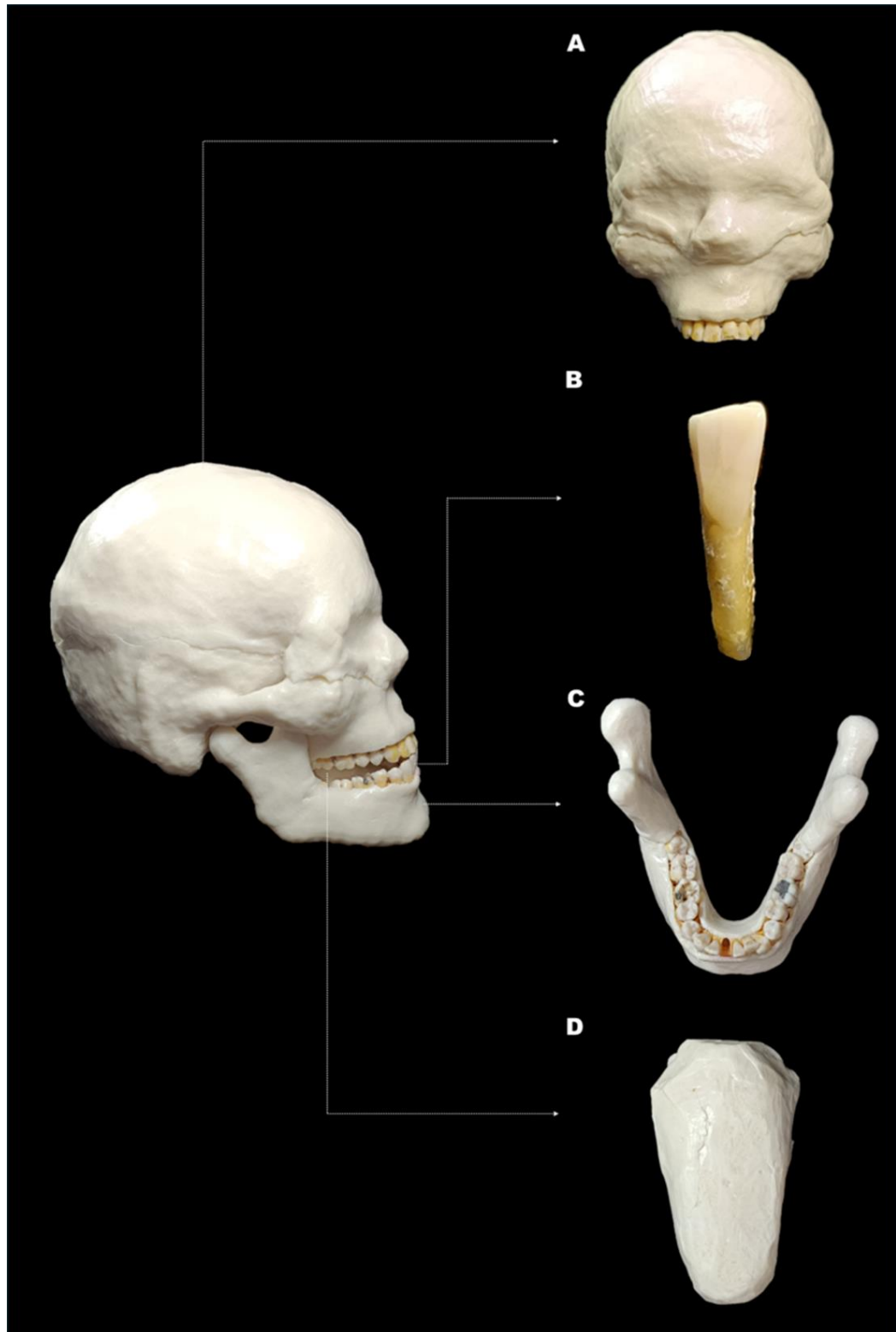


Figure 1. Anthropomorphic phantom consisting of a dry human skull with the mandible, both covered in Mix-D, along with a tongue model made with Mix-D. **(A)** Frontal view of the dry human skull; **(B)** Frontal view of the mandibular left central incisor; **(C)** Occlusal view of the mandible; **(D)** Tongue model made with Mix-D.

Table 1. Acquisition parameters of the cone-beam computed tomography dataset

CBCT device	kVp	mA	FOV (mm)	Voxel size (mm)
VeraView X800	70	5	40 x 40	0.08
OP300 Maxio	90	8	50 x 50	0.08

CBCT: cone-beam computed tomography; kVp: kilovoltage-peak; mA: milliamperes; FOV: field of view; mm: millimeters.

Micro-CT Image Evaluation

Each tooth's images were individually reconstructed using NRecon software (v.1.6.3, Bruker-microCT). The micro-CT images, serving as the reference standard, were then analyzed by an experienced operator (F.F.E.T) possessing extensive experience in microtomographic image evaluation. Each root canal was individually assessed for the detection of voids in the cervical/middle thirds (6 mm) and the apical third (3 mm), using the CTAn software (Bruker-microCT). A score of 0 was assigned if no voids were detected, while a score of 1 was given if voids were present. The same analysis was repeated to assess inter-rater agreement after 30 days.

CBCT Image Evaluation

Each CBCT scan was randomly allocated to one of two evaluation phases—either with or without the BAR filter—using the "RAND" function in Excel (Microsoft Co., Redmond, WA, USA). This process ensured that after each evaluation, the scans received a random code different from their original designation. Evaluations were conducted independently by an experienced oral radiologist (A.F.L), with over 20 years of practice, and two endodontics specialists (A.O.S.J and J.C.P), all highly skilled in image analysis.

Prior to the image analysis, the examiners underwent a calibration process involving CBCT scans that displayed voids and void-free regions in different thirds of the root canals (cervical/middle and apical). These calibration images were not used in the actual assessment. The examiners were kept unaware of the factors under study, including the presence or absence of voids in the filling material, the type of endodontic sealer, and the specific CBCT device used.

Examiners were instructed to realign the multiplanar reconstructions of the CBCT scans with the long axis of the root and to perform a dynamic examination of each CBCT scan in the axial, sagittal, and coronal planes. All CBCT scans were analyzed using the e-Vol DX software on a 25-inch color LED monitor with a resolution of 2560 x 1080 pixels, in a low-light and quiet room. Examiners were advised to thoroughly evaluate all CBCT scans across the different root thirds (i.e., cervical/middle and apical).

To ensure a standardized assessment of root canal fillings, each root was divided into two segments based on the location of the filling material. The first axial reconstruction that showed the filling material in the cervical third and the last axial reconstruction that displayed it in the apical third were used to determine the length of the root. This allowed for consistent measurement of each root into two segments: 6 mm for the cervical/middle thirds and 3 mm for the apical third. This approach ensured that all observers assessed the root canals in a standardized manner, as described by Fontenele et al²⁶. The detection of voids was carried out in two distinct steps:

Step 1: The examiners could manually adjust the brightness and contrast settings according to their preferences. The BAR filter was kept deactivated during this step.

Step 2: In the subsequent analysis, all CBCT scans were assessed with the BAR filter activated. Examiners used different intensities of the BAR filter (i.e., BAR 1, 2, 3, 4, or 5) to thoroughly examine the presence or absence of voids in the filling material.

Each CBCT scan was evaluated using a 5-point confidence scale to classify voids within the filling material across different root thirds: (1) no voids, (2) probable no voids, (3) uncertain, (4) probable presence of voids, and (5) presence of voids. To avoid visual fatigue, a maximum of 20 CBCT volumes were evaluated per day, with at least 24 hours between evaluation sessions. To verify intra- and inter-observer reproducibility, 30% of the sample was randomly selected and re-evaluated 30 days after the initial analysis.

Fig. 2 shows an example of a void present within the filling material, comparing the reference image (micro-CT axial reconstruction) with the corresponding visualization on each CBCT device tested (OP300 Maxio and VeraView X800).

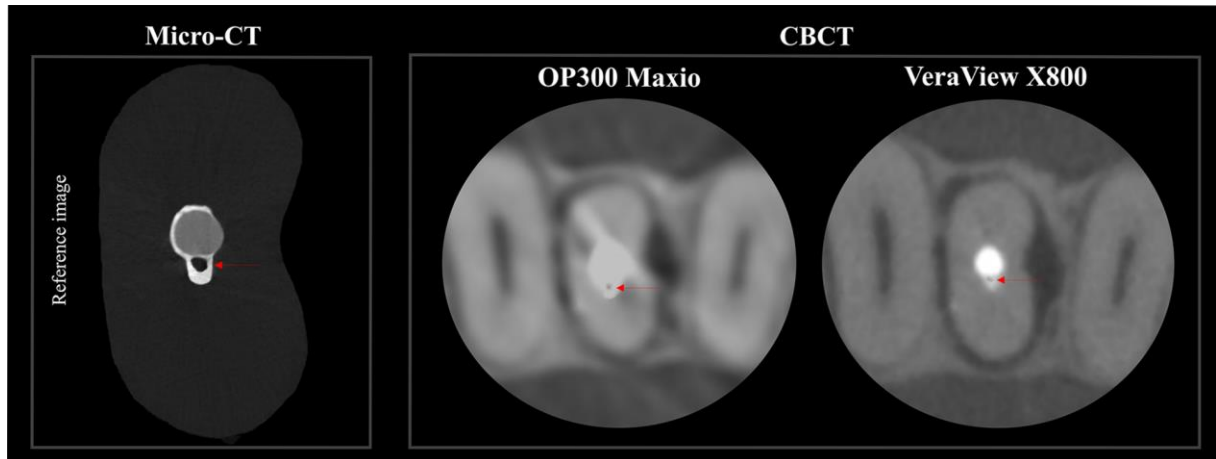


Figure 2. Axial reconstructions of the same specimen, obtained using micro-CT as a reference and CBCT scans from the OP300 Maxio and VeraView X800 devices, with red arrows indicating voids within the filling material.

Statistical Analysis

Statistical analyses were performed using MedCalc (version 22.0, MedCalc Software Ltd., Ostend, Belgium) and SPSS software (version 24.0, IBM Corp., Armonk, NY). Intra- and inter-observer agreements were assessed using the weighted Kappa index and interpreted based on the Landis and Koch scale²⁷. Diagnostic metrics, including the area under the receiver operating characteristic (ROC) curve, sensitivity, and specificity for void detection, were calculated for each studied factor (BAR filter use, type of endodontic sealer, and root canal third) within each CBCT device. Statistical comparisons were conducted using multi-way analysis of variance (ANOVA) with Tukey's post-hoc test. A significance level of 5% was used for all analyses.

RESULTS

Regarding intra- and inter-observer reliability, the intra-examiner agreement for evaluating CBCT scans was classified as moderate, with weighted Kappa values ranging from 0.50 to 0.52. The inter-examiner agreement for these scans ranged from moderate (0.47) to almost perfect (0.94). Moreover, the intra-examiner agreement for the micro-CT images, which served as the gold standard, indicated perfect calibration by the examiner, with a weighted Kappa value of 1.00, according to the Landis and Koch scale²⁷.

The micro-CT assessment of void distribution in different root canal thirds shows a consistent pattern regardless of the sealer used (**Table 2**). For both AH Plus Jet and Bio-C Sealer, voids were observed in 70% of the teeth in the cervical/middle thirds and in 60% of the teeth in the apical thirds.

Table 3 presents the diagnostic performance metrics—mean area under the ROC curve (AUC), sensitivity, and specificity values—for void detection, categorized by the use of the BAR filter, sealer type, and root canal third for the OP300 Maxio device. The use of the BAR filter significantly improved the AUC for detecting voids in the apical root third for both AH Plus Jet and Bio-C Sealer ($P < .05$). Without the BAR filter, both AH Plus Jet and Bio-C Sealer had an AUC value of 0.53 in the apical third. When the BAR filter was applied, the AUC values significantly increased, with AH Plus Jet reaching 0.72 and Bio-C Sealer reaching 0.65 ($P < .05$) (**Figure 3**). This improvement was statistically significant depending on the root third assessed for both sealers ($P < .05$). Specifically, the apical third (AUC of 0.72 for AH Plus Jet and 0.65 for Bio-C Sealer) showed higher AUC values compared to the cervical/middle root thirds (AUC of 0.61 for AH Plus Jet and 0.53 for Bio-C Sealer). Sensitivity values were not significantly influenced by the factors investigated ($P > .05$). However, specificity values were influenced by the type of sealer when using the BAR filter in the apical third ($P < .05$). In this context, AH Plus Jet demonstrated higher specificity (1.00) compared to Bio-C Sealer (0.42).

Table 4 presents the diagnostic performance for void detection according to the studied factors for the VeraView X800 device. The AUC and sensitivity values were not significantly influenced by the use of the BAR filter, sealer type, or root third ($P > .05$). However, the use of the BAR filter significantly improved the specificity for detecting voids in the cervical/middle root thirds when Bio-C Sealer was present ($P < .05$). Specifically, with the BAR filter, the specificity value increased from 0.58 to 1.00 (**Figure 4**).

Table 2. Distribution of teeth (percentage) regarding the presence or absence of voids in different root canal thirds based on sealer type in micro-CT assessment

Sealer	Cervical/ Middle		Apical	
	Absence	Presence	Absence	Presence
AH Plus Jet (10 Teeth)	3 (30)	7 (70)	4 (40)	6 (60)
Bio-C Sealer (10 Teeth)	3 (30)	7 (70)	4 (40)	6 (60)

Table 3. Mean (standard deviation) of the area under the receiver operating curve (AUC), sensitivity, and specificity values for the detection of voids based on BAR use, sealer, and root third in the OP300 Maxio device

BAR	Sealer	Root third	AUC	Sensitivity	Specificity
Without BAR	AH Plus Jet	Cervical/Middle	0.60 (0.01)	0.39 (0.00)	0.86 (0.01)
		Apical	0.53 (0.02)	0.40 (0.34)	0.80 (0.35)
	Bio C-Sealer	Cervical/Middle	0.57 (0.06)	0.73 (0.14)	0.50 (0.00)
		Apical	0.53 (0.02)	0.45 (0.48)	0.58 (0.29)
With BAR	AH Plus Jet	Cervical/Middle	0.61 (0.03)	0.63 (0.21)	0.67 (0.17)
		Apical	0.72 (0.07) *#	0.47 (0.11)	1.00 (0.00) +
	Bio C-Sealer	Cervical/Middle	0.53 (0.00)	0.67 (0.04)	0.50 (0.00)
		Apical	0.65 (0.03) *#	1.00 (0.00)	0.42 (0.14)

indicates a statistically significant difference in the use of BAR within the sealer and root third investigated ($p < 0.05$).

* indicates a statistically significant difference between the root thirds within both sealer and BAR conditions ($p < 0.05$).

+ indicates a statistically significant difference between the sealers within both root third and BAR conditions ($p < 0.05$).

Table 4. Mean (standard deviation) of the area under the receiver operating curve (AUC), sensitivity, and specificity values for the detection of voids based on BAR use, sealer, and root third in the VeraView X800 device

BAR	Sealer	Root third	AUC	Sensitivity	Specificity
Without BAR	AH Plus Jet	Cervical/Middle	0.67 (0.08)	0.51 (0.17)	0.80 (0.00)
		Apical	0.62 (0.04)	0.60 (0.20)	0.70 (0.10)
	Bio C-Sealer	Cervical/Middle	0.56 (0.04)	0.61 (0.29)	0.58 (0.29)
		Apical	0.54 (0.04)	0.56 (0.20)	0.50 (0.00)
With BAR	AH Plus Jet	Cervical/Middle	0.66 (0.10)	0.64 (0.27)	0.67 (0.11)
		Apical	0.56 (0.00)	0.40 (0.00)	0.80 (0.00)
	Bio C-Sealer	Cervical/Middle	0.82 (0.17)	0.66 (0.31)	1.00 (0.00) #
		Apical	0.72 (0.16)	0.61 (0.38)	0.83 (0.14)

indicates a statistically significant difference in the use of BAR within the sealer and root third investigated ($p < 0.05$).

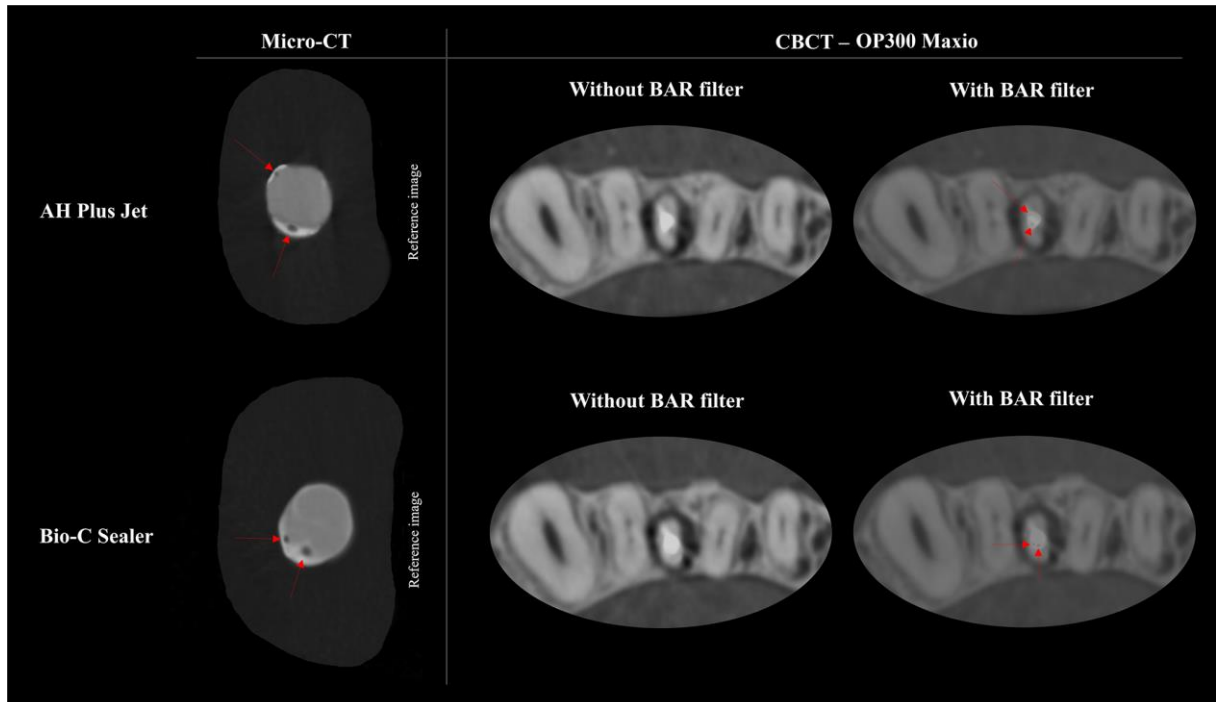


Figure 3. Examples of voids present in the apical third of long oval root canals filled with AH Plus Jet and Bio-C Sealer. Axial reconstructions of CBCT scans without the BAR filter do not reveal these voids. However, with the application of the BAR filter, the voids become visible, as indicated by the red arrows. The presence of these voids is confirmed by reference micro-CT images, also highlighted with red arrows.

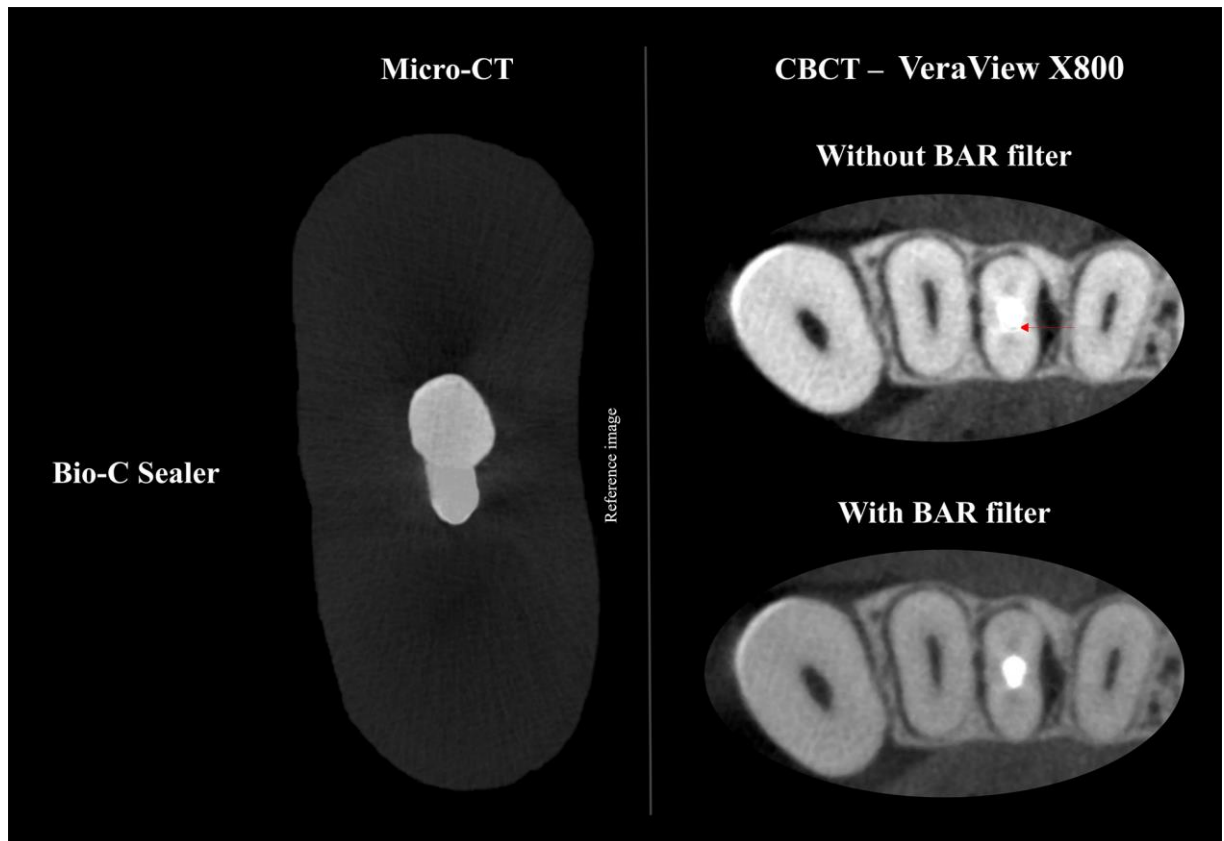


Figure 4. An example of an axial reconstruction of the CBCT scan showing a false positive detection of a void in the cervical/middle thirds of a canal filled with Bio-C Sealer, as indicated by the red arrow. After applying the BAR filter, the absence of the void was confirmed, as also seen in the reference micro-CT image.

DISCUSSION

Detecting voids in root canal fillings using CBCT scans is challenging in clinical practice, mainly due to beam-hardening and blooming artifacts⁶. These artifacts create hyperdense halos around high-density materials such as gutta-percha, endodontic sealers, and intracanal metal posts, as well as cause dimensional changes in these materials. This can lead to a false impression that the root canal is completely filled^{6,10-12,28}. This study is the first to evaluate the effect of the BAR filter on void detection in long-oval root canals of mandibular incisors filled with two endodontic sealers of different radiopacity. The overall findings were promising, indicating that the BAR filter significantly enhanced diagnostic accuracy for void detection across various contexts, ultimately refuting the null hypothesis.

The current findings indicate that applying the BAR filter to CBCT scans obtained with the OP300 Maxio device significantly improved the accuracy of void detection in the apical third of root canals filled with AH Plus Jet and Bio-C Sealer. With the BAR filter enabled, the AUC values for detecting voids in the apical third of root canals increased from 0.53 to 0.72 for AH Plus Jet and from 0.53 to 0.65 for Bio-C Sealer, approaching the ideal AUC values of 1.0, which signifies perfect accuracy **(Figure 3)**. This improvement can be attributed to the enhanced grayscale contrast provided by the BAR filter¹⁶⁻¹⁹, which significantly reduces blooming artifacts caused by intracanal materials (i.e., high-density materials) such as endodontic sealer and gutta-percha.

In addition, the current study showed that the specificity values for void detection with the OP300 Maxio device varied with the type of endodontic sealer used. AH Plus Jet, which has higher radiopacity, achieved a higher specificity (1.00) compared to Bio-C Sealer (0.42) in the apical third of the root canals. This is clinically significant because root canals filled with AH Plus Jet are more prone to blooming artifacts due to their high radiopacity, making void detection more difficult^{6,10-12}. The increased specificity for AH Plus Jet means that examiners were better able to accurately identify voids in the apical third, reducing the risk of false positives and avoiding unnecessary treatment (e.g., endodontic retreatment or tooth extraction)⁶. Therefore, using the BAR filter to evaluate CBCT scans of teeth filled with AH Plus Jet, when acquired with the OP300

Maxio device, can significantly enhance diagnostic accuracy. This improvement helps clinicians accurately identify voids in the filling material, reducing the risk of misdiagnosis and unnecessary treatments, and ultimately leading to better endodontic outcomes.

The diagnostic performance varied between different regions of the root canal when the BAR filter was applied to the OP300 Maxio scans. The AUC values were higher in the apical third compared to the cervical/middle thirds, regardless of the endodontic sealer. These differences can be attributed to the different cross-sections of the long-oval root canals used in this study. The apical third has a smaller volume compared to the cervical/middle thirds, resulting in a reduced amount of sealer^{2,3}. As a result, the expression of blooming artifacts may have caused a greater overestimation of sealer volume in the cervical/middle thirds^{6,10-12}. The greater amount of endodontic sealer in these areas may have limited the diagnostic performance in detecting voids even when the BAR filter was applied, as the expansion of the material may have masked the voids present. Nonetheless, the current findings are of great clinical importance because the apical third is the most critical zone of the root canals due to its complex anatomy, which includes ramifications, lateral canals, and apical delta, complicating proper preparation, disinfection, and obturation^{29,30}. Potentially, this effect of the root region was not observed in the images without the BAR filter due to the higher expression of artifacts throughout the root canal, regardless of the region. These artifacts compromised the image quality of the entire root.

CBCT scans acquired with the VeraView X800 device showed no significant influence from the variables analyzed in this study on AUC and sensitivity values. Potentially, these factors did not affect these diagnostic metrics on the VeraView X800 due to the overall higher accuracy metrics regardless of the use of the BAR filter, endodontic sealer, or root canal third. This can be attributed to the physical and technical characteristics of each CBCT device³¹. In this investigation, all CBCT scans were obtained using a high-resolution protocol that incorporated a smaller voxel size (0.08 mm) and the smallest available FOV on both devices (40 x 40 mm for the VeraView X800 and 50 x 50 mm for the OP300 Maxio). Previous studies have demonstrated that blooming artifacts are influenced by several factors, including voxel size, kilovoltage, tube current, detector pixel size, and FOV size^{6,10,11}. The VeraView X800 device featured a smaller FOV (40 x 40 mm) and a lower tube current (5 mA) compared to the OP300 device, which had an FOV of 50 x 50 mm and a tube current

of 8 mA. A smaller FOV and lower mA are associated with fewer blooming artifacts on CBCT scans of filled teeth¹⁰. These differences can justify the lack of influence of the study factors investigated in the present study on the VeraView X800 images.

In contrast, applying the BAR filter to CBCT scans from the VeraView X800 device significantly increased specificity values (from 0.58 to 1.00) for detecting voids in the cervical/middle thirds of samples filled with Bio-C Sealer. This improvement highlights that the BAR filter enhanced the examiners' ability to accurately confirm the absence of voids (**Figure 4**), which is crucial in clinical scenarios where beam hardening artifacts, such as hypodense streaks, can lead to false positives. These findings are clinically important because precise detection of voids on CBCT scans is essential for diagnosing potential treatment failures and planning effective endodontic retreatments, especially considering the frequent use of bioceramic sealers in endodontic practice

In this study, micro-CT images served as a reference standard for detecting voids and validating CBCT scan analysis results. This decision was strategically based on previous research demonstrating the precision of micro-CT in assessing endodontic filling quality^{1-3,6,10-12}. Different sealers can produce varying levels of blooming artifacts on CBCT scans, significantly compromising or even preventing accurate void detection in the filling material¹¹. However, it is crucial to highlight that micro-CT is confined to laboratory settings and is not applicable in clinical contexts¹². In light of this, the present study stands out for its pioneering approach and innovative findings by demonstrating the effectiveness of a post-processing filter applied to CBCT scans in improving void detection in specific imaging conditions. In this investigation, the micro-CT images of void distribution across different root canal thirds reveal a consistent pattern, irrespective of the sealer used. A high incidence of voids was observed in both the cervical/middle thirds (70%) and the apical third (60%). These results are consistent with previous findings^{2,3}.

To achieve the research objectives, an anthropomorphic phantom was constructed for ex vivo applications, consisting of a dry human skull and mandible covered with Mix-D material, along with a tongue model also made of Mix-D²⁵. This setup aimed to simulate the X-ray attenuation of facial soft tissues during CBCT scan acquisition, closely replicating a realistic clinical scenario^{25,32,33}. However, some limitations of the study should be noted. Firstly, patient movement could not be considered, which can result in motion artifacts commonly observed in CBCT scans,

reducing image quality and diagnostic accuracy³⁰. Secondly, the images were obtained from only two CBCT devices, which may limit the generalizability of the results to other units. Therefore, the current results should be interpreted with caution. Consequently, further studies are recommended to explore the impact of the BAR filter on void detection in root canals with different anatomical complexities. Additionally, it is important to test the BAR filter in canals filled using various obturation techniques, such as lateral compaction and the Tagger hybrid technique, as well as with different commercially available sealers.

The current findings hold significant clinical importance, indicating that the BAR filter could enhance diagnostic accuracy in visualizing voids within the root canal filling on CBCT scans. This advancement addresses the recurring challenges noted in the literature regarding this diagnostic task^{6,12}. The study's findings are pivotal for guiding a safe and reliable decision-making process in endodontic practice, allowing clinicians to better assess the quality of root canal obturations and investigate treatment failures more precisely. This approach may lead to more effective retreatments and reduce iatrogenic errors, potentially lowering the incidence of unnecessary tooth extractions. It is crucial to emphasize that recommending a CBCT scan is justified only when periapical radiographs provide inconclusive or clinically incompatible data, in accordance with guidelines from the American Association of Endodontists (AAE) and the European Commission on Radiological Protection regarding the use of CBCT^{34,35}. The high diagnostic complexity in clinical cases of suspected endodontic treatment failures is widely discussed in the literature, underscoring the need to assess the quality of root canal obturation to detect potential voids. In such specific clinical scenarios, the use of CBCT scans is essential for accurate analysis^{34,35}.

CONCLUSIONS

The BAR filter significantly enhances void detection accuracy in the apical third of root canals when using the OP300 CBCT unit for both AH Plus Jet and Bio-C Sealer. It also notably increases specificity for identifying voids in the apical third with AH Plus Jet. In contrast, while the VeraView X800 device did not show an overall improvement in diagnostic performance with the BAR filter, it did achieve a significant increase in specificity for detecting voids in the cervical/middle thirds of canals filled with Bio-C Sealer.

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CONFLICT OF INTEREST

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

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3.4 Publicação 4*

Shaping Ability and Pericervical Dentin Thickness in Mesio Buccal Root Canals of Maxillary Molars: An Integrated Study Using Micro-CT and CBCT

ABSTRACT

Introduction: This study evaluated the shaping ability and remaining dentin thickness of MB1 and MB2 canals of maxillary molars using ProTaper Ultimate (PU) or ProDesign Logic 2 (PDL2). **Methods:** MB1 and MB2 canals were randomly assigned to either PU or PDL2 groups. MB1 canals were prepared up to PU 30/.09 or PDL2 30/.05, while MB2 canals were prepared up to PU 25/.08 or PDL2 25/.05. Each tooth was scanned before and after preparation using micro-computed tomography (micro-CT) to assess volumetric increase, debris, uninstrumented surface, transportation, and root canal centralization. Additionally, cone-beam computed tomography (CBCT) images were obtained pre- and post-preparation to measure dentin removal and the percentage of critical remaining dentin at four points below the furcation level using e-Vol DX software. Micro-CT measurements were used as reference. Data were analyzed at 5%. **Results:** PU significantly increased the volume in the cervical third of the MB1 canal compared to PDL2, which produced less debris in the apical third ($P < .05$). Overall, both systems showed a similar percentage of uninstrumented surface ($P > .05$) and maintained critical dentin thickness above 0.5 mm. CBCT slightly underestimated dentin thickness compared to micro-CT measurements ($P < .05$). **Conclusions:** PU led to a substantial volumetric increase in the cervical third of the MB1 canal, while PDL2 was most effective in reducing debris accumulation in the apical third. Both systems preserved the original canal trajectory and maintained critical dentin thickness over 0.5 mm in the MB1 and MB2 canals. Overall, CBCT imaging reliably assessed dentin thickness.

KEY WORDS Cone-beam computed tomographic; danger zone; maxillary molars; micro-computed tomography; root canal treatment

* Artigo escrito nas normas do periódico *Journal of Endodontics*, ao qual se pretende submeter.

INTRODUCTION

Root canal preparation is essential for the effective cleaning and disinfection of the root canal system¹. Techniques and instruments are commercially available, including stainless steel hand files, nickel-titanium (NiTi) instruments in rotary or reciprocating motion, and ultrasonic tips designed for the mechanical removal of dentin^{2,3}. Understanding the complex anatomy of the root canal system is fundamental for efficiently reaching all canal walls, preventing the accumulation of debris and bacterial biofilm, which is essential for achieving successful clinical outcomes¹⁻³. Additionally, it is vital that root canal preparation maintains the original canal shape and preserves the tooth structure^{4,5}. This is particularly important in maxillary molars, where pericervical dentin plays a critical role in fracture resistance and long-term endodontic prognosis⁶.

ProTaper Ultimate (Dentsply Sirona, Ballaigues, Switzerland) is a NiTi rotary system with a parallelogram-shaped cross-section that offers a range of 8 instruments, including Slider (16/.02), SX (20.03), Shaper (20.04), F1 (20.07), F2 (25.08), F3 (30.09), FX (35.12), and FLX (50.10)⁷. They are manufactured from three different types of heat-treated NiTi alloys: M-Wire for the Slider, Gold-Wire for the SX, Shaper, F1, F2, and F3, and Blue-Wire for the FX and FXL⁷. ProTaper Ultimate demonstrates superior cyclic fatigue resistance compared to ProTaper Gold (Dentsply Sirona) and M3 UDG (United Dental Changzhou, Changzhou, China)⁸. Additionally, it has been reported to have a greater ability to preserve pericervical dentin in the root canals of maxillary incisors compared to the WaveOne Gold system (Dentsply Sirona)⁹. ProTaper Ultimate also exhibited a similar percentage of uninstrumented surface after the preparation of the buccal and palatal canals of extracted maxillary molars when compared to the RCS Rainbow (Ramo Medical, Suzhou, China), Rotate (VDW GmbH, Munich, Germany), RaCe EVO (FKG, Chaux-de-Fonds, Switzerland), and OneCurve (Micro-Mega, Besancon, France) instruments¹⁰.

The ProDesign Logic 2 system (Logic 2; Easy Equipamentos Odontológicas, Belo Horizonte, MG, Brazil) comprises instruments subjected to control memory (CM) heat treatment, designed for use in rotary movement^{11,12}. These instruments are available in various tip sizes, ranging from 15 to 50, and with different tapers (.01, .03, .04, .05, and .06)¹², presenting enhanced flexibility compared to the Rotate system¹¹. Additionally, the Logic 2 exhibited remarkable preparation capability, demonstrated by

low transportation and excellent centering ability in curved mesial canals of mandibular molars¹².

The asymmetric morphology and reduced pericervical dentin thickness of the mesiobuccal (MB) root in maxillary molars present significant challenges for preparing the first mesiobuccal (MB1) and second mesiobuccal (MB2) canals^{4,5,13-15}. Therefore, NiTi systems such as Protaper Ultimate and Logic 2, which are designed for conservative dentin removal⁹⁻¹², may be recommended. However, no studies have evaluated the efficacy of these instruments in preparing MB1 and MB2 canals and preserving pericervical dentin thickness, which is crucial for developing effective clinical protocols. Additionally, no previous investigation has assessed the impact of preparation on the remaining pericervical dentin in MB1 and MB2 canals using cone-beam computed tomography (CBCT) measurements, with micro-computed tomography (micro-CT) images serving as the reference standard for comparison.

Therefore, the primary objective of this study was to evaluate the shaping ability (volumetric increase, debris, uninstrumented surface, canal transportation, and centralization ability) of ProTaper Ultimate and Logic 2 instruments in the MB1 and MB2 canals of maxillary molars using micro-CT imaging. The secondary objective was to determine the remaining pericervical dentin thickness in these root canals after preparation, using CBCT images with micro-CT as a reference. The null hypothesis stated that there would be no significant differences in the examined variables.

MATERIAL AND METHODS

Sample size determination

The sample size was calculated using G* Power software (version 3.1.7 for Windows; Heinrich Heine Universität Düsseldorf, Düsseldorf, Germany). To ensure significant differences each group would require eight teeth. This calculation considered an alpha-type error of 0.05, a beta power of 0.90, and an effect size of 0.914¹⁴ for all variables.

Ethical Aspects and Specimen Selection

Ethical approval was obtained from the institutional research ethics committee (protocol number: 41916720.7.0000.5416). Sixteen maxillary molars, each with two distinct canals (MB1 and MB2) in the mesiobuccal roots and classified as Vertucci's type IV¹⁶, were selected for this investigation. The inclusion criteria required complete apical formation and the absence of root fractures, calcifications, internal and external resorptions, caries, or extensive restorations. Additionally, all selected teeth exhibited a root curvature between 20° and 30°, as determined by Schneider¹⁷, and a radius of curvature less than 10 mm, according to Pruett's method¹⁸. Teeth with extensive coronal destruction, previous endodontic treatment, open apices, and external or internal root resorption were excluded. These criteria were confirmed using digital radiographs (RVG 6100; Kodak Dental Systems, NY) and a micro-CT device (SkyScan 1174; Bruker-microCT, Kontich, Belgium). Micro-CT images were also used to calculate the preoperative volume of the MB1 and MB2 canals, ensuring consistent volumes across the selected samples for subsequent preparation. Additionally, the safety and danger zones of each MB canal were measured before preparation, ensuring that each experimental group comprised specimens with similar preoperative dentin thickness, as detailed in **Table 1**.

Table 1. Mean $\pm$ standard deviation of dentin thickness (before preparation) in the safety (mesial) and danger (distal) surfaces within each mesiobuccal canal according to the furcation level based on the micro-CT assessment

	MB1 A		MB2 B	
Furcation Level	Safety Zone	Danger Zone	Safety Zone	Danger Zone
1 mm a	1.60 $\pm$ 0.16	1.59 $\pm$ 0.32	1.32 $\pm$ 0.12	1.33 $\pm$ 0.29
2 mm b	1.50 $\pm$ 0.15	1.43 $\pm$ 0.19	1.24 $\pm$ 0.15	1.15 $\pm$ 0.25
3 mm b	1.39 $\pm$ 0.09	1.37 $\pm$ 0.19	1.20 $\pm$ 0.16	1.08 $\pm$ 0.23
4 mm b	1.38 $\pm$ 0.17	1.33 $\pm$ 0.28	1.14 $\pm$ 0.15	1.11 $\pm$ 0.25

There was no statistically significant difference between the safety (mesial) and danger (distal) zones within each furcation level of the same mesiobuccal canal ($P > .05$).

Different uppercase letters represent a significant statistical difference between first and second mesiobuccal root canal ($P < .05$).

Different lowercase letters represent a significant statistical difference between furcation levels ($P < .05$).

Root Canal Instrumentation

All preparation procedures were meticulously performed by a single experienced endodontic specialist, using an operating surgical microscope with 13X magnification (DF Vasconcellos, Valença, RJ, Brazil) to ensure precise inspection. Initially, each tooth underwent conventional coronal access using a #1012 diamond bur (Dentsply Sirona), attached to a high-speed handpiece with continuous water cooling. The MB2 canal was located using the E15 Finder ultrasonic tip (Helse Ultrasonic, Santa Rosa de Viterbo, SP, Brazil), activated by the Newtron® Booster ultrasonic device (Acteon North America, New Jersey, USA) at 30% power as per the manufacturer's recommendations. Subsequently, the MB1 and MB2 root canals were explored using #06, #08, and #10 C+ files (Dentsply Sirona). The working length (WL) was determined by subtracting 1.0 mm from the length at which the tip of the size #10 C+ file was visible at the apical foramen. At this stage, the WL was set to 17 ± 1 mm for all MB1 and MB2 canals to maintain uniformity across the experimental groups. Subsequently, the teeth were mounted in a device with acrylic resin and wrapped in condensation silicone (Oranwash, Zhermack SpA, Badia Polesine, Italy) to simulate the periodontal ligament during the root canal preparation. This procedure adhered to the specific instructions provided by the manufacturers for each system:

ProTaper Ultimate Group

MB1 root canals ($n = 8$): The MB1 canals were sequentially prepared using instruments 16/.02, 20/.04, 20/.07, 25/.08, and 30/.09. All files were operated in rotary

kinematics at a speed of 400 rotations per minute (rpm) and a torque of 4 Newton centimeters (Ncm).

MB2 root canals ($n = 8$): The MB2 canals were prepared using instruments 16/.02, 20/.04, 20/.07, and 25/.08. These files were used in rotary movement at a constant speed of 400 rpm and a torque of 4 Ncm.

ProDesign Logic 2 Group

MB1 root canals ($n = 8$): The MB1 canals were prepared in sequence using the following instruments: 25/.01, 15/.03, 25/.03, 25/.05, and 30/.05. Instrument 25/.01 was used in rotary movement at 350 rpm with a torque of 1 Ncm, while instrument 15/.03 operated at the same speed but with a torque of 2 Ncm. The 25/.03 instrument was operated at 600 rpm and 2 Ncm. Finally, instruments 25/.05 and 30/.05 were used at 600 rpm with a torque of 3 Ncm.

MB2 root canals ($n = 8$): The MB2 canals were prepared using instruments 25/.01, 15/.03, 25/.03, and 25/.05. The 25/.01 instrument was used in rotary movement at a speed of 350 rpm and torque of 1 Ncm. The 15/.03 file was used at 350 rpm and 2 Ncm. Instrument 25/.03 was operated at 600 rpm and 2 Ncm. Finally, instrument 25/.05 was used at 600 rpm and 3 Ncm.

All instruments were introduced into the root canal using an in-and-out movement up to WL, driven by an X-Smart Plus electric motor (Dentsply Sirona). For both groups, the irrigation protocol consisted of applying 5.0 mL of 2.5% sodium hypochlorite (NaOCl) (Ciclo Farma, Serrana, SP, Brazil) after using each instrument. This was done using a 5 mL syringe (Ultradent Products, South Jordan, UT, USA) with a 30-G Navitip needle (Ultradent Products) positioned 2 mm short of the WL, with in-and-out movement and with continuous flow and aspiration. The final irrigation was done with 5 mL of 2.5% NaOCl, followed by 2.0 mL of 17% EDTA (Biodinâmica, Ibiporã, PR, Brazil) and 5 mL of saline solution in each root canal. The samples were aspirated with capillary tips (Dentsply Sirona) and dried with absorbent paper cones (Dentsply Sirona) according to the apical dilation diameter of each root canal.

Micro-CT Acquisition

Each tooth underwent dual scanning using a micro-CT device (SkyScan 1174, Bruker-microCT), both before and after root canal preparation. The following

parameters were used to acquire the images: 50 kV, 800 mA, rotation step of 0.8°, aluminum filter of 0.5 mm, and voxel size of 19.7 μm .

CBCT Acquisition

An anthropomorphic model consisting of a dry human skull and a fully dentate mandible was covered with Mix-D material to simulate soft tissue X-ray attenuation¹⁹ (**Figure 1**). Furthermore, a tongue model was produced and positioned in its corresponding place on the model. The complete anthropomorphic model was used to acquire the CBCT scans in this study. The maxillary left first molar was extracted, and the previously selected maxillary molars were individually placed in the corresponding socket to acquire the CBCT scans. To ensure consistent positioning of the teeth during the acquisition of CBCT scans both before and after root canal preparation, individualized silicone guides were fabricated using condensation silicone ZetaPlus (Zhermack SpA, Badia Polesine, Italy). All CBCT scans were acquired using the VeraView X800 CBCT device (J Morita, Tokyo, Japan). The acquisition parameters were set at 5 milliamperes (mA), 70 kilovoltage-peak (kVp), voxel size of 0.08 mm, and a field of view (FOV) of 40 x 40 mm. Subsequently, all CBCT scans acquired were exported in Digital Imaging and Communication in Medicine (DICOM) format.

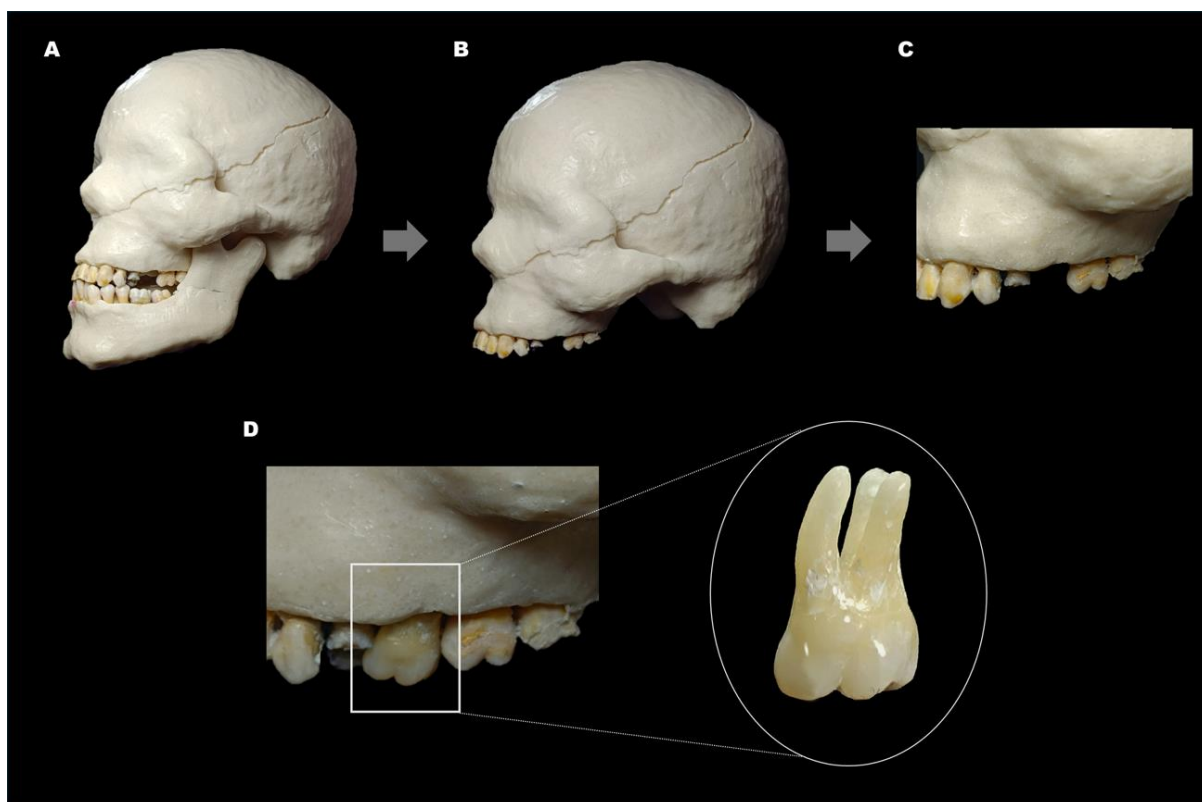


Figure 1. Representative images of the anthropomorphic phantom covered with Mix-D. **(A)** Lateral view of the anthropomorphic phantom composed of a dry human skull and a fully dentate mandible covered with Mix-D; **(B)** Lateral view of the dry human skull; **(C)** Lateral view of the maxilla showing the region of interest in the study; **(D)** Magnified view of the maxillary left first molar.

Micro-CT Image Analysis

The micro-CT scans of each specimen were reconstructed using NRecon software (v.1.6.3, Bruker-microCT) with specific parameters for beam-hardening correction (51%), smoothing (5), and ring artifact reduction (1). The pre- and post-preparation micro-CT images were superimposed through geometric realignment using the "3D registration" function in Data Viewer software (v.1.5.1, Bruker-microCT). Quantitative image analyses were conducted with CTAn software (v.1.14.4, Bruker-microCT), while three-dimensional models were generated using CTVox software (v.3.2, Bruker-microCT).

The preoperative volume of the root canals, the post-preparation volume, the surface area after preparation, and the volume of debris were determined. Based on these data, the percentage of volumetric increase (% volumetric increase), the percentage of debris (% debris), and the percentage of uninstrumented surface (%)

uninstrumented surface) were calculated^{2,3}. These calculations were performed for the entire root canal, as well as for the cervical, middle, and apical thirds of both the MB1 and MB2 canals.

$\% \text{ volumetric increase} = 100 - \text{volume of prepared canal} \times 100 / \text{preoperative volume}$

$\% \text{ debris} = \text{volume of debris} \times 100 / \text{volume of prepared canal}$

$\% \text{ uninstrumented surface} = \text{uninstrumented surface area} \times 100 / \text{surface area after preparation}$

To conduct the analyses of transportation and centralization in the apical third, superimposed axial images obtained before and after root canal preparation were used (**Figure 2**). Root canal transportation was calculated according to a previous study²⁰. Six different regions in the apical third of the MB1 and MB2 canals were measured using axial images with the CTAn software, and the arithmetic mean values were determined. Centralization data were ordered from 0 to 1, with values closest to 1 indicating complete centralization and those closest to 0 indicating no centralization. For the transportation data, values closer to zero indicated less deviation.

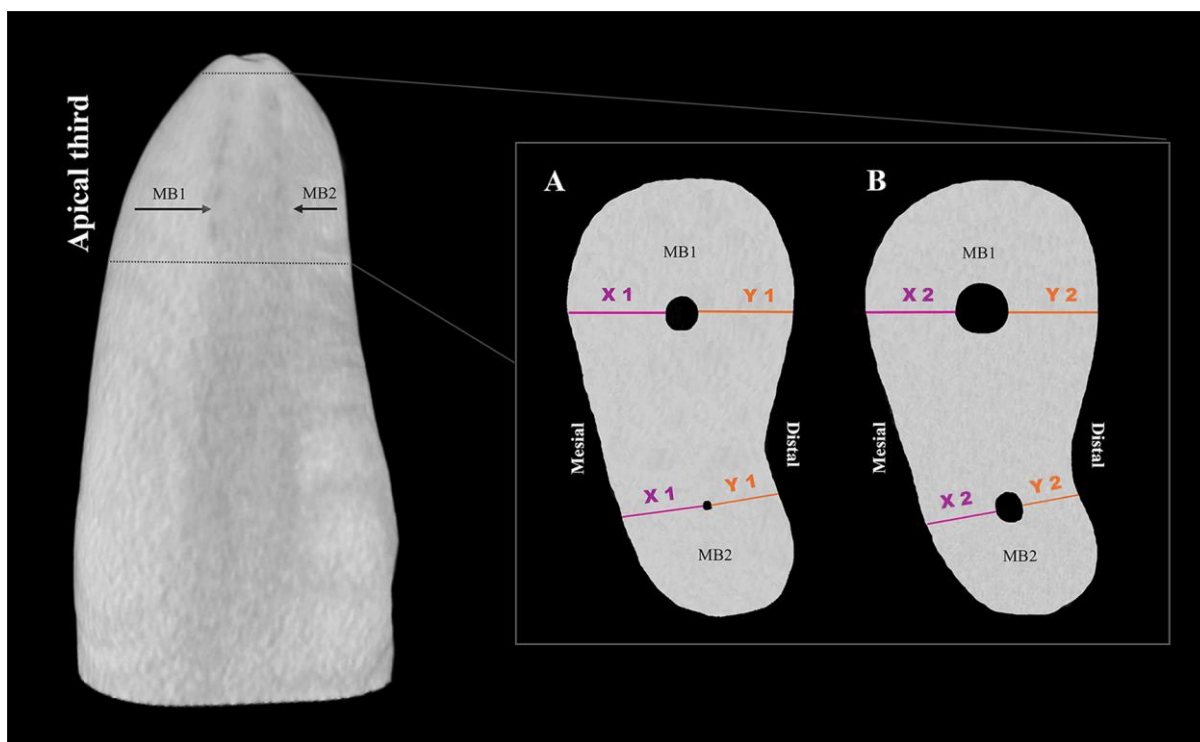


Figure 2. Axial reconstructions from micro-CT illustrating the analysis of transportation and canal centering in the apical third of MB1 and MB2 root canals. X1 and X2 represent the shortest distance between the mesial root edge and the canal before and after preparation with different NiTi systems, respectively. Similarly, Y1 and Y2 represent the shortest distance between the distal root edge and the canal before and after preparation. **A**, shows the canal in its preoperative state, and **B** depicts the canal after preparation.

The dentin thickness was measured linearly (in mm) at 1, 2, 3, and 4 mm below the furcation level in the MB1 and MB2 canals, both before and after root canal preparation using different NiTi systems. An experienced operator in micro-CT image analysis utilized axial reconstructions of each sample to conduct the measurements with CTAn software. These measurements considered the outer perimeter of the MB1 and MB2 canals extending towards the external surface of the MB root, encompassing both the distal aspect (danger zone) and the mesial aspect (safety zone). It is important to note that the measurements from the micro-CT images were used as a reference for comparison with those obtained from CBCT scans. After an interval of 4 weeks, 30% of the sample was randomly selected, and the measurements were repeated by the same evaluator to assess intra-examiner agreement.

CBCT Image Evaluation

The analysis of dentin thickness before and after the preparation of the MB1 and MB2 canals in the CBCT scans was conducted using e-Vol DX software (CDT Software, Bauru, SP, Brazil) on a 25-inch color LED monitor with a resolution of 2560 x 1080 pixel, in a room with subdued lighting and minimal noise. Adjustments to brightness, contrast, and zoom were allowed for image evaluation. Initially, the examiner received instructions to meticulously reorient all CBCT scans, ensuring that the axial, sagittal, and coronal reconstructions were precisely aligned with the long axis of each root canal. Following this, using the axial reconstructions from the CBCT scans, the same calibrated operator, who was familiar with the e-Vol DX software, measured the dentin thickness linearly in the MB1 and MB2 canals at 1, 2, 3, and 4 mm below the furcation level. This operator was not the same as the one responsible for evaluating the micro-CT images, ensuring independent assessments between the two imaging modalities. These measurements were taken at two different times: before and after the preparation of the root canals, by the same operator. Thirty days after the completion of the measurements, 30% of the sample was randomly re-evaluated by the same operator to assess intra-examiner agreement. To prevent visual fatigue for the examiner, a maximum of 10 CBCT scans were evaluated per session.

It is important to highlight that a dentin thickness of less than 0.5 mm after root canal preparation was classified as excessive dentin removal in all regions of interest in this study²¹, as assessed in both micro-CT and CBCT images.

Statistical Analysis

The intraclass correlation coefficient (ICC) was employed to assess the intra-operator agreement within each imaging modality investigated (micro-CT and CBCT). Data normality was checked using the Shapiro-Wilk test. A multiway analysis of variance (ANOVA) was used to compare the dentin thickness before root canal preparation using micro-CT assessment, considering the studied factors (MB root canals, root canal surface, and furcation level). The unpaired t-test was employed to compare the results regarding the micro-CT parameters between the NiTi systems. Unpaired and paired t-tests were used to compare the dentin removal values between the NiTi system and imaging modality, respectively. The Mann-Whitney and Wilcoxon tests were used to compare the results regarding the critical remaining dentin

percentages according to the scale adopted (<0.5 mm, 0.5-1 mm, and >1 mm)²², depending on the NiTi system and imaging modality, respectively. All statistical analyses were performed using SPSS software (version 24.0, IBM Corp., Armonk, NY, USA), with a significance level set at 5% ($\alpha = 0.05$).

RESULTS

For both imaging modalities, an almost perfect intra-operator agreement was achieved (ICC = 0.99), indicating the high reliability of the measurements performed by the operators.

Table 1 displays the mean and standard deviation of dentin thickness in the MB root canals before preparation, measured on both safety and danger surfaces at varying furcation levels using micro-CT. The analysis revealed that the MB2 consistently exhibited lower dentin thickness compared to the first MB1 canal across all furcation levels, with this difference being statistically significant ($P < .05$). Among the furcation levels, dentin thickness was significantly greater at 1 mm below the furcation level compared to levels at 2 mm, 3 mm, and 4 mm ($P < .05$). However, the dentin thickness at the 2 mm, 3 mm, and 4 mm levels did not differ significantly from each other ($P > .05$), irrespective of the MB canal. Importantly, there was no significant difference in dentin thickness between the safety and danger zones within each furcation level of the same MB canal ($P > .05$).

Table 2 provides a comprehensive comparison of NiTi file systems (Logic 2 and Protaper Ultimate) across quantitative micro-CT metrics in MB1 and MB2 root canals. For the MB1 canal, Protaper Ultimate achieved a significantly higher volume increase in the cervical third compared to Logic 2 ($P < .05$). In terms of debris, Logic 2 was more effective in reducing debris accumulation, especially in the apical region of MB1, where Protaper Ultimate retained more debris ($P < .05$). Regarding uninstrumented surface percentages, there were generally no significant differences between the file systems ($P > .05$), except in the MB2 canals where Logic 2 demonstrated a lower percentage of total uninstrumented surface ($P < .05$) (**Figure 3**). Both file systems exhibited minimal and comparable apical transportation and apical centralization abilities, indicating similar effectiveness in maintaining canal integrity ($P > .05$).

Table 3 presents the mean values of dentin removal measured using different imaging modalities at different furcation levels in MB1 and MB2 canals for both NiTi file systems. Overall, there were no statistically significant differences in dentin removal

between the imaging modalities within each file system or among the file systems within the same imaging modality across different MB canals ($P > .05$). However, notable exceptions were observed. Specifically, at 1 mm below the MB1 furcation level, Protaper Ultimate removed significantly more dentin in the danger zone compared to Logic 2 when using micro-CT ($P < .05$). Similarly, at 4 mm below the MB1 furcation level, Protaper Ultimate exhibited higher dentin removal in the safety zone compared to Logic 2 when assessed with CBCT ($P < .05$). Additionally, when differences between imaging modalities were observed, CBCT generally underestimated dentin removal compared to micro-CT measurements ($P < .05$) (**Figure 4**).

Table 4 presents the results regarding the critical remaining dentin percentages measured using micro-CT and CBCT for different NiTi systems. There was no statistically significant difference between the NiTi systems, regardless of the imaging modality, root canal, and root canal surface ($P > .05$). Both NiTi systems showed a very low percentage of critical remaining dentin (less than 0.5 mm) across the MB canal, root canal surface, and furcation levels. However, significant differences were observed between the imaging modalities for remaining dentin percentages at specific depths in the MB canal and root surface ($P < .05$). Specifically, for the Logic 2 system in the MB2 root canal's danger zone (at the 4 mm furcation level) and for Protaper Ultimate system in the MB1 root canal's safety zone (at the 4 mm level), as well as in MB2 root canal's safety zone (at the 1 mm furcation level) and danger zone (at the 2 mm level), CBCT underestimated the remaining dentin compared to micro-CT, presenting lower dentin thickness ($P < .05$).

Table 2. Mean (standard deviation) values of volume increase, debris, uninstrumented surface, apical transportation, and apical centralization ability in each mesiobuccal root canal according to the NiTi systems, analyzed using micro-CT

Canal	NiTi systems	Total	Increase in volume (%)		
			Cervical	Middle	Apical
MB1	Logic 2	220 (87.3) A	167 (57.3) B	307 (148) A	389 (157) A
	Protaper Ultimate	224 (66.7) A	238 (59.6) A	219 (94.1) A	213 (65.5) A
MB2	Logic 2	380 (74) A	472 (142) A	392 (77.5) A	291 (151) A
	Protaper Ultimate	313 (61.5) A	486 (81.2) A	348 (137) A	127 (27.7) B
Debris (%)					
		Total	Cervical	Middle	Apical
MB1	Logic 2	9.1 (5.1) A	12 (7.2) A	1.5 (1.1) B	6.1 (3.7) B
	Protaper Ultimate	8.1 (3.6) A	7.3 (5.3) A	5.8 (3.5) A	11.4 (5.7) A
MB2	Logic 2	12.4 (3.2) A	12 (2.7) B	14.1 (12) A	24.1 (20) A
	Protaper Ultimate	14.9 (2.7) A	15.1 (3) A	5.6 (1.3) A	25.2 (8.4) A
Uninstrumented surface (%)					
		Total	Cervical	Middle	Apical
MB1	Logic 2	32.7 (11.6) A	45.2 (17.9) A	10.5 (9) A	22.1 (9) A
	Protaper Ultimate	27.2 (9.2) A	29.2 (13.9) A	19.9 (8.5) A	33.6 (13.4) A
MB2	Logic 2	30.7 (2.6) B	28.7 (10.9) A	24 (14) A	41.9 (21.6) A
	Protaper Ultimate	38.3 (2.5) A	38.2 (7.1) A	18.8 (0.9) A	56.7 (5.3) A
Apical transportation					
MB1	Logic 2	0.05 (0.04) A			
	Protaper Ultimate	0.02 (0.04) A			
MB2	Logic 2	0.03 (0.05) A			
	Protaper Ultimate	0.03 (0.06) A			
Apical centralization ability					
MB1	Logic 2	0.13 (0.04) A			
	Protaper Ultimate	0.13 (0.03) A			
MB2	Logic 2	0.11 (0.03) A			
	Protaper Ultimate	0.09 (0.04) A			

Different uppercase letters represent a significant statistical difference between the NiTi systems within each mesiobuccal canal ($P < .05$).

Table 3. Mean $\pm$ standard deviation values of dentin removal according to furcation level, mesiobuccal canal, root canal surface, and imaging modality for NiTi file systems

Furcation Level	Canal	Surface	Logic 2		Protaper Ultimate	
			Micro-CT	CBCT	Micro-CT	CBCT
1 mm	MB1	Safety zone	0.16 $\pm$ 0.10	0.19 $\pm$ 0.11	0.15 $\pm$ 0.06	0.17 $\pm$ 0.10
		Danger zone	0.36 $\pm$ 0.13 b	0.34 $\pm$ 0.04	0.52 $\pm$ 0.11 Aa	0.23 $\pm$ 0.14 B
	MB2	Safety zone	0.12 $\pm$ 0.10	0.14 $\pm$ 0.05	0.12 $\pm$ 0.11	0.14 $\pm$ 0.13
		Danger zone	0.41 $\pm$ 0.10	0.35 $\pm$ 0.15	0.51 $\pm$ 0.14	0.42 $\pm$ 0.24
2 mm	MB1	Safety zone	0.15 $\pm$ 0.10	0.17 $\pm$ 0.12	0.22 $\pm$ 0.08 A	0.12 $\pm$ 0.08 B
		Danger zone	0.39 $\pm$ 0.13	0.34 $\pm$ 0.04	0.43 $\pm$ 0.20	0.28 $\pm$ 0.14
	MB2	Safety zone	0.20 $\pm$ 0.08	0.20 $\pm$ 0.04	0.21 $\pm$ 0.14	0.23 $\pm$ 0.22
		Danger zone	0.35 $\pm$ 0.06 A	0.21 $\pm$ 0.06 B	0.27 $\pm$ 0.15	0.22 $\pm$ 0.10
3 mm	MB1	Safety zone	0.15 $\pm$ 0.11	0.18 $\pm$ 0.04	0.19 $\pm$ 0.08	0.13 $\pm$ 0.08
		Danger zone	0.30 $\pm$ 0.05	0.26 $\pm$ 0.16	0.31 $\pm$ 0.14	0.21 $\pm$ 0.11
	MB2	Safety zone	0.31 $\pm$ 0.14	0.21 $\pm$ 0.08	0.27 $\pm$ 0.12 A	0.17 $\pm$ 0.17 B
		Danger zone	0.19 $\pm$ 0.13	0.09 $\pm$ 0.08	0.12 $\pm$ 0.13	0.15 $\pm$ 0.11
4 mm	MB1	Safety zone	0.21 $\pm$ 0.11	0.10 $\pm$ 0.08 b	0.21 $\pm$ 0.10	0.23 $\pm$ 0.11 a
		Danger zone	0.26 $\pm$ 0.16	0.28 $\pm$ 0.19	0.20 $\pm$ 0.12	0.22 $\pm$ 0.12
	MB2	Safety zone	0.30 $\pm$ 0.10	0.12 $\pm$ 0.07	0.26 $\pm$ 0.14	0.13 $\pm$ 0.08
		Danger zone	0.12 $\pm$ 0.10	0.11 $\pm$ 0.10	0.12 $\pm$ 0.07	0.18 $\pm$ 0.11

Different uppercase letters represent a significant statistical difference between the micro-CT and CBCT systems in terms of dentin removal measurement (measurement_{Baseline} – measurement_{T1}) within each mesiobuccal canal and root surface ($P < .05$). Different lowercase letters represent a significant statistical difference between the NiTi file systems in terms of dentin removal measurement (measurement_{Baseline} – measurement_{T1}) within each modality, mesiobuccal canal, and root surface ($P < .05$).

Table 4. Critical remaining dentin percentage using micro-CT and CBCT according to mesiobuccal root canals, root canal surfaces, and furcation levels for different NiTi systems

			Logic 2 (%)							
Root canal	Surface	Remaining dentin	1 mm	1 mm	2 mm	2 mm	3 mm	3 mm	4 mm	4 mm
			Micro-CT	CBCT	Micro-CT	CBCT	Micro-CT	CBCT	Micro-CT	CBCT
MB1	Safety Zone	< 0.5 mm	0	0	0	0	0	0	0	0
		0.5 - 1 mm	0	0	0	0	0	50	25	50
		> 1 mm	100	100	100	100	100	50	75	50
		P value	>.05		>.05		>.05		>.05	
MB1	Danger Zone	< 0.5 mm	0	0	0	0	0	0	0	0
		0.5 - 1 mm	37.5	37.5	50	50	37.5	50	25	37.5
		> 1 mm	62.5	62.5	50	50	62.5	50	75	62.5
		P value	>.05		>.05		>.05		>.05	
MB2	Safety Zone	< 0.5 mm	0	0	0	0	0	0	0	0
		0.5 - 1 mm	0	37.5	25	75	100	100	100	100
		> 1 mm	100	62.5	75	25	0	0	0	0
		P value	>.05		>.05		>.05		>.05	
MB2	Danger Zone	< 0.5 mm	0	0	12.5	12.5	0	0	0	37.5
		0.5 - 1 mm	75	100	62.5	62.5	75	75	50	37.5
		> 1 mm	25	0	25	25	25	25	50	25
		P value	>.05		>.05		>.05		<.05*	
Protaper Ultimate (%)										
Root canal	Surface	Remaining dentin	1 mm	1 mm	2 mm	2 mm	3 mm	3 mm	4 mm	4 mm
			Micro-CT	CBCT	Micro-CT	CBCT	Micro-CT	CBCT	Micro-CT	CBCT
MB1	Safety Zone	< 0.5 mm	0	0	0	0	0	0	0	0
		0.5 - 1 mm	0	25	0	0	0	25	0	87.5
		> 1 mm	100	75	100	100	100	75	100	12.5
		P value	>.05		>.05		>.05		<.05*	
MB1	Danger Zone	< 0.5 mm	0	0	0	0	0	0	0	0
		0.5 - 1 mm	50	37.5	50	87.5	37.5	75	37.5	75
		> 1 mm	50	62.5	50	12.5	62.5	25	62.5	25
		P value	>.05		>.05		>.05		>.05	
MB2	Safety Zone	< 0.5 mm	0	0	0	0	0	0	0	0
		0.5 - 1 mm	0	62.5	75	100	62.5	100	62.5	75
		> 1 mm	100	37.5	25	0	37.5	0	37.5	25
		P value	<.05*		>.05		>.05		>.05	
MB2	Danger Zone	< 0.5 mm	25	25	12.5	25	0	0	0	0
		0.5 - 1 mm	37.5	75	37.5	75	50	100	62.5	100
		> 1 mm	37.5	0	50	0	50	0	37.5	0
		P value	>.05		<.05*		>.05		>.05	

There was no statistically significant difference between the NiTi systems, regardless of the imaging modality, root canal, and root canal surface ($P>.05$). Asterisks (*) indicate a statistically significant difference between the imaging modalities for the percentages of remaining dentin measured within the mesiobuccal canal and root surface for each NiTi systems ($P<.05$).

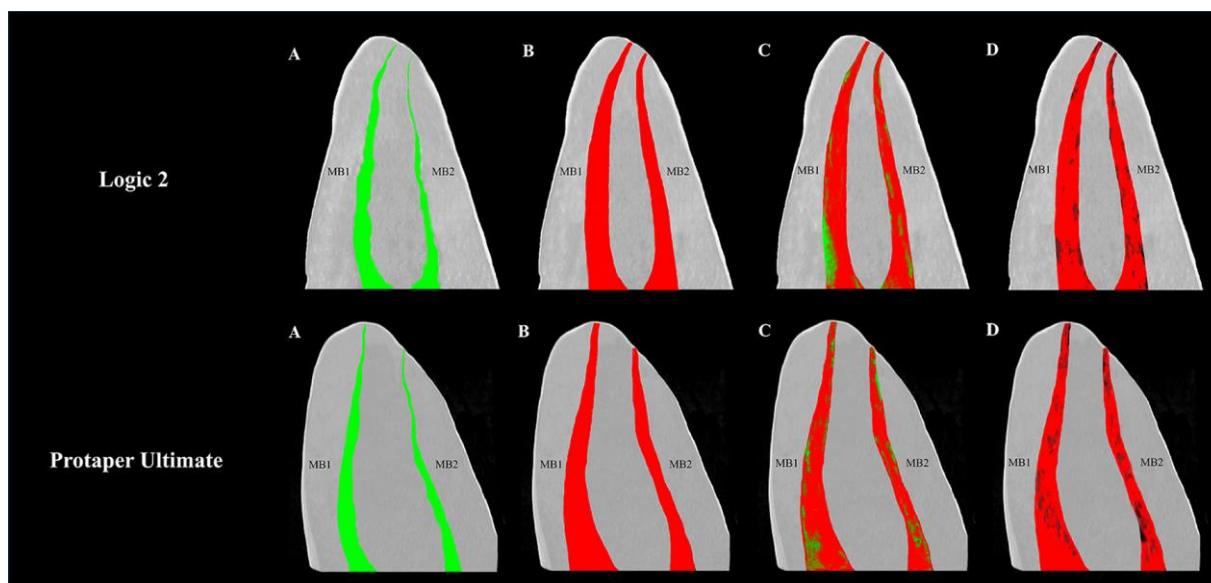


Figure 3. Three-dimensional micro-CT reconstructions of the MB1 and MB2 canals of maxillary molars prepared using the Logic 2 and Protaper Ultimate systems: **A**, preoperative canal (green); **B**, canal after preparation (red); **C**, superimposition of the initial canal on the prepared canal (the uninstrumented surface is represented in green); **D**, debris accumulated after preparation (black).

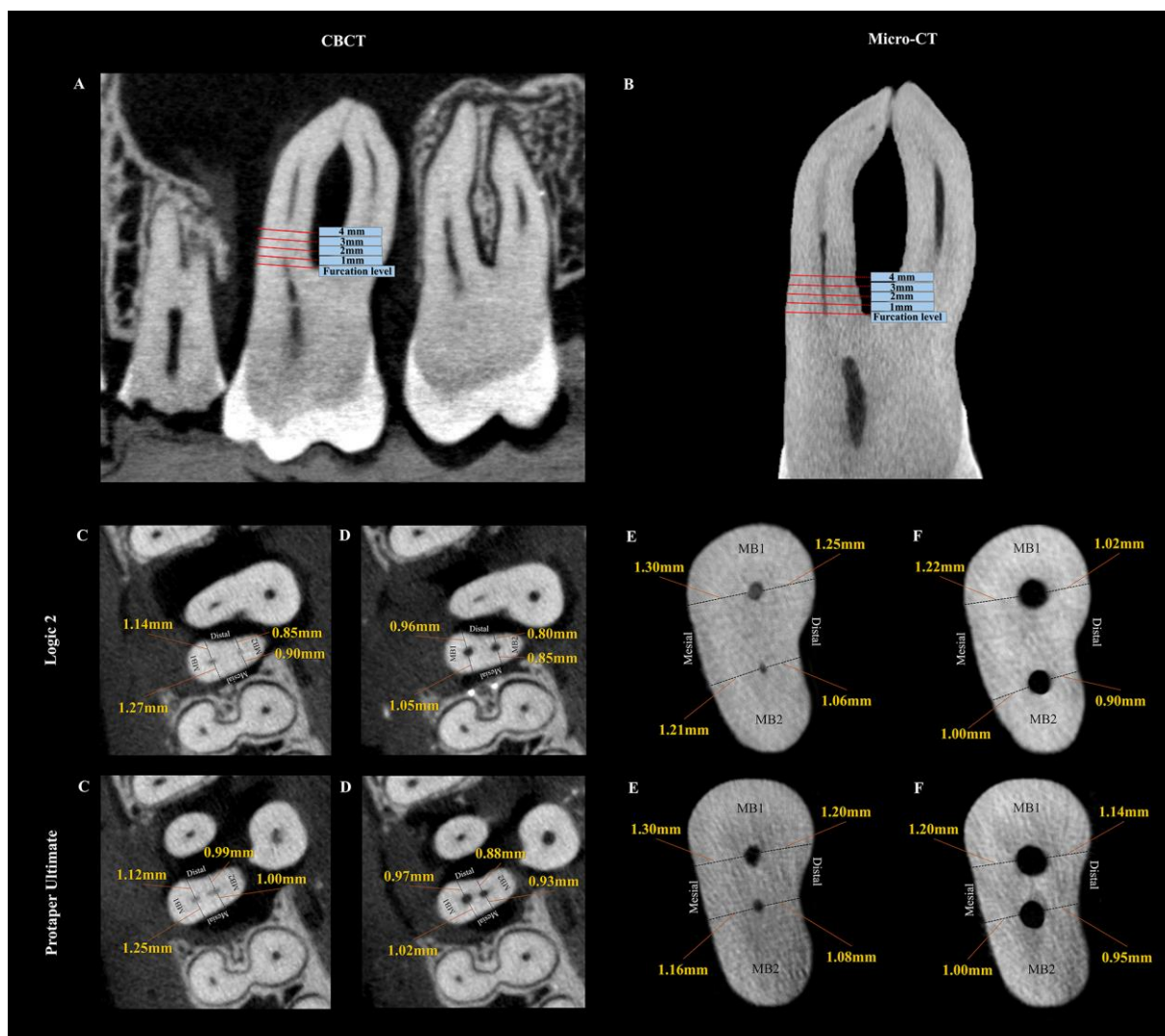


Figure 4. Sagittal reconstructions from CBCT (**A**) and micro-CT (**B**) depict the locations of dentin thickness measurements performed below the furcation level. Axial reconstructions from CBCT before (**C**) and after preparation (**D**) with different NiTi systems emphasize the dentin thickness measurements taken 2 mm below the furcation level on the mesial (safety zone) and distal (danger zone) aspects of the MB1 and MB2 canals. Corresponding axial reconstructions from micro-CT before (**E**) and after preparation (**F**) of the same teeth, evaluated under identical conditions as in the CBCT scans, illustrate the measurements used as a reference in the micro-CT images.

DISCUSSION

The anatomical complexities of the MB root in maxillary molars represent a significant challenge in preparing the MB1 and MB2 canals⁴⁻⁵. These root canals are both narrow and sharply curved, with the MB2 canal notably having consistently thin pericervical dentin⁶. These characteristics complicate effective shaping and often lead to procedural complications, including canal deviations, root fractures, strip perforations, and canal transportation, ultimately causing endodontic treatment failure^{4,5,13-15}. Therefore, this pioneering study was designed to provide a comprehensive evaluation of the efficacy and safety of the NiTi systems ProTaper Ultimate and Logic 2 in preparing the MB1 and MB2 canals. The current findings show some differences in the investigated variables between the instruments, resulting in the rejection of the null hypothesis.

Regarding the average dentin thickness before preparation in both the safety and danger zones of the MB1 and MB2 canals measured by micro-CT, the study's findings revealed that the MB2 canal had significantly thinner dentin at all levels compared to the MB1 canal, highlighting the notable distinctions between these canals. These findings are consistent with previous investigations^{4-6,13-15}, which reported extremely reduced preoperative dentin thickness values in the MB2 canals of maxillary molars. This suggests that the preparation of these canals must be performed with extreme caution to avoid strip perforation, making the shaping process highly challenging⁴. Furthermore, it is important to note that the micro-CT analysis revealed no differences in preoperative dentin thickness in both the danger zone and the safety zone at any of the levels analyzed between the MB1 and MB2 canals selected for this investigation. This underscores the standardization of the morphological parameters of the canals in terms of initial dentin thickness, ensuring that the experimental groups were reliably comparable.

The present study demonstrated that the ProTaper Ultimate system produced a larger volumetric increase in the cervical third of the MB1 canal compared to the Logic 2 system. Although instruments with larger tapers generally remove more dentin, potentially leading to a greater volumetric increase of the root canal^{4,5}, the taper 0.09 of the final instrument used in the Protaper Ultimate group is present only near the tip (from D0 to D3), gradually decreasing along the length of the instrument⁷. On the other hand, the taper 0.05 remains constant throughout the entire active part of the

instrument in Logic 2 system^{11,12}. Consequently, other variables, such as cross-sectional design, kinematics, diameter of the core metal, and thermal treatment applied to the instruments also play crucial roles in shaping outcomes^{4,10}.

The ProTaper Ultimate features an off-centered parallelogram cross-section, where the parallelograms are arranged in a discontinuous manner, allowing the point of contact with the canal walls to vary⁷. This design likely contributed to the greater volumetric increase in the cervical third, as well as increased dentin removal 4 mm below the furcation in the safety zone of the MB1 canal and 1 mm below the furcation in its danger zone. However, this cross-section also has a larger metal core^{7,10}, which may reduce the escape area for debris removal, as observed in our results. In contrast, the Logic 2 instrument utilizes CM heat treatment, which enhances its flexibility and resistance to cyclic fatigue but reduces its cutting efficiency¹¹. Additionally, the ProDesign Logic 2 has a triangular cross-section with a smaller metal core, providing a larger escape area¹¹, resulting in less debris accumulation in the apical third as observed in this study.

Overall, no significant disparities were observed in the percentages of uninstrumented surfaces between the two NiTi systems in the current study. This can be attributed to the similar kinematics of the instruments and their use in MB1 and MB2 canals with comparable morphologies¹⁰. Additionally, the present study revealed that both ProTaper Ultimate and Logic 2 exhibited minimal apical transportation and excellent ability to maintain the centralization of the MB1 and MB2 canals, along with an extremely low percentage of critical remaining dentin (i.e., less than 0.5 mm) in both the safety and danger zones, regardless of the furcation level. Moreover, there were no instances of instrument separation or strip perforations during the preparation of the MB1 and MB2 canals in this study. These findings indicate that ProTaper Ultimate and Logic 2 are effective in preserving adequate dentin thickness, highlighting the safety of these NiTi systems in challenging root canal anatomies.

In the present study, CBCT tended to underestimate the remaining dentin percentages compared to the measurements provided by micro-CT. This discrepancy can be attributed to the submillimeter resolution used to acquire the micro-CT images (19.7 μm)^{24,25} compared to CBCT images, which may limit CBCT's ability to accurately evaluate fine endodontic structures, such as narrow and curved root canals and their remaining dentin thickness^{24,26}. However, it is important to note that these differences were observed at very specific depths and root surfaces in the MB1 and MB2 canals.

In a broader context, CBCT measurements of remaining dentin thickness can be considered reliable when compared to the gold standard measurements obtained by micro-CT. These findings offer valuable insights with direct implications for clinical practice, given that CBCT is the primary imaging method for endodontic diagnosis and prognosis²⁷. Furthermore, since CBCT underestimated the remaining dentin thickness after preparation in this study, clinicians should recognize that dentin thickness measurements might appear reduced when performed using the methodology of this investigation. This underestimation could potentially provide a greater margin of safety in clinical practice.

The methodology employed in this study has intrinsic limitations due to the ex vivo setting. First, the study did not account for artifacts caused by movement and metallic objects on CBCT scans, which could affect the accuracy of dentin thickness measurements in the MB1 and MB2 canals^{13,15}. Secondly, using only a single CBCT device limits the generalizability of the results to other CBCT units with different technical specifications. Additionally, future studies should explore a variety of NiTi systems with different kinematics and thermal treatments to assess their effects on the variables investigated in this study. Despite these limitations, the study has several notable strengths. Highly detailed micro-CT measurements were used as the gold standard to validate CBCT measurements in determining the remaining dentin thickness in MB1 and MB2 canals. The study employed e-Vol DX software for CBCT image analysis, using post-processing filters to enhance image quality and improve measurement precision, as demonstrated in prior studies for measuring dentin thickness^{28,29} and determining root canal cross-sections³⁰. In addition, in this investigation, CBCT scans were acquired using an anthropomorphic phantom coated with Mix-D to simulate x-ray attenuation found in clinical scans, ensuring a high level of reproducibility that closely matches real clinical conditions¹⁹.

The results of this study have direct clinical implications, providing valuable insights into the preparation of MB1 and MB2 canals of maxillary molars using two different nickel-titanium systems. The study identifies the optimal balance between preparation effectiveness and safety concerning dentin thickness removal at 1, 2, 3, and 4 mm below the furcation level. This region is particularly vulnerable, underscoring the need to establish a safe preparation protocol when using NiTi instruments^{4-6,13-15}. Additionally, the current findings underscore the potential of CBCT imaging in aiding clinicians to accurately measure dentin thickness in the MB1 and MB2 canals, thereby

avoiding strip perforations and potentially enhancing endodontic treatment success rates.

CONCLUSIONS

The micro-CT analysis revealed that the ProTaper Ultimate system promotes a greater volumetric increase in the cervical third of the MB1 canal compared to Logic 2, which produced less debris in the apical third. Overall, both NiTi systems result in similar percentages of uninstrumented surfaces in the MB1 and MB2 canals and effectively maintain the original canal trajectory. Both systems are generally safe, maintaining a critical dentin thickness above 0.5 mm. CBCT scans are recommended for assessing dentin thickness in both the safety and danger zones of the MB1 and MB2 root canals. These scans provide crucial pre-instrumentation data, allowing clinicians to precisely evaluate the extent to which the canals can be safely enlarged, thus minimizing the risk of procedural errors. However, it is important to note that dentin thickness may be underestimated with CBCT scans in some cases using the protocol adopted in this investigation.

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CONFLICT OF INTEREST

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

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3.5 Publicação 5*

Effectiveness and Safety of Three NiTi Systems in Endodontic Retreatment of MB1 and MB2 Root Canals: A Combined Analysis Using Micro-CT and CBCT

ABSTRACT

Objectives To evaluate the endodontic retreatment performance and pericervical dentin preservation of ProDesign Logic 2 (PDL2), Reciproc Blue (RB), and WaveOne Gold (WOG) systems in first (MB1) and second (MB2) mesiobuccal canals.

Materials and Methods MB1 and MB2 canals were prepared, filled, and randomly assigned into four groups ($n = 8$). MB1 were retreated using PDL2 up to file 40/0.05 or RB R40 (40/0.06), and MB2 with PDL2 up to file 35/0.05 or WOG (35/0.06). Micro-computed tomography (micro-CT) scanning was performed before and after retreatment to assess remaining filling material, canal transportation and centralization. Cone-beam computed tomography (CBCT) measured dentin removal and remaining dentin at four levels below the furcation, with micro-CT as the reference.

Results RB was more effective in removing MB1 filling material than PDL2, while PDL2 outperformed WOG in the apical third of MB2 ($p < 0.05$). All systems showed minimal apical transportation ($p > 0.05$). Overall, dentin removal was similar ($p > 0.05$), but a significant reduction in MB2 danger zone dentin thickness below 0.5 mm was observed after retreatment.

Conclusions RB demonstrated greater effectiveness in MB1 retreatment, while PDL2 was more efficient in the MB2 apical third. A substantial decrease in dentin thickness in the MB2 danger zone was noted after retreatment. Generally, CBCT scans provided consistent dentin thickness assessments.

Clinical Relevance This study emphasizes the importance of using preoperative CBCT scans to select appropriate NiTi systems for the retreatment of MB1 and MB2 canals, particularly to protect pericervical dentin in the MB2 danger zone.

KEY WORDS: Cone-beam computed tomographic, Dentine thickness, Endodontic retreatment, Maxillary molars, Micro-computed tomography

* Artigo escrito nas normas do periódico *Clinical Oral Investigations*, ao qual se pretende submeter

INTRODUCTION

The failure of endodontic treatment is closely connected to the persistence of bacterial infection in the root canal system [1]. Therefore, completely remove the filling material during endodontic retreatment is essential, using hand files, nickel-titanium (NiTi) instruments and ultrasonic tips [2]. This approach allows that irrigating solutions and intracanal medication can effectively act in elimination or reduction of microorganisms, which is essential to control infection and allow periapical tissues healing [3].

The mesiobuccal (MB) root of maxillary molars presents significant anatomical challenges, including apical curvature and the presence of two distinct root canals, MB1 and MB2 [4, 5]. Additionally, the pericervical dentin thickness, both on the mesial aspect (safety zone) and the distal aspect (danger zone), is notably thin [4]. These factors make the preparation and retreatment of MB1 and MB2 canals particularly delicate, increasing the risk of perforation and reducing the root's resistance to fracture [5-9]. Consequently, it is crucial to establish safe enlargement protocols when using rotary or reciprocating NiTi instruments to minimize procedural errors in these root canals [4, 5-9].

Reciproc Blue (VDW GmbH, Munich, Germany) is a mechanized NiTi reciprocating system with Blue-Wire heat treatment, which offers greater resistance to cyclic fatigue and enhanced flexibility compared to its predecessor, Reciproc M-Wire (VDW GmbH) [10]. The adequate effectivity of Reciproc Blue in endodontic retreatment has been well-documented in the literature [11-13]. The WaveOne Gold instrument (Dentsply Sirona, Ballaigues, Switzerland) is a NiTi system treated with Gold-Wire technology and designed for reciprocating motion [14, 15], which showed effective preparation of MB1 canals in maxillary molars while minimizing unnecessary removal of root dentin [14]. Additionally, WaveOne Gold has proven effectiveness in removing filling material from MB1 root canals, with minimal apical transportation observed [15].

The ProDesign Logic 2 (Logic 2; Easy Equipamentos Odontológicos, Belo Horizonte, MG, Brazil) is a rotary NiTi system that utilizes Control Memory (CM) heat treatment and offers a range of tip sizes (from 15 to 50) and tapers (.01, .03, .04, .05, and .06) [16, 17]. This system has great flexibility [16] and reliable performance in the preparation of curved mesial canals in mandibular molars, with minimal apical transportation and excellent canal centralization [17].

Clinically, it is essential to prioritize strategies that ensure both effective removal of filling material and preservation of root integrity to prevent fractures [2]. This is particularly important in maxillary molars, where pericervical dentin is crucial for maintaining the tooth's structural integrity [5-9]. However, the current literature lacks studies on the retreatment of MB2 canals, a critical issue given the high prevalence (over 90%) of this root canal [18]. Moreover, there is currently no research evaluating the performance of NiTi systems such as Reciproc Blue, WaveOne Gold, and Logic 2 in the endodontic retreatment of MB2 root canals.

Therefore, this study aimed to compare the efficiency of filling material removal, canal centralization, and apical transportation in MB1 and MB2 canals using Reciproc Blue, WaveOne Gold, and Logic 2 instruments, analyzed through micro-computed tomography (micro-CT) images. Additionally, dentin removal and the percentage of remaining dentin were assessed at four distinct points below the furcation level in these canals using cone-beam computed tomography (CBCT) images, with micro-CT measurements serving as a reference for comparative analysis. The null hypothesis posits that no significant differences would be observed among the factors under investigation.

MATERIAL AND METHODS

Sample size determination

The sample size was calculated using G* Power 3.1.7 software for Windows (Heinrich-Heine-Universität Dusseldorf, Dusseldorf, Germany). The analysis determined that eight teeth per group were required to detect significant differences, with an alpha level of 0.05, a beta power of 0.90, and an effect size of 1.58 [5].

Selection of Teeth

The research protocol was approved by the institutional ethics committee (CAAE #41916720.7.0000.5416). Sixteen human maxillary molars were selected, each exhibiting two distinct root canals in the MB root (MB1 and MB2), classified as Vertucci's type IV [19]. The selection process utilized a digital radiography system (RVG 6100; Kodak Dental Systems, Rochester, NY) and micro-CT scans (SkyScan 1272; Bruker-microCT, Kontich, Belgium). The inclusion criteria required that the teeth

have complete apical formation, absence of root fractures, calcifications, or internal/external resorptions, a root curvature between 20° and 30° as defined by Schneider's method [20], and a radius of curvature less than 10 mm according to Pruett's method [21]. Additionally, the teeth needed to be free from caries and extensive restorations. Teeth with extensive coronal destruction, previous endodontic treatment, open apices, or external/internal root resorption were excluded from the study.

Root Canal Preparation

Coronal access was achieved using a #1012 diamond bur (Dentsply Sirona, Ballaigues, Switzerland). The MB2 canal was located with the E15 Finder ultrasonic tip (Helse Ultrasonic, Santa Rosa de Viterbo, SP, Brazil), powered by the Newtron® Booster ultrasonic device (Acteon North America, New Jersey, USA) set at 30% power, in accordance with the manufacturer's specifications. The MB1 and MB2 root canals were subsequently explored using #06, #08, and #10 C+ files (Dentsply Sirona). The working length (WL) was calculated by subtracting 1.0 mm from the point at which the tip of the #10 C+ file was visualized at the apical foramen. To ensure consistency across all experimental groups, the WL was standardized to 17 ± 1 mm for both MB1 and MB2 canals. The teeth were subsequently stabilized in a mounting apparatus using acrylic resin and encased in condensation silicone (Zhermack SpA, Badia Polesine, Italy) to simulate the periodontal ligament during the root canal preparation. All procedures were meticulously carried out by a single, highly skilled endodontic specialist under a surgical microscope with 13X magnification (DF Vasconcellos, Valença, RJ, Brazil). The preparation of the root canals strictly followed the manufacturer's guidelines for the Logic 2 (Easy Equipamentos Odontológicos) rotary system as follows:

Preparation of MB1 root canals ($n = 16$): MB1 root canals were prepared sequentially using 25/0.01, 15/0.03, 25/0.03, and 30/0.03 instruments in rotary kinematics. The 25/0.01 instrument was used at a speed of 350 revolutions per minute (rpm) with a torque of 1 Newton centimeter (Ncm), while the 15/0.03 instrument was operated at the same speed but with a torque of 2 Ncm. The 25/0.03 and 30/0.03 instruments were used at 600 rpm with a torque of 2 Ncm.

Preparation of MB2 root canals ($n = 16$): MB2 root canals were prepared sequentially using 25/0.01, 15/0.03, and 25/0.03 instruments, following the kinematic, rpm, and torque specifications previously described for these instruments.

All instruments were inserted into the root canals using in-and-out movements up to the WL, driven by the X-Smart Plus electric motor (Dentsply Sirona). The irrigation protocol for all samples was standardized and involved the application of 5.0 mL of 2.5% sodium hypochlorite (NaOCl) (Ciclo Farma, Serrana, SP, Brazil) after using each instrument. This was done using a 5 mL syringe (Ultradent Products, South Jordan, UT, USA) with a 30-G Navitip needle (Ultradent Products), positioned 2 mm short of the WL, with a back-and-forth movement and continuous flow and aspiration. The final irrigation sequence included 5 mL of 2.5% NaOCl, followed by 2.0 mL of 17% EDTA (Biodynamics, Ibiporã, PR, Brazil), and finally 5 mL of saline solution in each canal. The canals were then aspirated using capillary tips (Dentsply Sirona) and dried with absorbent paper points (Dentsply Sirona) corresponding to the apical enlargement diameter of each canal.

Root Canal Filling

All root canals were filled using the single-cone technique with AH Plus Jet sealer (Dentsply DeTrey, Konstanz, Germany). Gutta-percha cones, sized 25/.03 and 30/.03 (Easy Equipamentos Odontológicos), were selected based on their tip size and taper using a profilometer (Nikon Profile Projector model 6C-2, Nikon, Tokyo, Japan). Digital radiographs in buccolingual and mesiodistal directions confirmed the proper adaptation of the gutta-percha cones in each canal. The AH Plus Jet sealer was applied using a lentulo spiral (#30 or #25, Dentsply Sirona) connected to a low-speed motor (Micromotor N270 and contra-angle, Dabi-Atlante, Ribeirão Preto, SP, Brazil), positioned 2 mm short of the WL in the MB1 and MB2 canals, respectively. Additionally, a pre-curved K-file (#30 for MB1 canals or #25 for MB2 canals) was used to carry the sealer to the WL before inserting the gutta-percha cone [22, 23]. The MB1 canals were filled with 30/.03 gutta-percha cones coated with sealer, inserted to the WL, while the MB2 canals were filled with 25/.03 cones following the same protocol. Excess gutta-percha was removed from the cervical third and compacted vertically with a Paiva #2 plugger (Golgran, São Caetano do Sul, SP, Brazil). Final digital radiographs in mesiodistal and buccolingual directions ensured there were no voids and that the fillings were uniform. The root canals were restored with Coltosol (Vigodent, Rio de

Janeiro, Brazil) and stored at 37°C with 95% relative humidity for one week to allow the sealer to set completely.

Root Canal Retreatment

Micro-CT images were used to measure dentin thickness (in mm) before and after root canal preparation on both the safety and danger zones of each MB1 and MB2 canal, according to the furcation level (Table 1). Additionally, the volume of filling material (in mm³) was assessed using CTAn software (v.1.14.4, Bruker-microCT) after filling the root canals to ensure a homogeneous sample distribution for the endodontic retreatment procedures. These two factors were considered to ensure that the experimental groups were comparable during the endodontic retreatment.

After removing the temporary restorations, the same specialist who prepared and filled all the root canals carried out the retreatment procedures using a surgical microscope with 13X magnification (DF Vasconcellos). The root canals were randomly assigned to the following groups:

Retreatment of MB1 root canals with the Logic 2 system (n = 8): The Logic 2 instruments, sized 30/0.05, 35/0.05, and 40/0.05, were used sequentially. Each instrument was driven by the X-Smart Plus electric motor in rotary mode at 600 rpm with 3 Ncm torque, performing in-and-out movements up to the WL.

Retreatment of MB1 root canals with the Reciproc Blue R40 system (n = 8): The Reciproc Blue R40 (40/0.06) instruments were used in a reciprocating movement, activated by the X-Smart Plus motor in the “Reciproc All” function, according to the manufacturer's instructions. Each instrument was gradually inserted into the canal, performing in-and-out movements across the three root thirds (cervical, middle, and apical) up to the WL.

Retreatment of MB2 root canals with the Logic 2 system (n = 8): The Logic 2 instruments, sized 25/0.05, 30/0.05, and 35/0.05, were used in sequence. Each instrument was driven by the X-Smart Plus motor in rotary mode, operating at 600 rpm with a torque of 3 Ncm, performing in-and-out movements up to the WL.

Retreatment of MB2 root canals with the WaveOne Gold Medium system (n = 8): The WaveOne Gold Medium instruments (35/0.06) were used in a reciprocating movement, driven by the X-Smart Plus motor in the “WaveOne” function, as recommended by the manufacturer. Each instrument was gradually inserted into the

canal with in-and-out movements in the cervical, middle, and apical thirds up to the WL.

During retreatment, the irrigation protocol for all experimental groups followed the criteria previously established in the root canal preparation step.

Micro-CT Acquisition

All teeth were scanned before and after endodontic retreatment using a micro-CT system (SkyScan 1174; Bruker-microCT). The scan settings were 50 kV, 800 mA, rotation step of 0.8°, aluminum filter of 0.5 mm, and voxel size of 19.7 µm.

CBCT Acquisition

An anthropomorphic model was created using a dry human skull and a fully dentate mandible, both covered with Mix-D material to simulate X-ray attenuation, closely mimicking human soft tissue characteristics [24]. Additionally, a tongue model was crafted and placed in its anatomical position within the model. This comprehensive anthropomorphic model was utilized to acquire the CBCT scans for this study (**Figure 1**). The maxillary left first molar was carefully extracted, and the preselected maxillary molars were individually placed into the corresponding socket to obtain the CBCT scans. To ensure consistent positioning of the teeth during CBCT scans conducted before and after root canal retreatment, custom silicone guides were fabricated for each tooth using condensation silicone ZetaPlus (Zhermack SpA). All CBCT scans were performed using the VeraView X800 device (J Morita, Tokyo, Japan), with parameters set at 5 milliamperes (mA), 70 kilovoltage-peak (kVp), a 40 × 40 mm field of view (FOV), and a voxel size of 0.08 mm. All acquired CBCT scans were then exported in Digital Imaging and Communication in Medicine (DICOM) format.

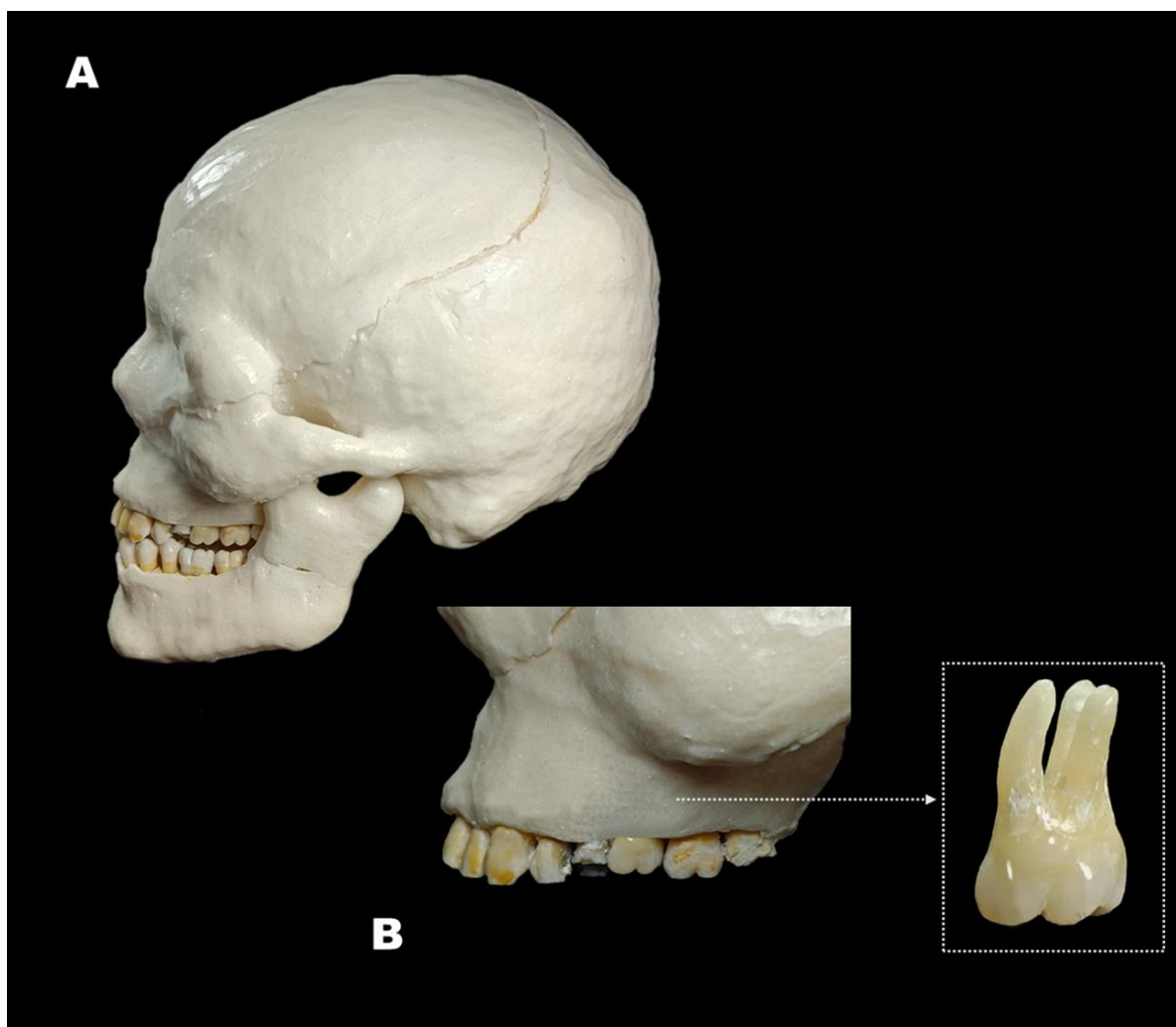


Figure 1. (A) Lateral view of the anthropomorphic phantom of a dry human skull with a full-dentate mandible covered with Mix-D; **(B)** Lateral view of the maxilla showing the region of interest in the study and a magnified view of the maxillary left first molar.

Micro-CT Image Evaluation

The micro-CT images were reconstructed using NRecon software (v.1.6.3, Bruker-microCT) with the parameters set for beam-hardening correction at 51%, smoothing at 5, and ring artifact reduction at 1. The pre- and post-endodontic retreatment images were aligned geometrically by superimposing the micro-CT scans using the "3D registration" function in Data Viewer software (v.1.5.1, Bruker-microCT). Quantitative analysis of the images was performed using CTAn software (Bruker-microCT), and three-dimensional models were subsequently generated with CTVox software (v.3.2, Bruker-microCT).

The volumes of the root canals and the remaining filling material were quantified after endodontic retreatment. The grayscale range for identifying each object

of interest was determined using adaptive thresholding based on a density histogram. To calculate the percentage of remaining filling material, the following formula was applied: filling material after retreatment $\times 100$ / filling material before retreatment [23]. This evaluation was conducted for the entire root canal as well as in the cervical, middle, and apical thirds of both the MB1 and MB2 canals.

To evaluate transportation and centralization in the apical third, superimposed axial images obtained before and after endodontic retreatment were carefully analyzed (**Figure 2**). Root canal transportation was calculated in accordance with the methodology outlined in a previous study [25]. Six distinct regions within the apical third of the MB1 and MB2 canals were measured using axial images processed through CTAn software (Bruker-microCT), with arithmetic mean values subsequently calculated for each region. Centralization scores were assigned on a scale from 0 to 1, where values closer to 1 indicated ideal centralization, and those nearer to 0 suggested less favorable outcomes. For transportation measurements, lower values indicated minimal deviation from the original canal trajectory.

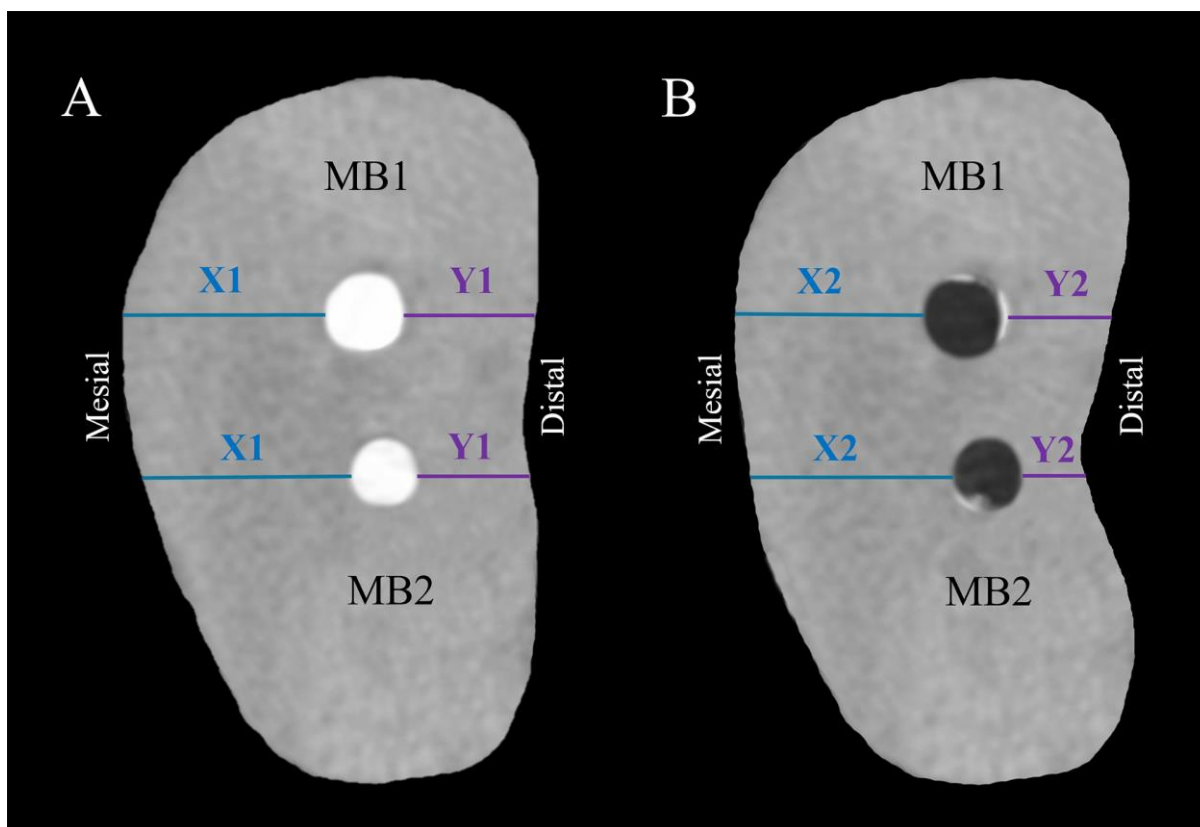


Figure 2. Axial micro-CT reconstructions demonstrating the analysis of transportation and centralization in the apical third of the MB1 and MB2 root canals. **(A)** shows the canals before and **(B)** after endodontic retreatment. X1 and X2 represent the shortest distance between the mesial root edge and the canal before and after retreatment with different NiTi systems, respectively. Similarly, Y1 and Y2 represent the shortest distance between the distal root edge and the canal before and after endodontic retreatment.

Dentin thickness was assessed at 1, 2, 3, and 4 mm below the furcation level in the MB1 and MB2 canals, both prior to and following endodontic retreatment with various NiTi systems. A skilled operator in micro-CT image analysis performed these measurements using axial reconstructions of each sample in CTAn software (Bruker-microCT). The measurements spanned from the external perimeter of the MB1 and MB2 canals to the outer surface of the MB root, covering both the distal (danger zone) and mesial (safety zone) regions. Micro-CT image measurements served as the reference standard for comparison with those obtained from CBCT scans. After a 4-week period, 30% of the samples were randomly selected, and the same operator repeated the measurements to evaluate intra-examiner reliability.

CBCT Image Evaluation

The e-Vol DX software (CDT Software, Bauru, SP, Brazil) was employed to measure dentin thickness in the CBCT scans. This was conducted on a 25-inch color LED monitor with a resolution of 2560 x 1080 pixel. The imaging assessment environment was kept dark and noise-free to maintain optimal conditions. Adjustments to image brightness, contrast, and zoom were made as needed, with a limit of 10 CBCT scans evaluated per session to prevent visual fatigue for the examiner. Initially, the CBCT scans were realigned to ensure that the axial, sagittal, and coronal reconstructions were properly aligned with the long axis of each root canal. A trained and calibrated examiner, experienced in using the e-Vol DX software, performed the dentin thickness measurements in the MB1 and MB2 canals at 1, 2, 3, and 4 mm below the furcation level, using the axial reconstructions from the CBCT scans. These measurements were taken by the same examiner before and after root canal retreatment. To assess intra-examiner agreement, 30% of the samples were randomly selected for reevaluation by the same examiner after 30 days.

For both imaging modalities used in this study, a dentin thickness of less than 0.5 mm following endodontic retreatment was considered indicative of excessive removal in all analyzed regions [26].

Statistical Analysis

The intraclass correlation coefficient (ICC) was used to evaluate intra-operator consistency for each imaging modality (micro-CT and CBCT). Data normality was assessed using the Shapiro-Wilk test. A multiway ANOVA was conducted to compare dentin thickness before and after root canal preparation for the MB1 and MB2 canals, as measured by micro-CT, considering the factors of MB root canals, root canal surface and furcation level. The Mann-Whitney test was used to compare micro-CT parameters between different NiTi systems, while unpaired and paired t-tests assessed differences in dentin removal after retreatment between the NiTi systems and imaging modalities, respectively. The Mann-Whitney and Wilcoxon tests were applied to compare the percentages of critical remaining dentin (<0.5 mm, 0.5-1 mm, and >1 mm) based on the NiTi system and imaging modality, respectively. All statistical analyses were performed using SPSS software (version 24.0, IBM Corp., Armonk, NY, USA), with a significance level set at 5% ($\alpha = 0.05$).

RESULTS

Based on the ICC analysis, the intra-operator reliability for both micro-CT and CBCT analyses was found to be almost perfect, with an ICC value of 0.99.

Table 1 presents the mean and standard deviation of dentin thickness in MB root canals before and after root canal preparation, assessed by micro-CT. MB2 consistently had lower dentin thickness than MB1 in danger zones ($p < 0.05$). There was no significant difference in dentin thickness between MB1 and MB2 in safety zones overall ($p > 0.05$), except at 3 and 4 mm from the furcation level, where MB2 had lower thickness ($p < 0.05$). Generally, there was no significant difference between safety and danger zones within the same MB root canal before and after preparation ($p > 0.05$), except for MB2 after preparation, where the danger zone had significantly lower dentin thickness ($p < 0.05$).

Table 2 shows the performance of NiTi systems in MB root canals after endodontic retreatment based on the micro-CT analysis. In the MB1 canal, Logic 2 consistently left more filling material than Reciproc Blue ($p < 0.05$), except in the cervical third where their performance was similar ($p > 0.05$). In the MB2 canal, there were no significant differences between the NiTi systems overall ($p > 0.05$), but WaveOne Gold retained more filling material than Logic 2 in the apical third ($p < 0.05$) (**Figure 3**). Apical transportation was minimal and similar for both systems in the MB1 and MB2 canals, with no significant differences ($p > 0.05$). Regarding centralization ability, Logic 2 performed better than Reciproc Blue in the MB1 canal ($p < 0.05$). However, there was no significant difference between Logic 2 and WaveOne Gold in the MB2 canal ($p > 0.05$).

Table 3 presents the comparison between imaging modalities and NiTi systems in terms of dentin removal after endodontic retreatment. For the MB1 root canal, there was generally no statistically significant difference between the imaging modalities in measuring dentin removal, regardless of the NiTi system used (Logic 2 and Reciproc Blue) ($p > 0.05$). However, under certain conditions, CBCT measurements underestimated dentin removal ($p < 0.05$). Specifically, this underestimation occurred at 2 mm and 4 mm from the furcation level in the safety zone when using the Logic 2 system, and at 1 mm (danger zone) and 3 mm (safety and danger zones) with the Reciproc Blue system. For the MB2 root canal, CBCT consistently underestimated dentin removal compared to the reference measurement (micro-CT) for both NiTi systems ($p < 0.05$). Exceptions to this behavior included no differences observed at 2

mm from the furcation level in the safety zone for the Logic 2 system, and at 1 mm and 2 mm (safety zone) and 4 mm (danger zone) for the WaveOne Gold system, where measurements from the tested imaging modalities were consistent ($p > 0.05$).

Within the same imaging modality, in general, there were no statistically significant differences between the NiTi systems in terms of dentin removal measurement ($p > 0.05$), except for the measurements performed on CBCT images at 3 mm and 4 mm in the danger zones of the MB1 root canal, where the dentin removal measurement was lower in the Reciproc Blue system compared to Logic 2 ($p < 0.05$). Differently, for the MB2, few differences were observed in the reference measurement performed on micro-CT in the safety zone at 1 mm and 4 mm from the furcation levels, where the WaveOne Gold system showed lower values than the Logic 2 system ($p < 0.05$) (**Table 3**).

Table 4 presents the remaining dentin percentages in the MB1 root canal of the maxillary first molar following endodontic retreatment. The analysis revealed no statistically significant differences between the imaging modalities or NiTi systems, regardless of the root canal surfaces or furcation levels ($p > 0.05$). Notably, no cases showed critically low remaining dentin (less than 0.5 mm) in either the safety or danger zones with any NiTi system, irrespective of the imaging modality used. For the MB2 root canal (**Table 5**), there was also no significant difference in remaining dentin assessment between the imaging modalities, regardless of the NiTi system ($p > 0.05$). Similar to the MB1 root canal, no cases exhibited critically low remaining dentin in the safety zone of the MB2 root canal, except for one case where critical remaining dentin was found at a 4 mm furcation level when assessed with micro-CT. However, in the danger zone, higher percentages of critically low (less than 0.5 mm) and moderately low (0.5–1 mm) remaining dentin were observed, regardless of the NiTi system or imaging modality used (**Figure 4**).

Table 1. Mean $\pm$ standard deviation of dentin thickness before and after root canal preparation in the safety (mesial) and danger (distal) surfaces within each mesiobuccal canal according to the furcation level based on the micro-CT assessment

BASELINE					AFTER PREPARATION			
Furcation Level	MB1		MB2		MB1		MB2	
	Safety Zone	Danger Zone	Safety Zone	Danger Zone	Safety Zone	Danger Zone	Safety Zone	Danger Zone
1 mm	1.60 $\pm$ 0.28	1.61 $\pm$ 0.39 A	1.44 $\pm$ 0.38	1.33 $\pm$ 0.28 B	1.48 $\pm$ 0.24 A	1.32 $\pm$ 0.42 A	1.30 $\pm$ 0.30 A	0.91 $\pm$ 0.36 B*
2 mm	1.48 $\pm$ 0.24	1.43 $\pm$ 0.28 A	1.36 $\pm$ 0.39	1.17 $\pm$ 0.36 B	1.34 $\pm$ 0.21 A	1.18 $\pm$ 0.25 A	1.17 $\pm$ 0.32 A	0.83 $\pm$ 0.39 B*
3 mm	1.41 $\pm$ 0.22	1.40 $\pm$ 0.23 A	1.30 $\pm$ 0.40	1.09 $\pm$ 0.31 B	1.27 $\pm$ 0.18 A	1.18 $\pm$ 0.26 A	1.05 $\pm$ 0.33 B	0.90 $\pm$ 0.39 B*
4 mm	1.41 $\pm$ 0.27	1.43 $\pm$ 0.24 A	1.24 $\pm$ 0.37	1.14 $\pm$ 0.29 B	1.25 $\pm$ 0.25 A	1.24 $\pm$ 0.26 A	1.03 $\pm$ 0.39 B	0.93 $\pm$ 0.37 B*

There was no statistically significant difference between the different furcation levels, regardless of the root canal surface or the mesiobuccal root canal ($P > .05$).

Different uppercase letters indicate a statistically significant difference between the first and second mesiobuccal root canals within the same root canal surface (safety or danger) at same furcation level ($P < .05$).

Asterisks (*) indicate a statistically significant difference between the safety and danger zones within the mesiobuccal root canal at same furcation level ($P < .05$).

Table 2. Median (minimum-maximum) values of remaining filling material, apical transportation, and centralization ability in each mesiobuccal root canal according to the NiTi system based on the micro-CT assessment

Canal	NiTi systems	Total	Remaining Filling Material (%)		
			Cervical	Middle	Apical
MB1	Logic 2	13.9 (8.1 – 73.6) A	12.8 (4.3 – 19.6) A	26.5 (7.7 – 98.1) A	20.6 (0 – 93.5) A
	Reciproc Blue	7 (0.4 – 11.3) B	10.6 (0.01 – 17) A	2.8 (0 – 10.2) B	2.7 (0 – 12.9) B
MB2	Logic 2	17.5 (1.4 – 85.8) A	14.1 (0 – 33.7) A	13.3 (1.5 – 94.3) A	14.9 (0 – 97.7) B
	WaveOne Gold	33.1 (11 – 56.5) A	11.6 (0.18 – 54.3) A	37.4 (6.4 – 86.1) A	54.2 (16 – 84.8) A
Apical Transportation					
MB1	Logic 2		0.02 (0 – 0.09) A		
	Reciproc Blue		0.03 (0 – 0.09) A		
MB2	Logic 2		0.08 (0.04 – 0.23) A		
	WaveOne Gold		0.02 (0 – 0.41) A		
Apical Centralization ability					
MB1	Logic 2		0.07 (0.03 – 0.12) B		
	Reciproc Blue		0.11 (0.08 – 0.20) A		
MB2	Logic 2		0.06 (0.01 – 0.14) A		
	WaveOne Gold		0.44 (0 -14.5) A		

Different uppercase letters represent a significant statistical difference between the NiTi system within each mesiobuccal canal ($P < .05$).

Table 3. Mean $\pm$ standard deviation values of dentin removal in the safety and danger zones, categorized by furcation level, mesiobuccal canal, and imaging modality for NiTi file systems

Furcation Level	Surface	MB1				MB2			
		Logic 2		Reciproc Blue		Logic 2		WaveOne Gold	
		Micro-CT	CBCT	Micro-CT	CBCT	Micro-CT	CBCT	Micro-CT	CBCT
1 mm	Safety zone	0.23 $\pm$ 0.13 Aa	0.14 $\pm$ 0.10 Aa	0.19 $\pm$ 0.09 Aa	0.16 $\pm$ 0.10 Aa	0.32 $\pm$ 0.14 Aa	0.14 $\pm$ 0.07 Ba	0.17 $\pm$ 0.12 Ab	0.12 $\pm$ 0.09 Aa
	Danger zone	0.55 $\pm$ 0.34 Aa	0.33 $\pm$ 0.18 Aa	0.56 $\pm$ 0.20 Aa	0.32 $\pm$ 0.07 Ba	0.62 $\pm$ 0.15 Aa	0.37 $\pm$ 0.14 Ba	0.55 $\pm$ 0.23 Aa	0.24 $\pm$ 0.15 Ba
2 mm	Safety zone	0.26 $\pm$ 0.15 Aa	0.17 $\pm$ 0.12 Ba	0.21 $\pm$ 0.05 Aa	0.17 $\pm$ 0.15 Aa	0.21 $\pm$ 0.36 Aa	0.19 $\pm$ 0.12 Aa	0.23 $\pm$ 0.11 Aa	0.20 $\pm$ 0.19 Aa
	Danger zone	0.46 $\pm$ 0.05 Aa	0.36 $\pm$ 0.15 Aa	0.36 $\pm$ 0.19 Aa	0.32 $\pm$ 0.11 Aa	0.54 $\pm$ 0.13 Aa	0.23 $\pm$ 0.07 Ba	0.43 $\pm$ 0.21 Aa	0.14 $\pm$ 0.09 Ba
3 mm	Safety zone	0.19 $\pm$ 0.14 Aa	0.15 $\pm$ 0.08 Aa	0.26 $\pm$ 0.10 Aa	0.16 $\pm$ 0.09 Ba	0.38 $\pm$ 0.07 Aa	0.19 $\pm$ 0.07 Ba	0.31 $\pm$ 0.12 Aa	0.17 $\pm$ 0.15 Ba
	Danger zone	0.38 $\pm$ 0.13 Aa	0.33 $\pm$ 0.16 Aa	0.35 $\pm$ 0.15 Aa	0.18 $\pm$ 0.10 Bb	0.38 $\pm$ 0.21 Aa	0.16 $\pm$ 0.11 Ba	0.37 $\pm$ 0.31 Aa	0.09 $\pm$ 0.06 Ba
4 mm	Safety zone	0.26 $\pm$ 0.12 Aa	0.12 $\pm$ 0.07 Ba	0.26 $\pm$ 0.08 Aa	0.20 $\pm$ 0.10 Aa	0.38 $\pm$ 0.13 Aa	0.15 $\pm$ 0.08 Ba	0.24 $\pm$ 0.10 Ab	0.10 $\pm$ 0.07 Ba
	Danger zone	0.33 $\pm$ 0.15 Aa	0.34 $\pm$ 0.15 Aa	0.33 $\pm$ 0.19 Aa	0.18 $\pm$ 0.12 Ab	0.32 $\pm$ 0.16 Aa	0.11 $\pm$ 0.08 Ba	0.26 $\pm$ 0.20 Aa	0.16 $\pm$ 0.08 Aa

Different uppercase letters indicate a statistically significant difference between the micro-CT and CBCT systems in measuring dentin removal (measurement_{Baseline} – measurement_{After retreatment}) within each mesiobuccal canal and root surface at the same furcation level ($P < .05$).

Different lowercase letters represent a significant statistical difference between the NiTi file systems in terms of dentin removal measurement removal (measurement_{Baseline} – measurement_{After retreatment}) within each modality, mesiobuccal canal, and root surface at the same furcation level ($P < .05$).

Table 4. Critical remaining dentin percentages on the MB1 root canal of maxillary first molar after endodontic retreatment based on micro-CT and CBCT analysis by root canal surface, furcation level, and NiTi systems

Surface	Remaining dentin	Logic 2 (%)							
		1 mm	1 mm	2 mm	2 mm	3 mm	3 mm	4 mm	4mm
		Micro-CT	CBCT	Micro-CT	CBCT	Micro-CT	CBCT	Micro-CT	CBCT
Safety Zone	< 0.5 mm	0	0	0	0	0	0	0	0
	0.5 – 1 mm	0	12.5	12.5	25	0	50	37.5	50
	> 1mm	100	87.5	87.5	75	100	50	62.5	50
	<i>P</i> value	> .05		> .05		> .05		> .05	
Danger Zone	< 0.5 mm	0	0	0	0	0	0	0	0
	0.5 – 1 mm	50	50	50	50	62.5	62.5	62.5	62.5
	> 1mm	50	50	50	50	37.5	37.5	37.5	37.5
	<i>P</i> value	> .05		> .05		> .05		> .05	
Surface	Remaining dentin	Reciproc Blue (%)							
		1 mm	1 mm	2 mm	2 mm	3 mm	3 mm	4 mm	4mm
		Micro-CT	CBCT	Micro-CT	CBCT	Micro-CT	CBCT	Micro-CT	CBCT
Safety Zone	< 0.5 mm	0	0	0	0	0	0	0	0
	0.5 – 1 mm	0	25	0	12.5	12.5	37.5	37.5	75
	> 1mm	100	75	100	87.5	87.5	62.5	62.5	25
	<i>P</i> value	> .05		> .05		> .05		> .05	
Danger Zone	< 0.5 mm	0	0	0	0	0	0	0	0
	0.5 – 1 mm	62.5	75	87.5	87.5	50	75	37.5	50
	> 1mm	37.5	25	12.5	12.5	50	25	62.5	50
	<i>P</i> value	> .05		> .05		> .05		> .05	

There was no statistically significant difference between the imaging modalities and the NiTi system regardless of the root canal surface and furcation level ($P>.05$).

Table 5. Critical remaining dentin percentages on the MB2 root canal of maxillary first molar after endodontic retreatment based on micro-CT and CBCT analysis by root canal surface, furcation level, and NiTi systems

		Logic 2 (%)							
Surface	Remaining dentin	1 mm	1 mm	2 mm	2 mm	3 mm	3 mm	4 mm	4mm
		Micro-CT	CBCT	Micro-CT	CBCT	Micro-CT	CBCT	Micro-CT	CBCT
Safety Zone	< 0.5 mm	0	0	0	0	0	0	0	0
	0.5 – 1 mm	12.5	37.5	50	75	75	100	75	87.5
	> 1mm	87.5	62.5	50	25	25	0	25	12.5
	<i>P</i> value	> .05		> .05		> .05		> .05	
Danger Zone	< 0.5 mm	12.5	12.5	25	25	25	12.5	25	25
	0.5 – 1 mm	62.5	87.5	50	50	50	62.5	50	50
	> 1mm	25	0	25	25	25	25	25	25
	<i>P</i> value	> .05		> .05		> .05		> .05	
		WaveOne Gold (%)							
Surface	Remaining dentin	1 mm	1 mm	2 mm	2 mm	3 mm	3 mm	4 mm	4mm
		Micro-CT	CBCT	Micro-CT	CBCT	Micro-CT	CBCT	Micro-CT	CBCT
Safety Zone	< 0.5 mm	0	0	0	0	0	0	12.5	0
	0.5 – 1 mm	25	50	50	87.5	62.5	87.5	62.5	87.5
	> 1mm	75	50	50	12.5	37.5	12.5	25	12.5
	<i>P</i> value	> .05		> .05		> .05		> .05	
Danger Zone	< 0.5 mm	37.5	37.5	37.5	25	25	12.5	12.5	0
	0.5 – 1 mm	37.5	50	50	62.5	50	87.5	62.5	87.5
	> 1mm	25	12.5	12.5	12.5	25	0	25	12.5
	<i>P</i> value	> .05		> .05		> .05		> .05	

There was no statistically significant difference between the imaging modalities and the NiTi system regardless of the root canal surface and furcation level ($P > .05$).

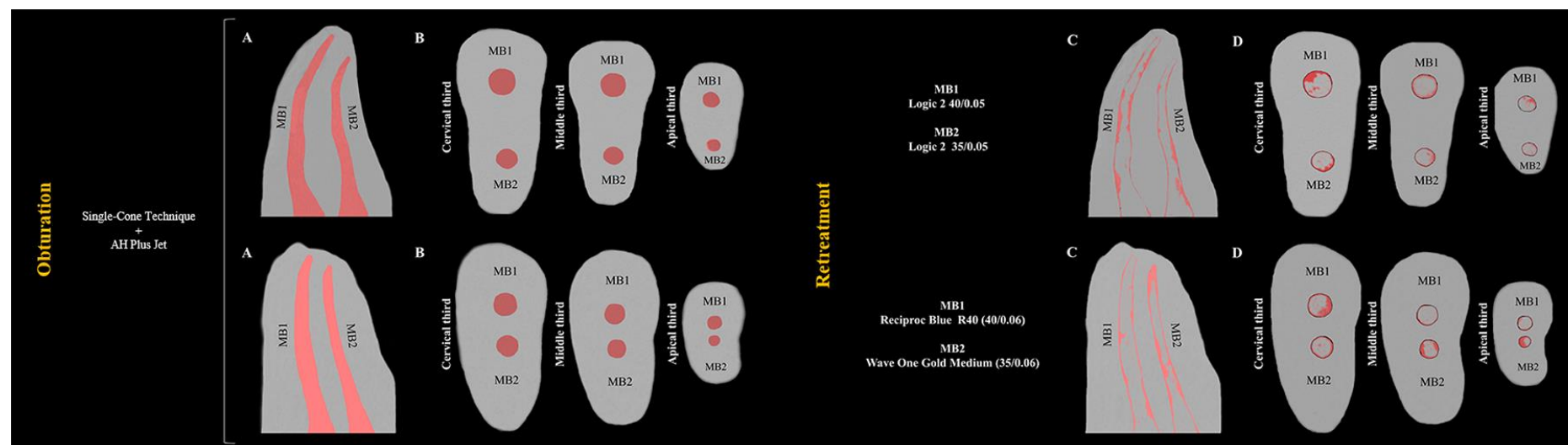


Figure 3. Three-dimensional and cross-sectional micro-CT reconstructions of the cervical, middle, and apical thirds of the MB1 and MB2 canals in two maxillary molars. **(A)** and **(B)** depict the canals after obturation, while **(C)** and **(D)** illustrate the canals following endodontic retreatment with various NiTi systems. The filling material and remaining filling material are shown in pink.

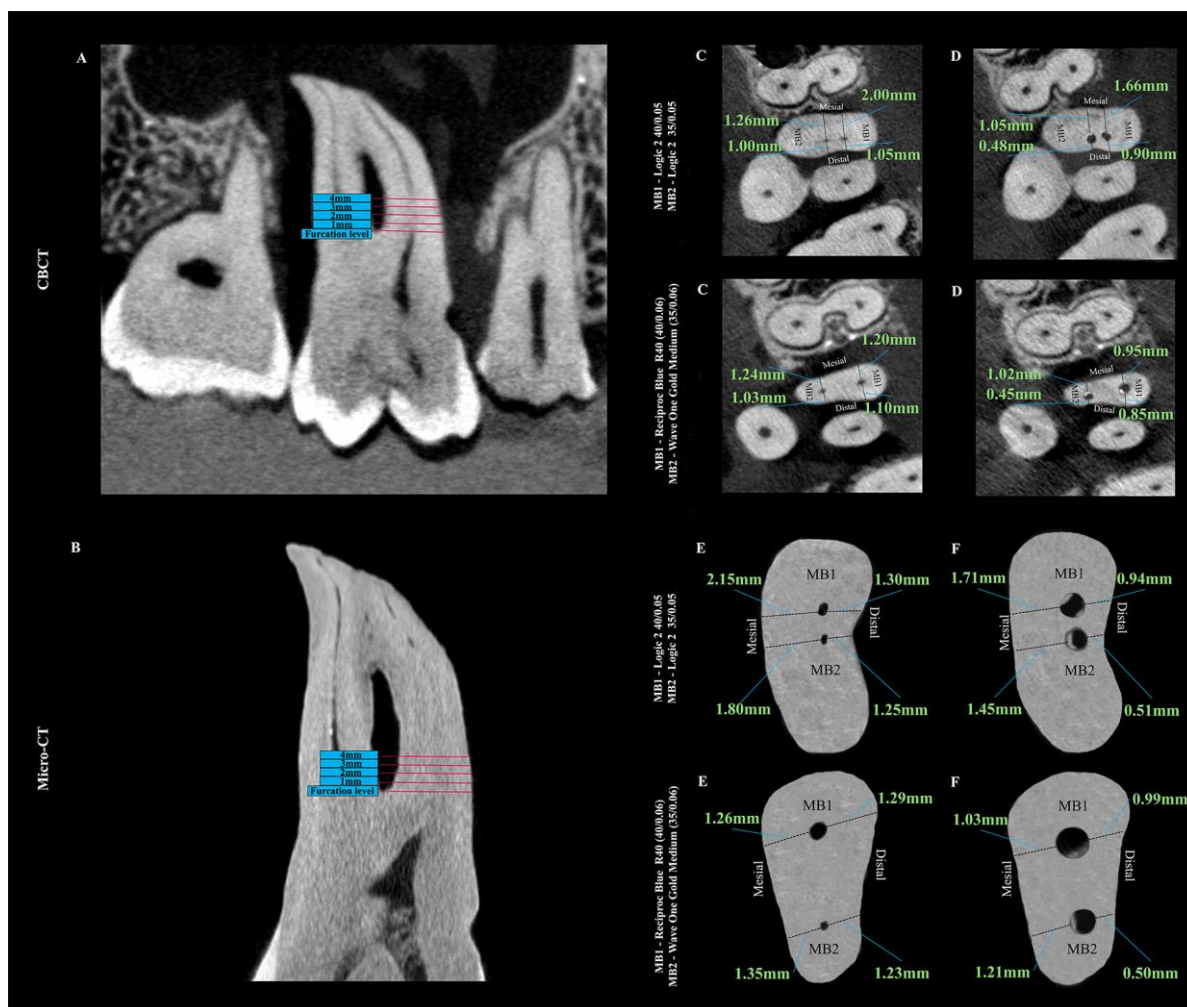


Figure 4. (A) and (B) show the sagittal reconstructions of CBCT and micro-CT, respectively, highlighting the locations where dentin thickness measurements were taken below the furcation level. The axial reconstructions of CBCT for the MB1 and MB2 canals, both in the preoperative state (C) and after endodontic retreatment with different NiTi systems (D), display the dentin thickness measurements taken 2 mm below the furcation level, on the mesial (safety zone) and distal (danger zone) aspects. The corresponding axial reconstructions from micro-CT of the same MB1 and MB2 canals, before (E) and after endodontic retreatment (F), evaluated under the same conditions described for the CBCT scans, illustrate the dentin thickness measurements used as references in the micro-CT images.

DISCUSSION

The morphological features of the MB root in maxillary molars, particularly the critical dentin thickness in the danger zone, pose significant challenges for effective preparation, cleaning, and disinfection [5-9]. Preserving the pericervical integrity of the MB1 and MB2 canals is essential for successful endodontic outcomes [4]. The presence of isthmuses, abrupt curvatures, apical ramifications, and narrow canals, especially in the MB2 canals, further complicates treatment [5-9]. Although endodontic retreatment is the primary approach when initial treatment fails [1, 3], there is a notable lack of research specifically focused on the retreatment of MB1 and MB2 canals, particularly MB2. This study tackles the issue by evaluating the efficacy of three NiTi systems and their safety in preserving dentin in both safety and danger zones during the endodontic retreatment of MB1 and MB2 canals. The results revealed differences in certain parameters among the NiTi systems, leading to the rejection of the null hypothesis.

The findings of this investigation clearly demonstrated that the preoperative dentin thickness in the MB2 canal was consistently thinner in the danger zone compared to the MB1 canal across all evaluated furcation levels (as detailed in Table 1). These results align with those reported in previous studies [4, 5-9]. Consequently, meticulous treatment planning is imperative for clinicians to minimize the risk of perforation in the furcation area [5]. Furthermore, this study revealed a significant reduction in dentin thickness in the danger zone of MB2 canals after preparation, even with the conservative approach employed. All MB2 canals were consistently prepared using the Logic 2 instrument with a 25-tip size and 0.03 taper, in line with previous recommendations [6]. This outcome can be attributed to the tendency of instruments to exert pressure on the distal wall during canal shaping, likely leading to increased dentin removal in the danger zone [5].

The micro-CT analysis in this study revealed that the Reciproc Blue system was more effective than Logic 2 in removing filling material, both throughout the entire canal and specifically in the middle and apical thirds of the MB1 canals. This increased efficacy may be attributed to the variable taper of Reciproc Blue R40, which features a 0.06 taper in the final 3 mm of the instrument [27], while Logic 2 maintains a constant 0.05 taper throughout its active length [16, 17]. The greater taper of Reciproc Blue likely contributed to its superior ability to remove filling material in the MB1 canals.

Additionally, the thermal treatment applied to these instruments may have significantly influenced the results. The CM wire thermal treatment of Logic 2 provides greater flexibility compared to the Blue-Wire treatment of Reciproc Blue [28]. However, this increased flexibility of Logic 2 may have hindered effective penetration into the filling material, resulting in a higher percentage of residual material in the MB1 canals. Conversely, the reduced flexibility of Reciproc Blue may have facilitated better penetration, leading to more effective removal of filling material.

For the MB2 root canals, the current results indicated that both Logic 2 and WaveOne Gold systems were equally effective in removing filling material. However, Logic 2 outperformed WaveOne Gold in the apical third, leaving significantly less residual filling material. This difference could be attributed to the higher operating speed of Logic 2, which runs at 600 rpm compared to the 350 rpm of WaveOne Gold [13], both in accordance with the manufacturer's guidelines. The higher working speed of the Logic 2 system may have been a key factor in its more efficient removal of filling material in the apical third of the MB2 canals. Nonetheless, it is important to note that none of the systems were able to completely remove the filling material from the MB1 and MB2 canals, underscoring the inherent complexity of endodontic retreatment in these root canals.

Regarding dentin removal during endodontic retreatment of the MB1 and MB2 canals at various furcation levels, the micro-CT reference measurements generally did not reveal significant differences among the Logic 2, Reciproc Blue, and WaveOne Gold systems. This uniformity across the different NiTi instruments likely reflects continuous advancements in their mechanical properties, such as design, surface finish, nickel/titanium ratios, thermal treatments, and flexibility [29]. Moreover, the findings of this study indicate a minimal degree of apical transportation in both the MB1 and MB2 canals, irrespective of the NiTi system employed. Furthermore, all NiTi instruments demonstrated adequate capability to maintain canal centralization in the apical region following retreatment procedures. Overall, these factors indicate that both the Logic 2 and Reciproc systems are generally safe in terms of dentin removal in MB1 canals, while the Logic 2 and WaveOne Gold systems demonstrate similar safety in MB2 root canals. However, it is important to note that in some specific cases, CBCT measurements underestimated dentin removal compared to micro-CT.

The study identified a higher incidence of critically low (less than 0.5 mm) and moderately low (0.5–1 mm) remaining dentin in the danger zone of the MB2 canal after

endodontic retreatment, regardless of the NiTi system or imaging modality used (micro-CT or CBCT). These findings highlight the significant challenges posed by the danger zone in the MB2 canal, where the dentin is inherently thin due to the concave shape of the MB root in maxillary molars [5-9]. This thinness is further exacerbated by the pressure applied by NiTi instruments during canal enlargement, particularly in this anatomically vulnerable area [5]. Clinically, these results are crucial, as this study is the first to evaluate the impact of various NiTi instruments on pericervical dentin preservation following the retreatment of MB1 and MB2 canals. A reduction in dentin thickness to 0.5 mm can compromise fracture resistance and negatively impact the endodontic prognosis [5-9].

These findings emphasize the importance of clinicians considering not just the taper and tip diameter of the instrument, but also how the taper varies within the pericervical dentin region [30], particularly in critical areas such as the danger zone of the MB2 canal. While it is crucial to prioritize the preservation of pericervical dentin, this focus should not compromise the effectiveness of filling material removal [1-3]. Proper enlargement, particularly in the apical third, is essential for thorough cleaning and disinfection, which are key to successful endodontic retreatment [31]. Moreover, this study highlights the valuable role of CBCT imaging in planning the endodontic retreatment of MB1 and MB2 canals. Preoperative CBCT scans offer clinicians essential insights into dentin thickness [4, 8, 9], allowing them to devise retreatment strategies that minimize unnecessary dentin removal in the pericervical region of these canals. Additionally, the study reinforces the reliability of CBCT imaging for assessing dentin thickness during the retreatment planning process, as no significant differences were found between CBCT and micro-CT, which served as the reference standard, in evaluating the remaining dentin percentages in MB1 and MB2 canals after retreatment.

When interpreting the results of this study, certain limitations should be considered. A notable limitation is the absence of demographic information on the tooth donors, as pericervical dentin thickness can vary across different population groups [6]. Additionally, since the study was conducted *ex vivo*, movement artifacts on CBCT images were not a factor. Furthermore, the generalizability of the findings may be limited when applied to other CBCT units with differing technical specifications. Consequently, future studies are strongly recommended to address these additional variables. Further investigations should also explore the effectiveness of other NiTi systems with varying tapers, designs, and thermal treatments to evaluate their safety

and efficacy during the retreatment of MB1 and MB2 canals, particularly with regard to pericervical dentin removal.

Despite these limitations, this study boasts several significant strengths. High-resolution micro-CT measurements were employed as the reference standard to validate CBCT evaluations of the remaining dentin thickness after the retreatment of MB1 and MB2 canals. The use of an anthropomorphic phantom coated with Mix-D material successfully replicated the X-ray attenuation characteristics of facial soft tissues, providing a realistic simulation of clinical conditions during CBCT image acquisition. Furthermore, the study utilized e-Vol DX software for CBCT image analysis, applying the *Blooming Artifact Reduction* (BAR) post-processing filter to minimize volumetric distortion artifacts commonly observed in root canals containing remaining filling material after retreatment. This approach enhances the accuracy and reliability of CBCT-based dentin thickness measurements [32-34]. Ultimately, the findings of this study provide valuable insights into the efficacy and safety of three different NiTi systems for the retreatment of MB1 and MB2 canals, with particular emphasis on the preservation of pericervical dentin. These results are crucial for guiding retreatment strategies and clinical decision-making.

CONCLUSION

In conclusion, the micro-CT analysis demonstrated that Reciproc Blue was more effective at removing filling material from MB1 canals compared to Logic 2, while Logic 2 outperformed WaveOne Gold in the apical third of MB2 canals. All NiTi systems exhibited minimal apical transportation and maintained effective canal centralization in both MB1 and MB2. Overall, the systems showed comparable performance in dentin removal. However, a significant reduction in dentin thickness below 0.5 mm in the danger zone of MB2 canals was observed after retreatment, regardless of the NiTi system used. Preoperative CBCT scans are vital for planning the endodontic retreatment of MB1 and MB2 canals, offering critical information into pericervical dentin thickness and allowing clinicians to develop strategies that minimize unnecessary dentin removal.

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Data availability All data are available from the corresponding author upon request.

Declarations

Ethical approval This study was conducted in accordance with the principles outlined in the Declaration of Helsinki. Ethical approval was obtained from the Ethics Committee of São Paulo State University (UNESP) (approval number 41916720.7.0000.5416).

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

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4 DISCUSSÃO

O sistema de canais radiculares apresenta anatomia complexa, apresentando diversas secções transversais, ramificações, curvaturas e canais acessórios. Essa complexidade impõe desafios significativos ao tratamento endodôntico, especialmente no preparo, desinfecção e selamento tridimensional, podendo comprometer o sucesso¹⁻⁷. Para superar esses desafios, é essencial que o clínico tenha um conhecimento aprofundado da morfologia dos canais radiculares. Nesse contexto, a obtenção precisa de modelos 3D das estruturas endodônticas, como a câmara pulpar e os canais radiculares, é crucial para um fluxo de trabalho digital eficaz na Endodontia⁵⁸⁻⁶². Entretanto, a segmentação dessas estruturas em imagens de TCFC ainda representa um desafio significativo com os métodos tradicionais^{55,56}. Nesse cenário, a IA surge como uma ferramenta promissora para superar as limitações inerentes à subjetividade e variabilidade humanas.

Os resultados das **Publicações 1 e 2** revelaram que o algoritmo de IA desenvolvido e validado proporcionou segmentações automatizadas extremamente precisas das estruturas endodônticas em dentes unirradiculares e birradiculares, gerando modelos 3D de alta acurácia. Esses achados abrem caminhos para avanços significativos no diagnóstico, no planejamento de tratamento e na educação clínica em Endodontia. Além disso, é importante enfatizar que a IA demonstrou desempenho superior à abordagem manual altamente especializada conduzida por humanos em várias métricas de diagnóstico. Esse resultado pode ser atribuído à eliminação de fatores subjetivos, emocionais e técnicos característicos dos especialistas humanos⁶⁴. A eficiência de tempo também foi substancialmente otimizada, com a IA sendo 54 vezes mais rápida para dentes unirradiculares e 75 vezes mais rápida para birradiculares, em comparação ao método manual. Tomados em conjunto, esses resultados têm o potencial de transformar o fluxo de trabalho digital em Endodontia, proporcionando modelos 3D altamente precisos do sistema de canais radiculares, o que é especialmente útil em casos de anatomia interna complexa, como em canais radiculares calcificados que exigem acesso endodôntico guiado. Além disso, esses achados abrem novas perspectivas para a segmentação das câmaras pulpares e dos canais radiculares de molares superiores e inferiores, sinalizando um avanço significativo nessa área em estudos futuros.

O preparo adequado do canal radicular é fundamental para assegurar um prognóstico endodôntico favorável^{3,4}. Os molares superiores, devido à sua anatomia complexa e à alta prevalência do canal MV2 na população, apresentam desafios clínicos consideráveis. Adicionalmente, a espessura reduzida de dentina na região pericervical do canal MV2 eleva o risco de perfuração durante o preparo, exigindo cuidados específicos no tratamento¹³⁻¹⁵. Para enfrentar esses desafios, é indispensável utilizar instrumentos de NiTi mecanicamente aprimorados, insertos ultrassônicos, microscópios cirúrgicos e imagens de TCFC^{19,20}. Esses recursos são essenciais para assegurar um planejamento e tratamento eficazes dos canais MV1 e MV2. Os achados da **Publicação 4** confirmam a eficácia e segurança dos sistemas de NiTi ProTaper Ultimate e Logic 2 no preparo desses canais radiculares. Um aspecto fundamental para o desempenho adequado desses sistemas na prática clínica é a manutenção de uma espessura de dentina superior a 0,5 mm, essencial para prevenir fraturas radiculares e garantir um prognóstico favorável^{16,17}. Espessuras inferiores a 0,5 mm são críticas e estão associadas a um risco elevado de complicações^{16,17}. Além disso, os resultados da **Publicação 4** ressaltam a importância das imagens de TCFC na mensuração da espessura de dentina pré-operatória nos canais MV1 e MV2. Esse recurso é crucial para a escolha adequada dos instrumentos de NiTi, especialmente no que se refere ao taper, com o objetivo de preservar a região pericervical e evitar seu enfraquecimento.

A infecção bacteriana persistente é um fator decisivo no fracasso do tratamento endodôntico². Além disso, a delicada e previamente reduzida espessura da dentina pericervical nos canais MV2 antes do retratamento torna o procedimento ainda mais desafiador. Os dados da **Publicação 5** mostram algumas variações na eficácia de remoção de material obturador entre os sistemas Reciproc Blue e Logic 2 no canal MV1, assim como entre o WaveOne Gold e o ProDesign Logic 2 no canal MV2 (**Publicação 5, Tabela 2**). No entanto, as variações nas porcentagens de dentina remanescente após o retratamento não foram significativas, indicando que todos os sistemas de NiTi avaliados são geralmente seguros para o retratamento dos canais MV1 e MV2. Contudo, é fundamental destacar que, independentemente do sistema de NiTi utilizado, houve uma redução significativa na espessura da dentina para menos de 0,5 mm na zona de perigo dos canais MV2 após o retratamento. Esses resultados destacam a relevância das imagens de TCFC pré-operatórias na avaliação da espessura da dentina antes do retratamento endodôntico. Essa prática permite a

seleção precisa do instrumento de NiTi com o taper adequado, garantindo um planejamento específico para o caso clínico, com ênfase na preservação da dentina pericervical na zona de risco do canal MV2. A solicitação da TCFC nesse cenário é justificada pelos desafios intrínsecos associados ao preparo e retratamento dos canais MV1 e MV2, que influenciam diretamente o sucesso do planejamento endodôntico¹³.

A complexidade diagnóstica em casos de possíveis falhas no tratamento endodôntico é amplamente discutida na literatura, ressaltando a importância de uma avaliação criteriosa da obturação do canal radicular para identificar vazios no preenchimento^{65,66}. No ambiente clínico, essa análise é geralmente realizada por meio de radiografias periapicais⁶⁵. No entanto, quando os sintomas sugerem uma falha no tratamento, os exames de TCFC tornam-se essenciais para um planejamento de retratamento preciso e confiável⁶⁶. A detecção de vazios no material obturador é especialmente desafiadora devido aos artefatos de distorção volumétrica presentes nas imagens de TCFC de dentes obturados, o que compromete a qualidade das imagens para fins diagnósticos⁶⁶.

Os resultados da **Publicação 3** indicam que a aplicação do filtro BAR nas imagens de TCFC, especificamente com o aparelho OP300 Maxio, melhora a acurácia diagnóstica na detecção de vazios em canais ovais longos obturados com os cimentos AH Plus Jet e Bio-C Sealer. Além disso, o filtro BAR aumenta significativamente a especificidade na detecção de vazios nos terços cervical/médio dos canais radiculares ovais obturados com Bio-C Sealer em exames adquiridos com o aparelho VeraView X800. Esses achados têm grande relevância clínica, pois, em casos de suspeita de fracasso endodôntico, é fundamental avaliar com precisão a qualidade da obturação do canal radicular. Uma avaliação detalhada possibilita um planejamento adequado do retratamento ou a identificação das causas do insucesso, evitando decisões equivocadas, como a extração desnecessária do dente⁶⁶.

Em síntese, os resultados inovadores e originais das cinco publicações apresentadas neste estudo trazem contribuições significativas para a prática endodôntica, com aplicação clínica direta. Esses achados não apenas aprimoram a precisão diagnóstica e a eficácia dos tratamentos, mas também têm o potencial de transformar a tomada de decisão clínica. Ao possibilitar um planejamento de tratamento mais individualizado e adaptado às necessidades específicas de cada paciente, esses avanços abrem novas perspectivas na endodontia, contribuindo para maiores taxas de sucesso nos tratamentos endodônticos.

5 CONCLUSÃO

Com base nos resultados obtidos, pode-se concluir que:

Publicação 1: A ferramenta proposta baseada em IA demonstrou desempenho altamente preciso e rápido na segmentação de canais radiculares em dentes unirradiculares em imagens de TCFC. Esses resultados têm o potencial de transformar o fluxo de trabalho digital em endodontia, possibilitando tratamentos mais consistentes e previsíveis.

Publicação 2: O algoritmo de IA desenvolvido e validado proporcionou uma segmentação automática altamente precisa dos canais radiculares de dentes birradiculares, exigindo um tempo mínimo de processamento. A ferramenta proposta possui a capacidade de representar um grande avanço no planejamento digital para o tratamento endodôntico, tornando mais simples o fluxo de trabalho digital em endodontia.

Publicação 3: O filtro BAR mostrou um aprimoramento significativo na acurácia diagnóstica para a detecção de espaços vazios no terço apical dos canais radiculares ovais longos ao utilizar o aparelho de TCFC OP300 Maxio, tanto com o cimento AH Plus Jet quanto com o Bio-C Sealer. Adicionalmente, o filtro BAR aumentou substancialmente a especificidade na identificação de espaços vazios no terço apical com o AH Plus Jet. Embora o dispositivo VeraView X800 não tenha mostrado uma melhora geral no desempenho diagnóstico ao utilizar o filtro BAR, ele apresentou um aumento significativo na especificidade para detectar espaços vazios nos terços cervical/médio dos canais preenchidos com o Bio-C Sealer.

Publicação 4: O sistema ProTaper Ultimate promove maior aumento volumétrico no terço cervical do canal MV1 em comparação ao Logic 2, que, em contrapartida, gerou menos debris no terço apical, conforme revelado pelas análises de micro-CT. De modo geral, ambos os sistemas de NiTi apresentaram percentuais semelhantes de superfícies não instrumentadas nos canais MV1 e MV2, mantendo eficazmente a trajetória original dos canais e preservando uma espessura de dentina superior a 0,5 mm. As imagens de TCFC são recomendadas para avaliar a espessura

dentinária nas zonas de segurança e perigo dos canais radiculares MV1 e MV2. Contudo, é importante destacar que, em alguns casos, a espessura da dentina pode ser subestimada nas imagens de TCFC, dependendo do protocolo utilizado nesta investigação.

Publicação 5: O sistema Reciproc Blue mostrou-se mais eficaz na remoção de material obturador dos canais MV1 em comparação ao Logic 2, enquanto o Logic 2 superou o WaveOne Gold no terço apical dos canais MV2. Todos os sistemas de NiTi apresentaram mínima alteração na trajetória apical e mantiveram uma centralização eficaz dos canais MV1 e MV2, como demonstrado pelas análises de micro-CT. De modo geral, os sistemas de NiTi tiveram desempenhos semelhantes na remoção de dentina. Contudo, foi observada uma redução significativa na espessura da dentina abaixo de 0,5 mm na zona de perigo dos canais MV2 após o retratamento, independentemente do sistema de NiTi empregado e do tipo de imagem utilizada, seja TCFC ou micro-CT. As imagens pré-operatórias de TCFC são importantes para o planejamento do retratamento endodôntico dos canais MV1 e MV2, fornecendo informações valiosas sobre a espessura da dentina pericervical e permitindo que os clínicos desenvolvam estratégias para minimizar a remoção desnecessária de dentina.

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APÊNDICE A – METODOLOGIA EXPANDIDA

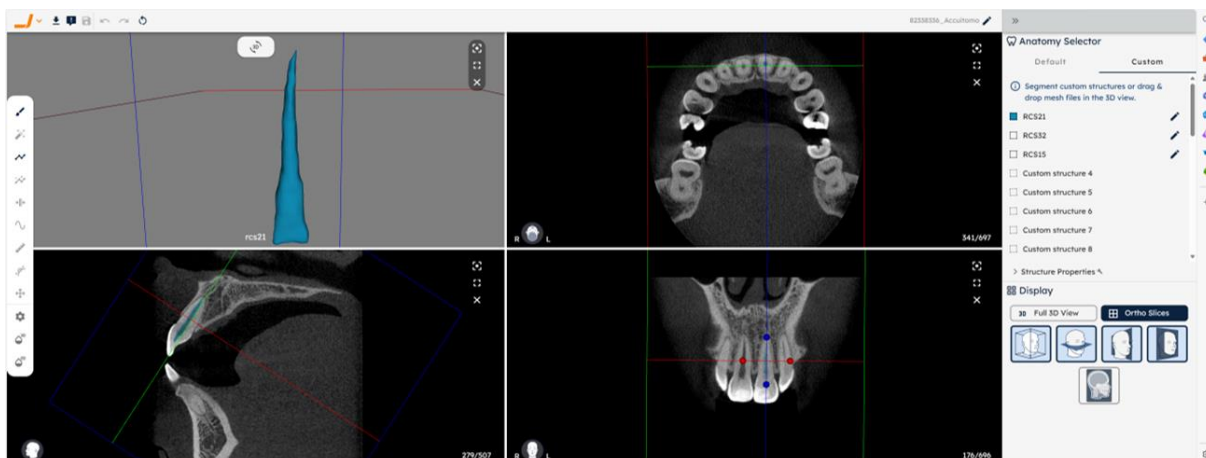
PUBLICAÇÕES 1 e 2

Arquitetura das redes neurais convolucionais (RNC)

A segmentação baseada em inteligência artificial (IA) foi realizada através da combinação de múltiplas redes tridimensionais (3D) com a arquitetura U-Net. Cada uma dessas redes consistia em 4 blocos de codificação e 3 blocos de decodificação, onde cada bloco realizava 2 convoluções com um kernel de $3 \times 3 \times 3$, seguido pela ativação da unidade linear retificada (ReLU) e normalização em grupo com 8 mapas de características. Essas redes interconectadas foram fundamentais para a segmentação automática das estruturas da cavidade pulpar, como a câmara pulpar e o canal radicular. A opção por uma abordagem em duas etapas foi estratégica, reconhecendo as limitações inerentes das RNC quando aplicadas a imagens de tomografia computadorizada de feixe cônico (TCFC) com um grande campo de visão. Na primeira etapa, a rede neural realizou uma detecção inicial das estruturas de interesse, servindo como um modelo preliminar de segmentação. Posteriormente, na segunda etapa, a rede refinou a segmentação obtida na etapa anterior, permitindo a segmentação automática das estruturas endodônticas em resolução total. Esses modelos de RNC foram implementados utilizando PyTorch, e técnicas de aumento de dados foram aplicadas para enriquecer o conjunto de dados de treinamento, aumentando a robustez do modelo de IA desenvolvido. Para isso, foram utilizadas técnicas como corte aleatório, dimensionamento, rotação, espelhamento e deformação elástica. Além disso, os parâmetros do modelo de IA foram otimizados utilizando o algoritmo de otimização ADAM, que envolveu a redução da taxa de aprendizado e a implementação de interrupção prematura baseada no conjunto de validação, garantindo a generalização do modelo. Após esses procedimentos, o modelo de IA desenvolvido foi integrado à plataforma online baseada em nuvem "Virtual Patient Creator", disponível no site: <https://relu.eu/>. O acesso à plataforma requer registro do usuário. Essa plataforma é especializada na segmentação automatizada de estruturas dentomaxilofaciais em imagens de TCFC, incluindo dentes, canal mandibular, canal incisivo mandibular e osso alveolar maxilar. Nas **Figuras 1 e 2**, são exibidos os modelos 3D dos dentes 21 e 14 respectivamente,

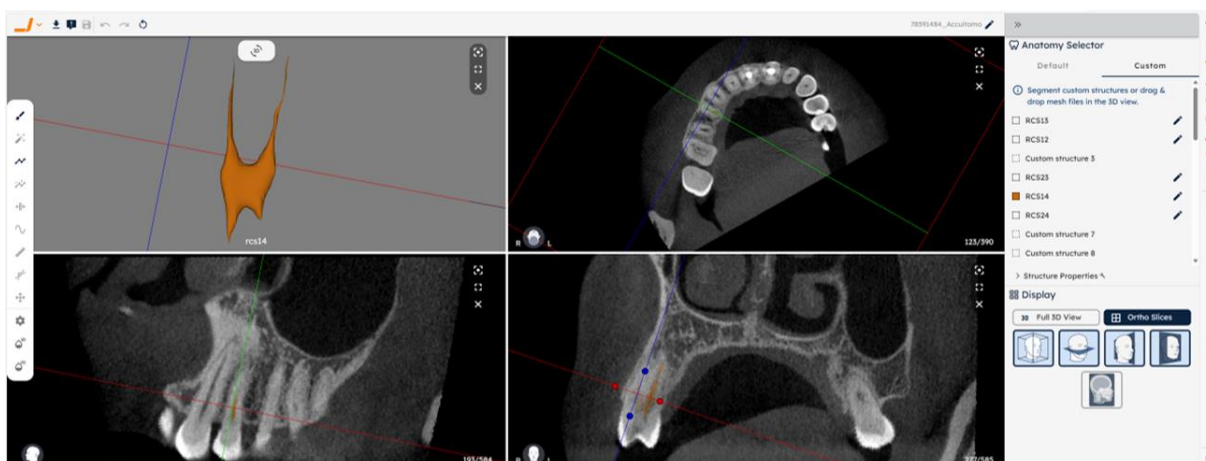
juntamente com os mapas de segmentação 3D correspondentes, nas reconstruções axial, sagital e coronal dos exames de TCFC na plataforma de IA "Virtual Patient Creator".

Figura 1 – Plataforma online de segmentação baseada em IA exibindo o modelo 3D do canal radicular e da câmara pulpar do dente 21, junto com as reconstruções multiplanares da TCFC, destacando o mapa de segmentação em azul



Fonte: Arquivo pessoal do autor.

Figura 2 – Plataforma online de segmentação orientada por IA mostrando a câmara pulpar e os canais radiculares do dente 14, junto com as reconstruções axial, sagital e coronal, destacando o mapa de segmentação em laranja



Fonte: Arquivo pessoal do autor.

PUBLICAÇÕES 3, 4 e 5

Fantoma antropomórfico

Um crânio humano e uma mandíbula secos (**Figura 3**) foram viabilizados para serem utilizados durante a aquisição dos exames de TCFC das publicações 3, 4 e 5.

Figura 3 – Imagem representativa do crânio humano e mandíbula secos para aquisição dos exames de TCFC



Fonte: Arquivo pessoal do autor.

Foi realizado um estudo piloto para preparar o material Mix-D, uma combinação de cera de parafina, polietileno, óxido de magnésio e óxido de titânio (**Figura 4, Tabela 1**). O fantoma antropomórfico completo foi então revestido com o Mix-D, empregado para simular a absorção de raios-X semelhante à dos tecidos moles humanos, conforme descrito por Oenning et al¹. Além disso, um modelo de língua foi criado com o mesmo material e posicionado na região lingual da mandíbula (**Figuras 5 e 6**).

Figura 4 – Imagem ilustrativa dos materiais utilizados para obter o material Mix-D: **A)** Óxido de titânio IV, **B)** Óxido de magnésio P.A, **C)** Polietileno e **D)** Cera de parafina



Fonte: Arquivo pessoal do autor.

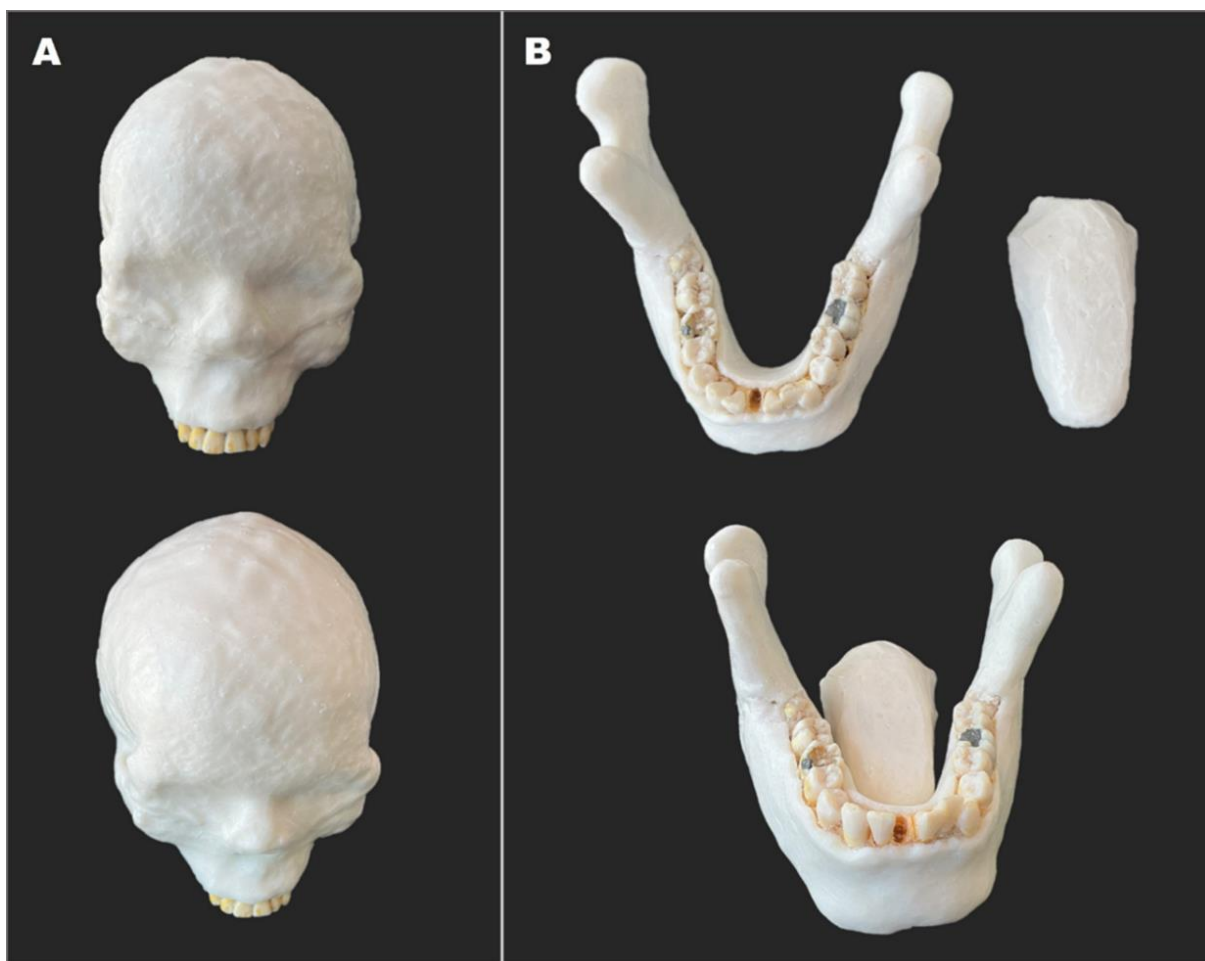
Tabela 1 – Materiais, com as respectivas quantidades em gramas (g), utilizados para a confecção do material Mix-D

Materiais	Quantidade (g)
Cera de Parafina	304
Polietileno	152
Óxido de Magnésio P.A	32
Óxido de Titânio IV	12

Observação: os valores descritos correspondem ao preparo de uma porção do material Mix-D.

Fonte: Elaboração própria.

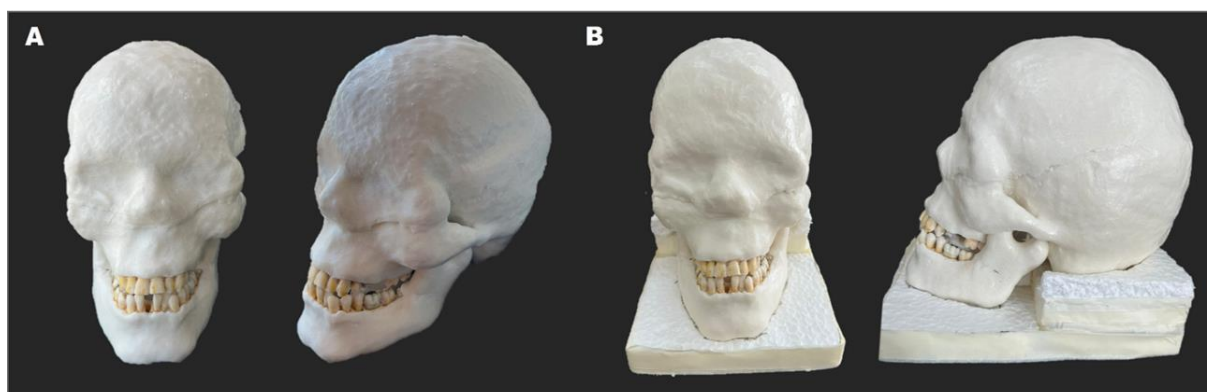
Figura 5 – Imagem representativa do fantoma antropomórfico coberto com o material Mix-D



A, Crânio humano seco totalmente revestido com Mix-D. B, Mandíbula humana seca após aplicação do material Mix-D e modelo de língua confeccionado a partir do mesmo material.

Fonte: Arquivo pessoal do autor.

Figura 6 – Imagem representativa do fantoma antropomórfico coberto com o Mix-D



A, Fantoma antropomórfico composto por crânio humano seco e mandíbula totalmente revestidos com Mix-D. B, Fantoma antropomórfico posicionado em um aparato confeccionado com isopor para garantir estabilidade durante os escaneamentos em TCFC.

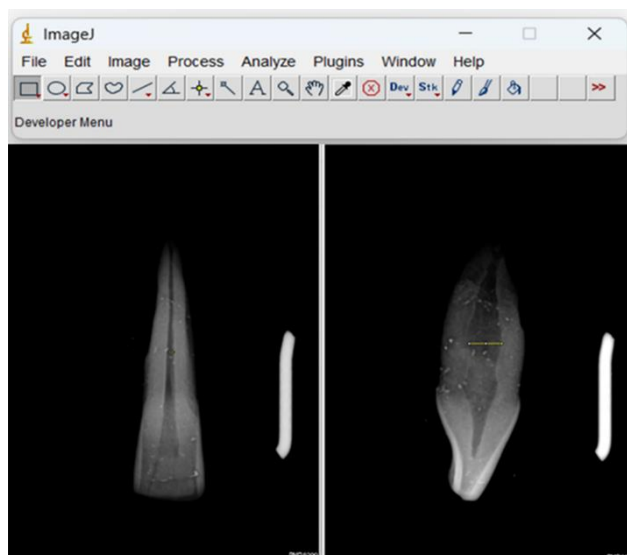
Fonte: Arquivo pessoal do autor.

PUBLICAÇÃO 3

Seleção dos dentes

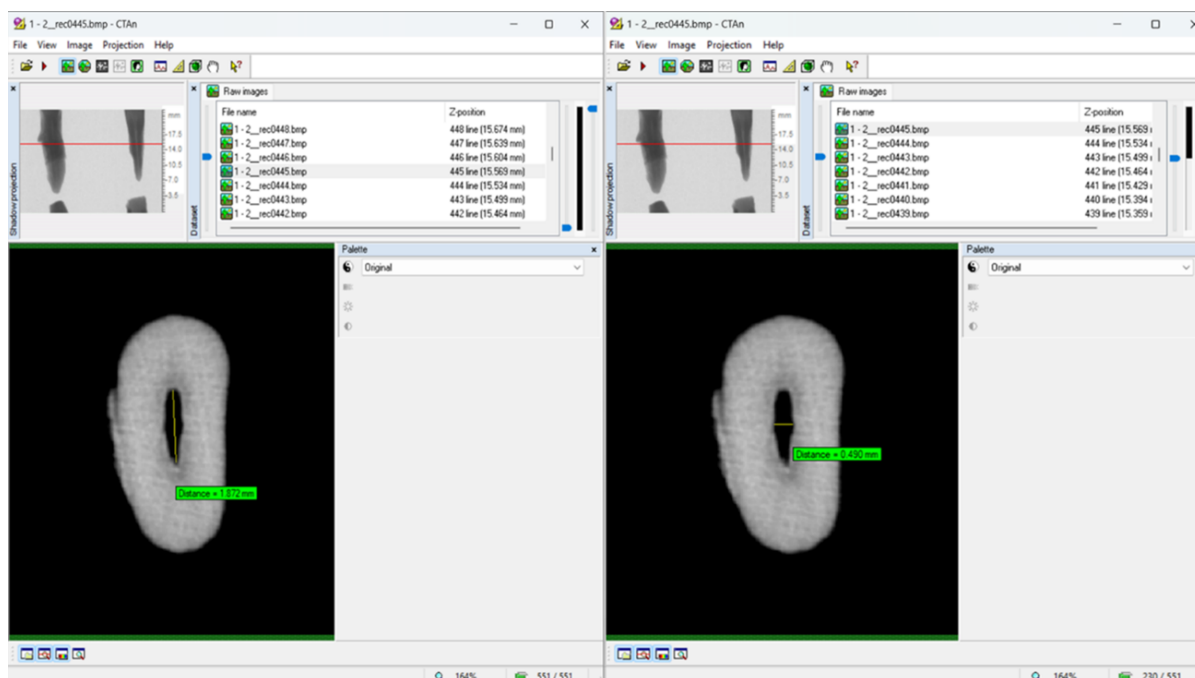
Após a aprovação pelo Comitê de Ética em Pesquisa da FOAr-UNESP (CAAE: 41916720.7.0000.5416), foram selecionados 20 incisivos inferiores humanos extraídos, com canais radiculares ovais longos identificados por meio de análise radiográfica digital (Kodak RVG 6100; Digital Radiography System, Marne-la-Vallée, France). As radiografias foram realizadas nos sentidos vestibulo-lingual e méso-distal dos dentes, e as imagens foram analisadas com o software ImageJ (National Institutes of Health, Bethesda, EUA) (**Figura 7**). Em seguida, os espécimes considerados como tendo canais ovais longos nas radiografias foram submetidos a escaneamento por micro-CT (SkyScan 1272, Bruker-microCT, Kontich, Bélgica), utilizando os seguintes parâmetros: 80 kV, 300 uA, rotação de 180°, passo de rotação de 0,6, frame 3, filtro de alumínio de 0,5 mm, tempo de exposição de 125 ms e tamanho de voxel de 24,5 μ m. A relação de diâmetro foi determinada medindo-se o comprimento vestibulo-lingual e méso-distal dos canais. Os canais radiculares foram considerados ovais longos quando o diâmetro vestibulo-lingual era de 2 a 4 vezes maior que o diâmetro méso-distal², a uma distância de 9 mm do ápice radicular³, utilizando o software CTAn (v.1.14.4, Bruker-microCT, SkyScan, Bélgica) (**Figura 8**).

Figura 7 – Imagem representativa das amostras sendo medidas no software ImageJ, no sentido mésio-distal e vestibulo-lingual, para determinar a seção transversal oval longa dos canais radiculares de incisivos centrais inferiores humanos



Fonte: Arquivo pessoal do autor.

Figura 8 – Imagem representativa das amostras sendo medidas no software CTAn, no sentido vestibulo-lingual e mésio-distal, para determinar a seção transversal oval longa dos canais radiculares de incisivos centrais inferiores humanos



Fonte: Arquivo pessoal do autor.

Preparo dos canais radiculares

Foram realizadas cavidades de acesso convencionais com uma broca diamantada #1012, seguidas pela exploração inicial dos canais radiculares com uma lima tipo K #10 (Dentsply Sirona, Ballaigues, Suíça). O comprimento de trabalho (CT) foi estabelecido subtraindo 1.0 mm da medida obtida quando a ponta da lima K #10 era visível no forame apical. O preparo dos canais radiculares foi conduzido utilizando os instrumentos Reciproc Blue R40 (VDW GmbH, Munique, Alemanha), acionados pelo motor elétrico X-Smart Plus (Dentsply Sirona), em cinemática recíproca na função “Reciproc All”, conforme as orientações do fabricante. Cada instrumento foi gradualmente introduzido em cada canal radicular, com movimentos de entrada e retirada nos terços cervical, médio e apical, até atingir o CT. Posteriormente, foram realizados dois movimentos de pincelamento em direção às paredes vestibular e lingual para alcançar as regiões de achatamento do canal radicular, como descrito por Santos-Junior et al⁴. Para a etapa de irrigação, foram utilizados 6 mL de hipoclorito de sódio 2.5% (NaOCl; Ciclo Farma, Serrana, SP, Brasil), sendo 2 mL para cada terço (cervical, médio e apical), utilizando uma agulha NaviTip 30-G (Ultradent, South Jordan, UT) adaptada a uma seringa de 5 mL (Ultradent), posicionada 2 mm aquém do CT.

Com o objetivo de otimizar a limpeza após o preparo com Reciproc Blue R40, todos os canais radiculares foram submetidos ao protocolo de irrigação ultrassônica passiva (PUI) usando o inserto ultrassônico Irrisonic (Helse Ultrasonic, Santa Rosa de Viterbo, São Paulo, Brasil). Conforme orientações do fabricante, Irrisonic foi ativada com 10% de potência e 50 Hz de frequência em um aparelho ultrassônico Newtron® Booster (ACTEON, North America, NJ, Estados Unidos), posicionado dentro de cada canal radicular a 2 mm aquém do CT, com movimentos suaves de entrada e retirada, sem contato com as paredes do canal radicular. Foram realizados três ciclos de agitação em cada canal radicular, com duração de 20 segundos cada. No primeiro e terceiro ciclo, foram utilizados 2 mL de NaOCl 2.5% em cada um, enquanto no segundo ciclo, empregou-se 2 mL de EDTA 17%. Posteriormente, foi realizada irrigação final com 5 mL de água destilada em cada amostra⁵.

Obturação dos canais radiculares

Após o preparo dos canais radiculares, os espécimes foram divididos em dois grupos experimentais (n=10) usando randomização estratificada simples. Essa divisão levou em conta o volume (mm³) dos canais radiculares após o preparo, medido pelo software CTAn (Bruker-microCT), para garantir volumes semelhantes na etapa de obturação. Todos os canais radiculares foram obturados utilizando a técnica de cone único com os cimentos AH Plus Jet (Dentsply DeTrey, Konstanz, Alemanha) ou Bio-C Sealer (Angelus, Londrina, Paraná, Brasil) (n = 10). Os cones principais de gutapercha R40 (VDW GmbH) foram selecionados de acordo com o tamanho de ponta e conicidade utilizando o aparelho perfilômetro (Profile Projector Nikon model 6C-2; Nikon, Tokyo, Japan). Foram realizadas radiografias digitais em todas as amostras no sentido méso-distal e vestibulo-lingual para verificar a adaptação dos cones de gutapercha no CT. O cimento AH Plus foi inserido nos canais radiculares usando uma broca Lentulo tamanho #40 (Dentsply Sirona), acoplada em um motor de baixa rotação (Micromotor N270 e contra ângulo, Dabi-Atlante, Ribeirão Preto, SP, Brasil), 2 mm aquém do CT. Além disso, uma lima manual tipo K #40 (Dentsply Sirona) também foi utilizada com movimentos de entrada e retirada até atingir o CT. Nos canais obturados com o Bio-C Sealer, este foi injetado nos canais radiculares usando seringas e agulhas plásticas, posicionadas a 4 mm aquém do CT, conforme recomendado pelo fabricante. O êmbolo da seringa foi pressionado suavemente até que o cimento Bio-C Sealer fluísse de volta para a câmara pulpar, indicando o preenchimento completo dos canais radiculares. Os cones de gutapercha R40 foram revestidos com os respectivos cimentos de acordo com cada grupo experimental e inseridos nos canais até o CT. Em seguida, o excesso de material obturador foi removido e condensado verticalmente com calcadores de Paiva. Foram realizadas radiografias digitais nas direções méso-distal e vestibulo-lingual para verificar o preenchimento adequado em todas as amostras. Em seguida, os dentes foram restaurados com Coltosol e mantidos em uma estufa a 37 °C e 95% de umidade por 7 dias para garantir a completa presa do cimento obturador.

Aquisição das imagens por microtomografia-computadorizada (micro-CT)

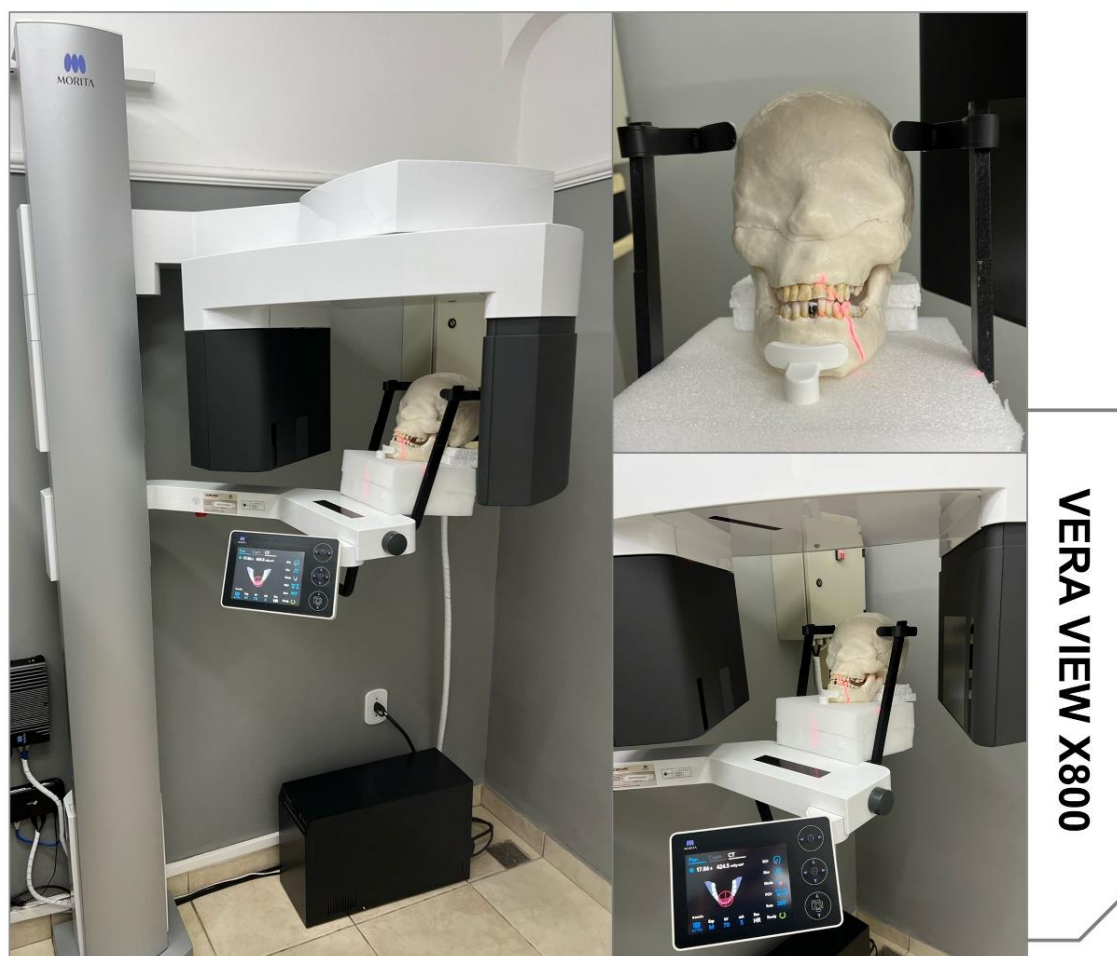
Para obter uma referência padrão de alta qualidade para comparações com os exames de TCFC, os dentes foram escaneados individualmente em um dispositivo de micro-CT de alta resolução (SkyScan 1272; Bruker-microCT). O escaneamento foi

realizado com os seguintes parâmetros: tamanho de voxel de 9 μm , filtro de alumínio de 1 mm, tempo de exposição de 87 ms, rotação de 180° em torno do eixo vertical, passo de rotação de 0.5° a 80 kV e 300 μA .

Aquisição das imagens por tomografia computadorizada de feixe cônico (TCFC)

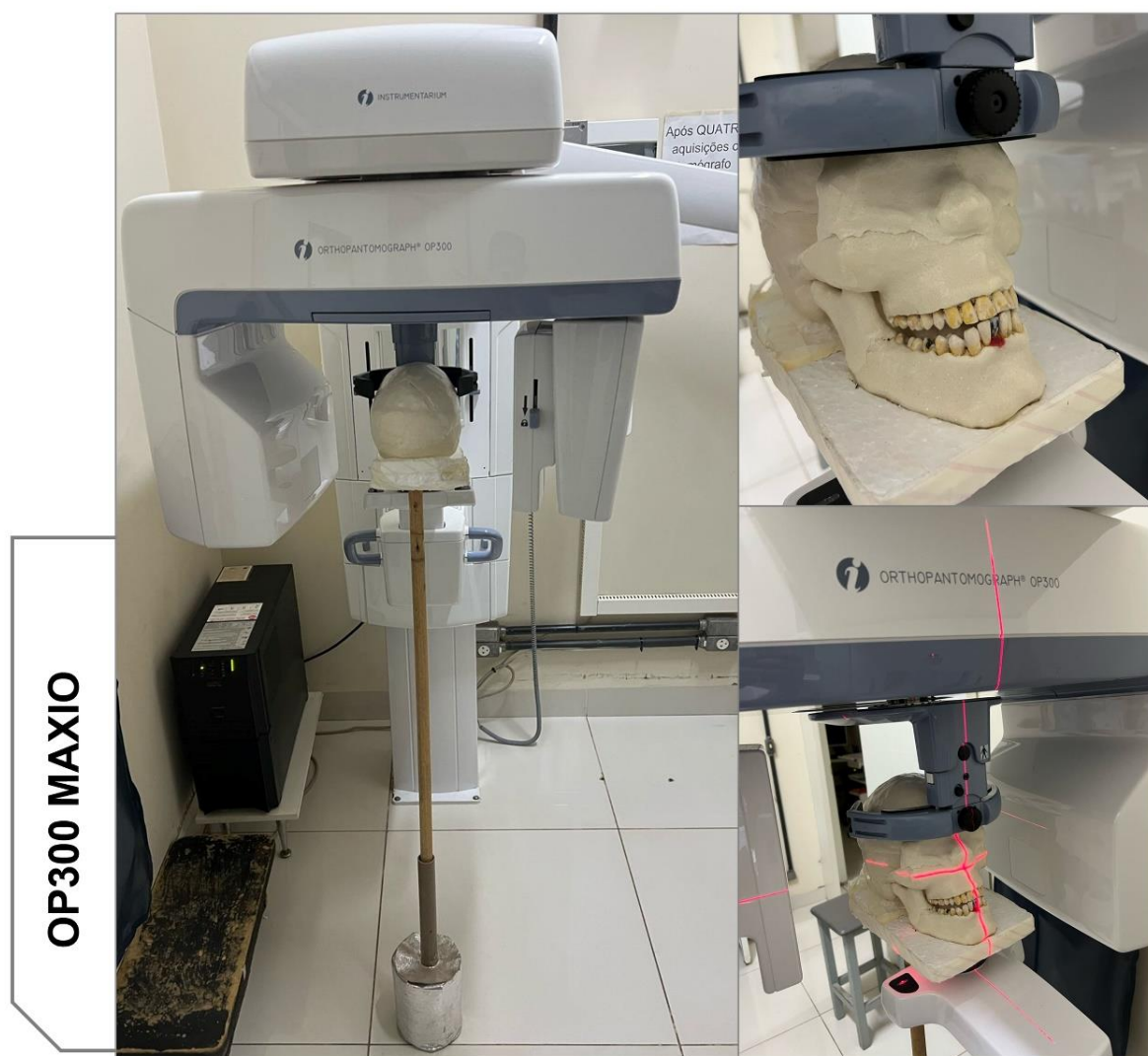
Para adquirir as imagens de TCFC, foi utilizado um modelo antropomórfico composto por um crânio humano seco e uma mandíbula totalmente dentada. Todo o fantoma foi revestido com um material conhecido como Mix-D, utilizado para simular a atenuação dos raios-X semelhante à dos tecidos moles humanos, conforme descrito anteriormente por Oenning et al¹. Além disso, um modelo de língua foi criado usando o mesmo material e fixado na região lingual da mandíbula. Posteriormente, o incisivo central inferior esquerdo da mandíbula seca foi removido delicadamente, e os dentes com canais radiculares ovais longos previamente selecionados foram colocados individualmente no alvéolo vazio. O fantoma completo foi escaneado usando dois dispositivos de TCFC: VeraView X800 (J Morita, Tóquio, Japão) (**Figura 9**) e OP300 Maxio (Instrumentarium Dental, Tuusula, Finlândia) (**Figura 10**). Os protocolos de aquisição para cada dispositivo de TCFC estão descritos na **Tabela 2**. Posteriormente, as imagens de TCFC foram exportadas no formato Digital Imaging and Communication in Medicine (DICOM).

Figura 9 – Imagem representativa do fantoma antropomórfico sendo escaneado no aparelho de TCFC VeraView X800



Fonte: Arquivo pessoal do autor.

Figura 10 - Imagem representativa do fantoma antropomórfico sendo escaneado no aparelho de TCFC OP300 MAXIO



Fonte: Arquivo pessoal do autor.

Tabela 2 - Protocolos de aquisição dos exames de TCFC

Aparelho de TCFC	kVp	mA	FOV (mm)	Tamanho de voxel (mm)
VeraView X800	70	5	40 x 40	0.08
OP300 Maxio	90	8	50 x 50	0.08

TCFC, Tomografia Computadorizada de Feixe Cônico; kVp, Quilovoltagem-pico; mA, Miliamperagem; FOV, Campo de visão.

Fonte: Elaboração própria.

Avaliação das Imagens de Micro-CT

Cada dente teve suas imagens reconstruídas individualmente utilizando o software NRecon (v.1.6.3, Bruker-microCT). As imagens de micro-CT, servindo como padrão de referência, foram então analisadas por um operador com ampla experiência na avaliação de imagens microtomográficas. Cada canal radicular foi avaliado individualmente para a detecção de espaços vazios nos terços cervical/médio (6 mm) e no terço apical (3 mm), utilizando o software CTAn (Bruker-microCT). Foi atribuído um escore de 0 se não foram detectados espaços vazios, enquanto um escore de 1 foi dado se os espaços vazios estavam presentes. A mesma análise foi repetida para avaliar a concordância intra-avaliador após 30 dias.

Avaliação das Imagens de TCFC

Cada exame de TCFC foi aleatoriamente atribuído a uma das duas fases de avaliação — com ou sem o filtro BAR — utilizando a função "RAND" no Excel (Microsoft Co., Redmond, WA, EUA). Esse processo garantiu que, após cada avaliação, os exames recebessem um código aleatório diferente da designação original. As avaliações foram conduzidas de forma independente por um radiologista oral experiente, com mais de 20 anos de prática, e dois especialistas em endodontia, todos altamente qualificados em análise de imagens.

Antes da análise das imagens, os examinadores passaram por um processo de calibração envolvendo exames de TCFC que exibiam espaços vazios e regiões sem vazios em diferentes terços dos canais radiculares (cervical/médio e apical). Essas imagens de calibração não foram utilizadas na avaliação posterior. Os examinadores desconheciam os fatores em estudo, incluindo a presença ou ausência de espaços vazios no material obturador, o tipo de cimento endodôntico e o dispositivo de TCFC utilizado.

Os examinadores foram instruídos a realinhar as reconstruções multiplanares dos exames de TCFC com o longo eixo da raiz e a realizar uma análise dinâmica em cada exame de TCFC nos planos axial, sagital e coronal. Todos os exames de TCFC foram analisados utilizando o software e-Vol DX (CDT Software, Bauru, SP, Brasil) em um monitor LED colorido de 25 polegadas com resolução de 2560 x 1080 pixels, em uma sala com pouca luz e silenciosa. Os examinadores foram instruídos a avaliar minuciosamente todos os exames de TCFC nos diferentes terços radiculares (ou seja, cervical/médio e apical).

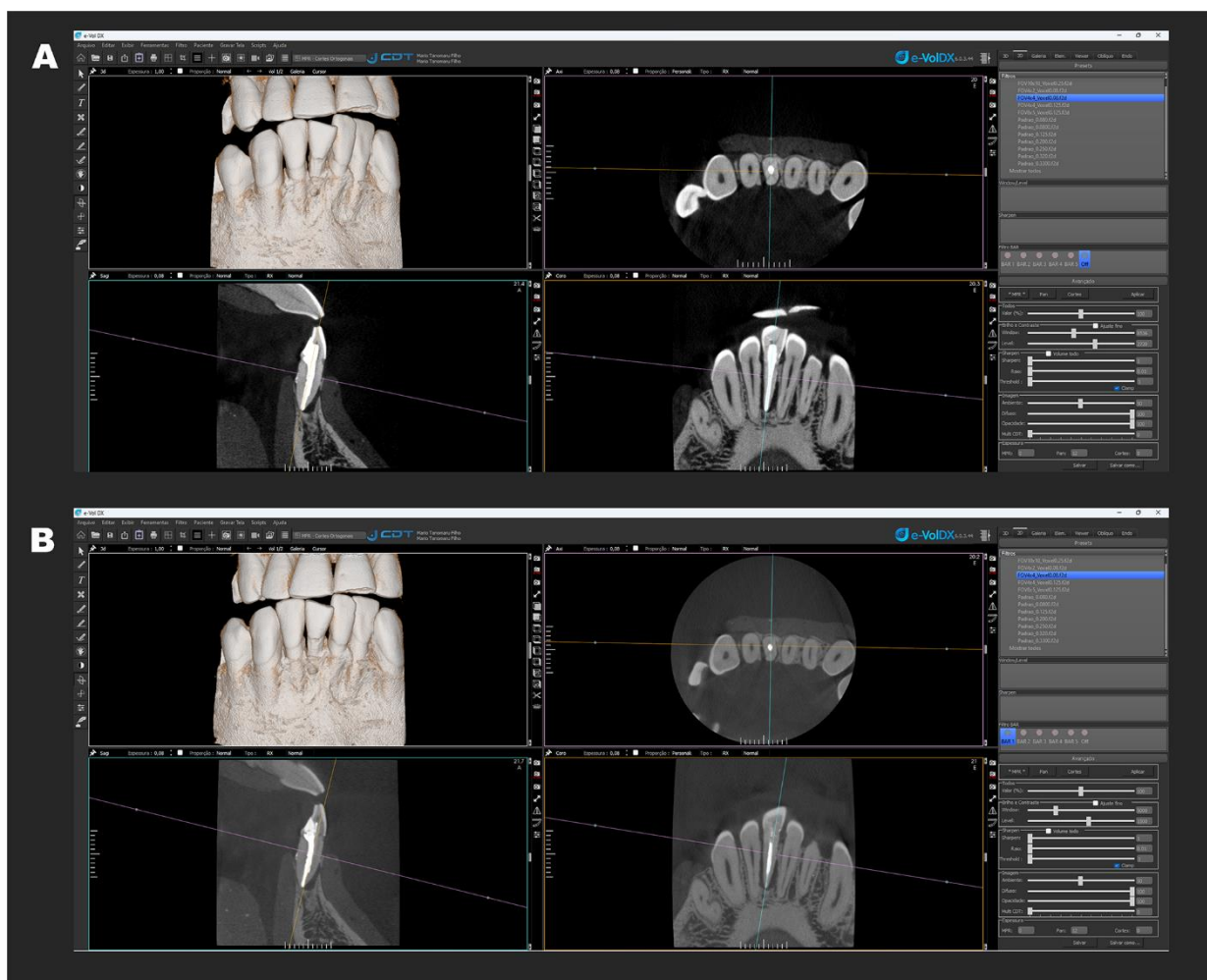
Para garantir uma avaliação padronizada das obturações dos canais radiculares, cada raiz foi dividida em dois segmentos com base na localização do material obturador. A primeira reconstrução axial que mostrou o material obturador no terço cervical e a última reconstrução axial que o exibiu no terço apical foram usadas para determinar o CT. Isso permitiu uma medição consistente de cada raiz em dois segmentos: 6 mm para os terços cervical/médio e 3 mm para o terço apical. Essa abordagem garantiu que todos os observadores avaliassem os canais radiculares de maneira padronizada, conforme metodologia descrita por Fontenele et al⁶. A detecção de espaços vazios foi realizada em duas etapas distintas:

Etapla 1: Os examinadores podiam ajustar manualmente as configurações de brilho e contraste de acordo com suas preferências. O filtro *Blooming Artifact Reduction* (BAR) foi mantido desativado durante esta etapa.

Etapla 2: Todos os exames de TCFC foram avaliados com o filtro BAR ativado. Os examinadores utilizaram diferentes intensidades do filtro BAR (ou seja, BAR 1, 2, 3, 4 ou 5) para examinar minuciosamente a presença ou ausência de espaços vazios no material obturador.

Cada exame de TCFC foi avaliado usando uma escala de confiança de 5 pontos para classificar os espaços vazios no material obturador nos diferentes terços radiculares: (1) sem espaços vazios, (2) provavelmente sem espaços vazios, (3) incerto, (4) provável presença de espaços vazios e (5) presença de espaços vazios. Para evitar fadiga visual, um máximo de 20 exames de TCFC foram avaliados por dia, com um intervalo mínimo de 24 horas entre as sessões de avaliação. Para verificar a reprodutibilidade intra e interobservador, 30% da amostra foi aleatoriamente selecionada e reavaliada 30 dias após a análise inicial.

Figura 11 - Imagem representativa das duas condições distintas para avaliação de espaços vazios dentro do material obturador nos diferentes terços radiculares usando o software e-Vol DX



A, Valores de brilho e contraste ajustados de acordo com a preferência individual dos avaliadores. **B**, Avaliação dos exames de TCFC com o filtro BAR ativado.

Fonte: Arquivo pessoal do autor.

Análise estatística

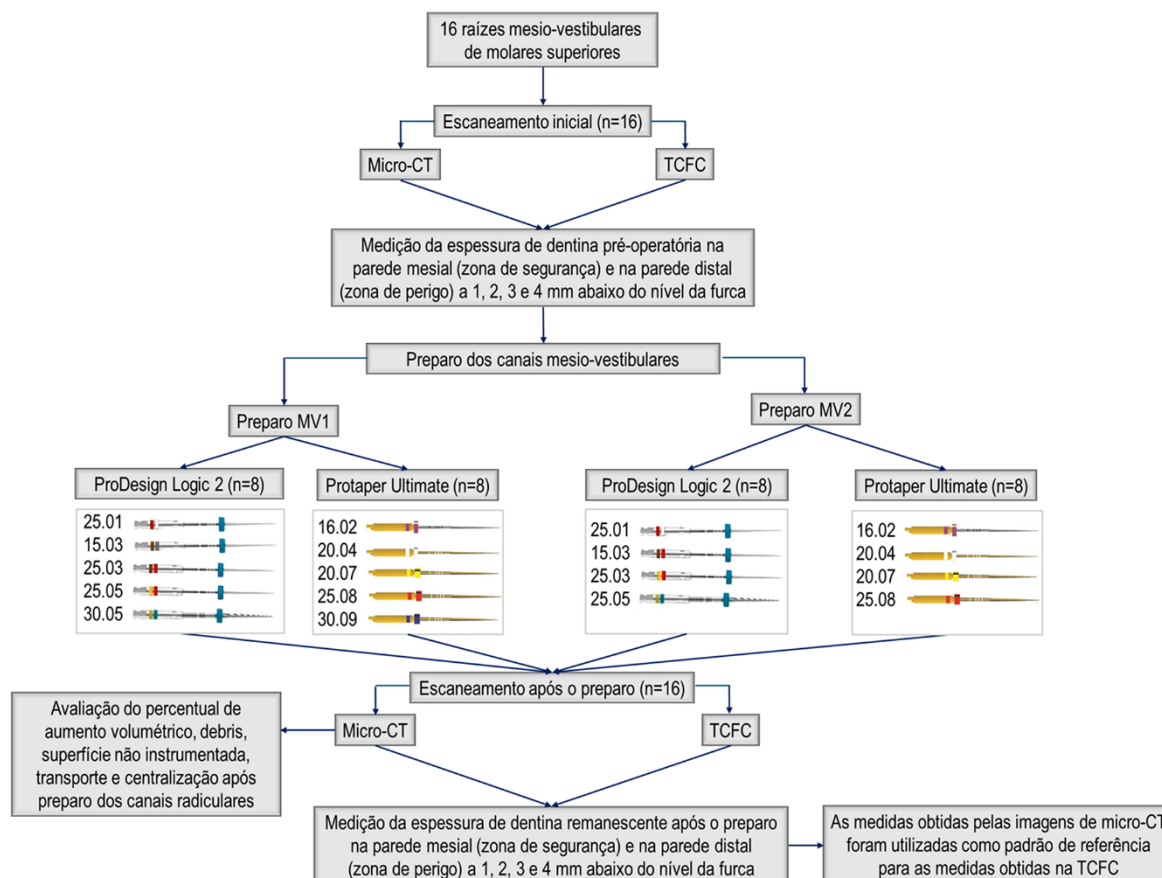
As análises estatísticas foram realizadas utilizando o software MedCalc (versão 22.0, MedCalc Software Ltd., Ostend, Bélgica) e o software SPSS (versão 24.0, IBM Corp., Armonk, NY). As concordâncias intra e interobservador foram avaliadas utilizando o teste Kappa ponderado e interpretadas com base na escala de Landis & Koch⁷. As métricas diagnósticas, incluindo a área sob a curva ROC (AUC), sensibilidade e especificidade para a detecção de espaços vazios, foram calculadas para cada fator estudado (uso do filtro BAR, tipo de cimento endodôntico e terço do canal radicular) em cada dispositivo de TCFC. As comparações estatísticas foram

realizadas utilizando a análise de variância multifatorial (ANOVA) com o teste post-hoc de Tukey. Um nível de significância de 5% foi adotado para todas as análises.

PUBLICAÇÃO 4

O desenho metodológico da publicação 4 está ilustrado na **Figura 12**.

Figura 12 - Fluxograma mostrando a visão geral do desenho do estudo, incluindo os instrumentos, métodos de análises e as variáveis de interesse



Fonte: Elaboração própria.

Seleção dos dentes

Antes do início do estudo, foi obtida a aprovação ética do comitê de ética em pesquisa institucional (número de protocolo: 41916720.7.0000.5416). Dezesseis dentes molares superiores humanos, que possuíam dois canais separados na raiz méso-vestibular (MV1 e MV2) de acordo com a classificação do tipo IV de Vertucci⁸, foram selecionados para esta investigação. Os critérios de inclusão incluíam a presença de formação apical completa, ausência de fraturas radiculares, calcificações e reabsorções internas e externas, além de estarem livres de cáries e restaurações extensas. Além disso, todos os dentes selecionados tinham uma curvatura radicular

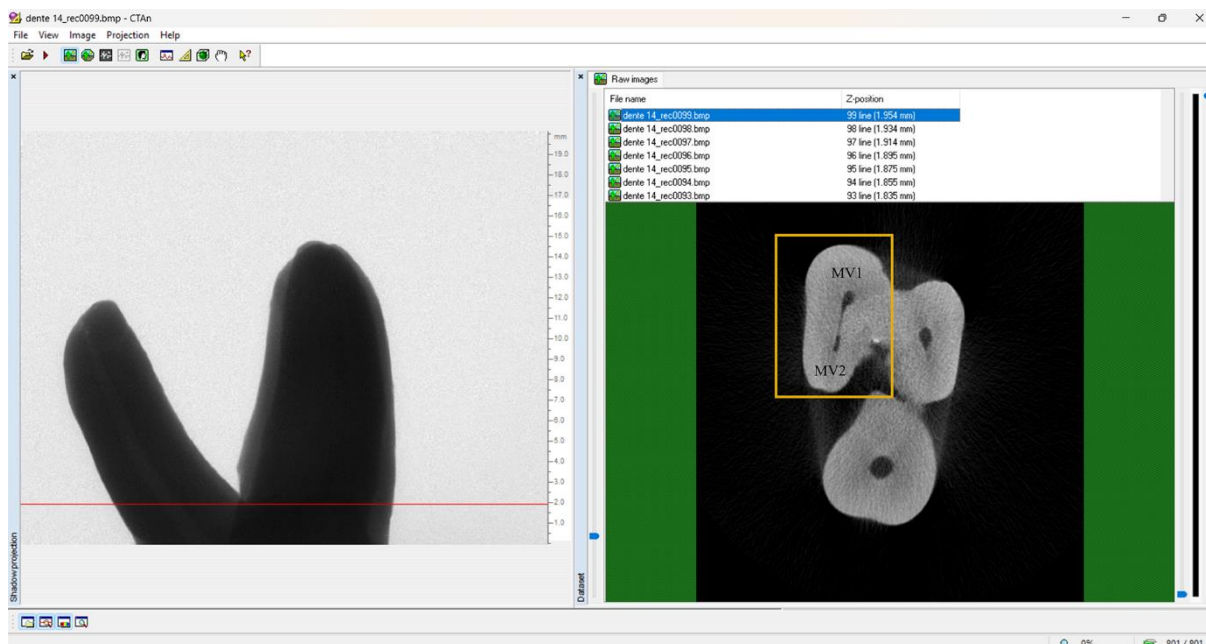
entre 20° e 30°, conforme determinado por Schneider⁹, e um raio de curvatura inferior a 10 mm, conforme determinado pelo método de Pruett¹⁰. Dentes com destruição coronal extensa, tratamento endodôntico prévio, ápices abertos e reabsorções radiculares externas ou internas foram excluídos do estudo. Esses critérios foram confirmados por radiografias das amostras usando um sistema digital (RVG 6100) **(Figura 13)** e um dispositivo de micro-CT (SkyScan 1174; Bruker-microCT, Kontich, Belgium) **(Figura 14)** utilizando os seguintes parâmetros: 50 kV, rotação de 180°, passo de rotação de 0,8, frame 3, filtro de alumínio de 0,5 mm, tempo de exposição de 125 ms e tamanho de voxel de 19,7 μm .

Figura 13 – Radiografias periapicais digitais para confirmar os critérios de inclusão nos canais MV1 e MV2 de molares superiores



Fonte: Arquivo pessoal do autor.

Figura 14 – Imagem representativa das amostras sendo avaliadas no software CTAn para confirmar os critérios de inclusão nos canais MV1 e MV2 de molares superiores



Fonte: Arquivo pessoal do autor.

Preparo dos canais radiculares

Todos os procedimentos de preparo foram realizados por um único operador especialista em endodontia, com ampla experiência, sob cuidadosa inspeção utilizando um microscópio cirúrgico operatório ajustado para uma ampliação de 13X (DF Vasconcellos, Valença, RJ, Brasil). Inicialmente, foi feita uma cavidade de acesso convencional em cada dente usando uma broca diamantada #1012 (Dentsply Sirona), acoplada a um micromotor de alta rotação com resfriamento contínuo por água. O canal MV2 foi localizado usando o inserto ultrassônico E15 Finder (Helse Ultrasonic). Em seguida, os canais radiculares foram explorados com limas K C+ nos tamanhos #06, #08 e #10 (Dentsply Sirona). Quando a ponta do instrumento K tamanho #10 foi visível através do forame apical, 1,0 mm foi subtraído para estabelecer o CT. Os dentes foram montados em um dispositivo com resina acrílica e envoltos em silicone de condensação (Oranwash, Zhermack SpA, Badia Polesine, Itália) para simular o ligamento periodontal. O preparo dos canais radiculares seguiu as instruções do fabricante para cada sistema de níquel-titânio (NiTi).

Sistema Protaper Ultimate

Canais radiculares MV1 (n = 8): Os instrumentos 16.02, 20.04, 20.07, 25.08 e 30.09 foram usados sequencialmente para preparar os canais MV1 dos molares superiores. Todas as limas foram operadas em cinemática rotatória, com uma velocidade de 400 rotações por minuto (rpm) e um torque de 4 Newton centímetros (Ncm).

Canais radiculares MV2 (n = 8): Os canais MV2 foram preparados usando os instrumentos 16.02, 20.04, 20.07 e 25.08. Durante esse processo, as limas foram usadas em movimento rotatório a uma velocidade constante de 400 rpm e um torque de 4 Ncm.

Sistema ProDesign Logic 2

Canais radiculares MV1 (n = 8): Os canais MV1 foram preparados em sequência usando os seguintes instrumentos: 25.01, 15.03, 25.03, 25.05 e 30.05. O instrumento 25.01 foi usado em movimento rotatório a 350 rpm com um torque de 1 Ncm, enquanto o instrumento 15.03 teve a mesma velocidade, mas com um torque de 2 Ncm. O instrumento 25.03 foi operado a 600 rpm e 2 Ncm de torque. Por fim, os instrumentos 25.05 e 30.05 foram usados a 600 rpm com um torque de 3 Ncm.

Canais radiculares MV2 (n = 8): Para preparar os canais MV2, foi usada a sequência de instrumentos 25.01, 15.03, 25.03 e 25.05. O instrumento 25.01 foi usado em movimento rotatório a uma velocidade de 350 rpm e torque de 1 Ncm. O instrumento 15.03 também foi usado a 350 rpm, mas com um torque de 2 Ncm. O instrumento 25.03 foi operado a 600 rpm e torque 2 Ncm. Por fim, o instrumento 25.05 foi usado a 600 rpm e torque de 3 Ncm.

Todos os instrumentos foram introduzidos no canal radicular usando um movimento de entrada e retirada até o comprimento de trabalho, acionados por um motor elétrico X-Smart Plus (Dentsply Sirona). Para ambos os grupos, o protocolo de irrigação consistiu na aplicação de 5,0 mL de NaOCl a 2,5% após o uso de cada instrumento. Isso foi feito usando uma seringa de 5 mL (Ultradent Products) com uma agulha Navitip de 30 G (Ultradent Products) posicionada a 2 mm do CT, com movimento de entrada e retirada e com fluxo e aspiração contínuos. A irrigação final foi feita com 5 mL de NaOCl a 2,5%, seguido por 2,5 mL de EDTA a 17% (Biodinâmica) e 5 mL de solução salina em cada canal radicular. As amostras foram aspiradas com pontas capilares (Dentsply Sirona) e secas com cones de papel absorvente (Dentsply Sirona) de acordo com o diâmetro de dilatação apical de cada canal radicular.

Aquisição das imagens por micro-CT

Cada dente foi submetido a um duplo escaneamento utilizando um dispositivo de micro-CT (SkyScan 1174, Bruker-microCT), tanto antes quanto após o preparo do canal radicular. Os seguintes parâmetros foram utilizados para a aquisição das imagens: 50 kV, 800 mA, passo de rotação de 0,8°, filtro de alumínio de 0,5 mm e tamanho de voxel de 19,7 μm .

Aquisição das imagens por TCFC

Um modelo antropomórfico composto por um crânio humano seco e uma mandíbula completamente dentada foi revestido com o material Mix-D para simular a atenuação dos raios-X em tecidos moles¹. Além disso, um modelo de língua foi produzido e posicionado em seu local correspondente no modelo. O modelo antropomórfico completo foi utilizado para adquirir os exames de TCFC neste estudo. O primeiro molar superior esquerdo foi extraído, e os molares superiores previamente selecionados foram individualmente colocados no alvéolo correspondente para a aquisição dos exames de TCFC. Para garantir o mesmo posicionamento dos dentes durante a aquisição dos exames de TCFC antes e após o preparo do canal radicular, guias de silicone individualizadas foram produzidas com silicone de condensação (Zhermack SpA, Badia Polesine, Itália). Todos os exames de TCFC foram adquiridos utilizando o dispositivo de TCFC VeraView X800 (J Morita). Os parâmetros de aquisição foram definidos em 5 mA, 70 kVp, tamanho de voxel de 0,08 mm e um campo de visão de 40 x 40 mm. Posteriormente, todos os exames de TCFC foram exportados no formato DICOM.

Avaliação das Imagens de Micro-CT

As imagens de Micro-CT de cada espécime foram reconstruídas utilizando o software NRecon (Bruker-microCT). As imagens de micro-CT, antes e após o preparo, foram sobrepostas por meio de realinhamento geométrico utilizando a função "3D registration" no software Data Viewer (Bruker-microCT). As análises quantitativas das imagens foram realizadas com o software CTAn (Bruker-microCT), enquanto modelos tridimensionais foram gerados utilizando o software CTVox (Bruker-microCT).

O volume pré-operatório dos canais radiculares, o volume pós-preparo, a área de superfície após o preparo e o volume de debris foram determinados. Com base nesses dados, foram calculados o percentual de aumento volumétrico (% de aumento

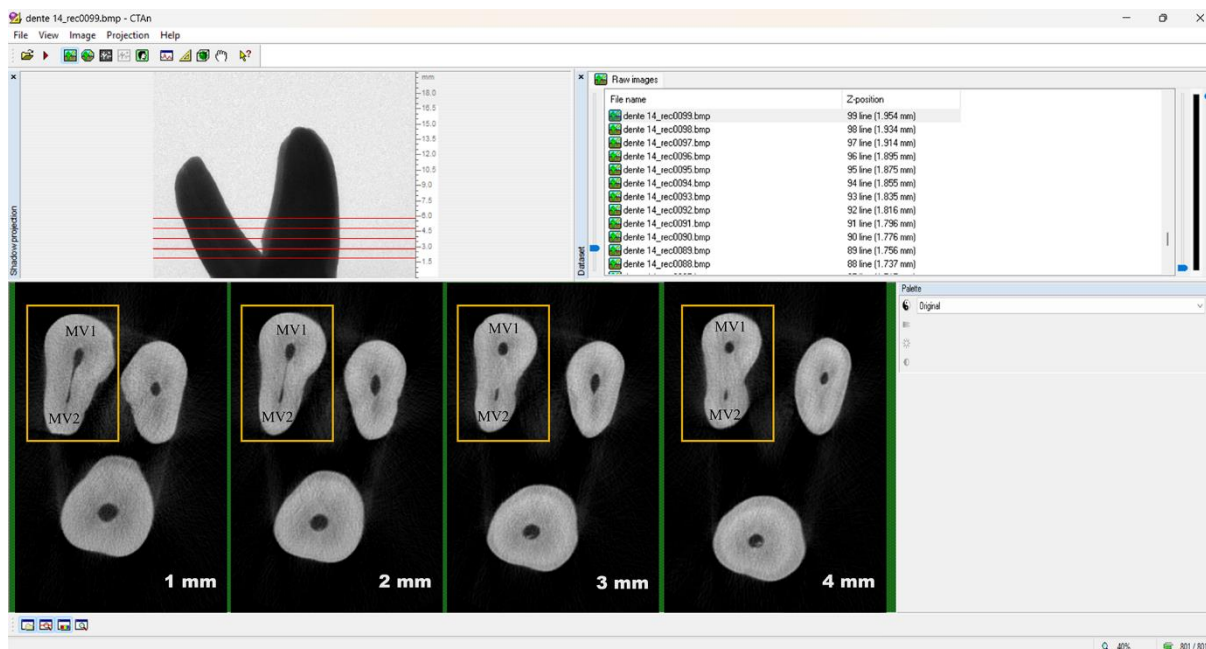
volumétrico), o percentual de debris (% de debris) e o percentual de superfície não instrumentada (% de superfície não instrumentada). Esses cálculos foram realizados para todo o canal radicular, bem como para os terços cervical, médio e apical dos canais MV1 e MV2.

- % de aumento volumétrico = $100 - \text{volume do canal preparado} \times 100 / \text{volume pré-operatório}$.
- % de detritos = $\text{volume de debris} \times 100 / \text{volume do canal preparado}$.
- % de superfície não instrumentada = $\text{área de superfície não instrumentada} \times 100 / \text{área de superfície após o preparo}$.

Para realizar as análises de transporte e centralização no terço apical, foram utilizadas imagens axiais de micro-CT sobrepostas obtidas antes e após o preparo do canal radicular. O transporte do canal radicular foi calculado de acordo com um estudo anterior¹¹. Seis diferentes regiões no terço apical dos canais MV1 e MV2 foram medidas usando imagens axiais com o software CTAn (Bruker-microCT), e os valores médios aritméticos foram determinados. Os dados de centralização foram ordenados de 0 a 1, com valores mais próximos de 1 indicando centralização completa e aqueles mais próximos de 0 indicando ausência de centralização. Para os dados de transporte, valores mais próximos de zero indicaram menor desvio.

A espessura da dentina foi medida linearmente (em mm) a 1, 2, 3 e 4 mm abaixo do nível da furca nos canais MV1 e MV2, tanto antes quanto após o preparo do canal radicular utilizando diferentes sistemas de NiTi. Um operador experiente em análise de imagens de micro-CT utilizou as reconstruções axiais de cada amostra para realizar as medições com o software CTAn (Bruker-microCT). Essas medições consideraram o perímetro externo dos canais MV1 e MV2, estendendo-se até a superfície externa da raiz mésio-vestibular, abrangendo tanto o aspecto distal (zona de perigo) quanto o aspecto mesial (zona de segurança). É importante destacar que as medições das imagens de micro-CT foram usadas como referência para comparação com aquelas obtidas a partir de exames de TCFC. Após um intervalo de 4 semanas, 30% da amostra foi selecionada aleatoriamente, e as medições foram repetidas pelo mesmo avaliador para avaliar a concordância intraexaminador.

Figura 15 – Imagem representativa das amostras no software CTAn utilizando a reconstrução axial



Foram realizadas medições da espessura de dentina nos canais MV1 e MV2 dos molares superiores, tanto antes quanto após o preparo, a 1, 2, 3 e 4 mm abaixo do nível da furca.

Fonte: Arquivo pessoal do autor.

Avaliação das Imagens de TCFC

A análise da espessura da dentina antes e após o preparo dos canais MV1 e MV2 nos exames de TCFC foi realizada utilizando o software e-Vol DX em um monitor LED colorido de 25 polegadas, com resolução de 2560 x 1080 pixels, em uma sala com iluminação suave e mínimo ruído. Foram permitidos ajustes de brilho, contraste e zoom para a avaliação das imagens. Inicialmente, o examinador recebeu instruções para reorientar meticulosamente todos os exames de TCFC, garantindo que as reconstruções axial, sagital e coronal estivessem precisamente alinhadas com o longo eixo de cada canal radicular. Em seguida, utilizando as reconstruções axiais dos exames de TCFC, o mesmo operador calibrado, familiarizado com o software e-Vol DX, mediu linearmente a espessura da dentina nos canais MV1 e MV2 a 1, 2, 3 e 4 mm abaixo do nível da furca. Essas medições foram realizadas em dois momentos diferentes: antes e após o preparo dos canais radiculares, pelo mesmo operador. Trinta dias após a conclusão das medições, 30% da amostra foi reavaliada aleatoriamente pelo mesmo operador para avaliar a concordância intraexaminador.

Para prevenir a fadiga visual do examinador, um máximo de 10 exames de TCFC foram avaliados por sessão.

É importante destacar que uma espessura de dentina inferior a 0,5 mm após o preparo do canal radicular foi classificada como remoção excessiva de dentina em todas as regiões de interesse deste estudo¹², conforme avaliado tanto em imagens de micro-CT quanto em imagens de TCFC.

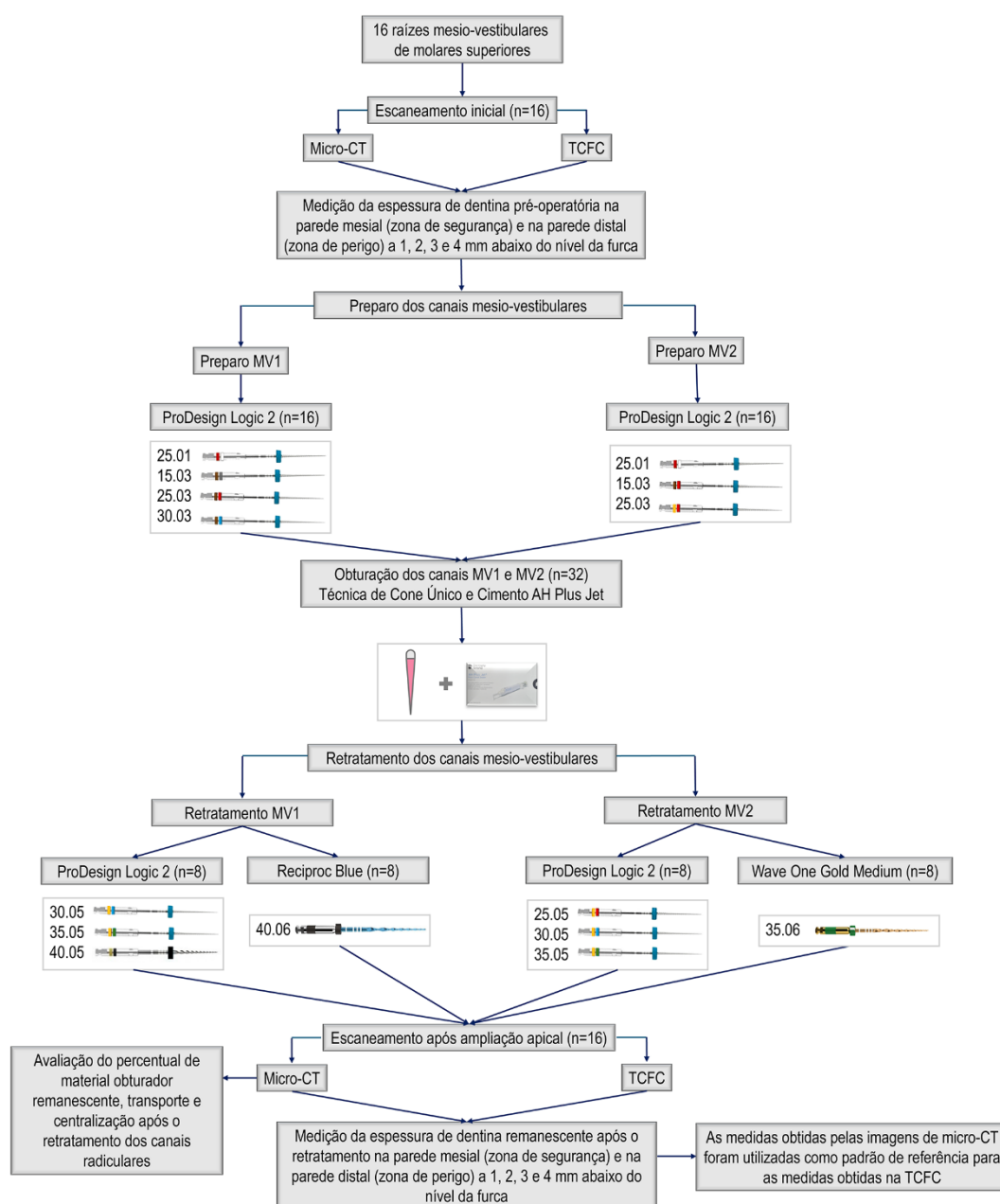
Análise Estatística

O coeficiente de correlação intraclasse (ICC) foi utilizado para avaliar a concordância intraoperador dentro de cada modalidade de imagem investigada (micro-CT e TCFC). A normalidade dos dados foi verificada utilizando o teste de Shapiro-Wilk. Uma análise de variância multifatorial (ANOVA) foi utilizada para comparar a espessura da dentina antes do preparo do canal radicular com a avaliação por micro-CT, considerando os fatores estudados (canais MV1 e MV2, superfície do canal radicular e nível da furca). O teste t não pareado foi empregado para comparar os resultados dos parâmetros de micro-CT entre os sistemas de NiTi. Testes t pareados e não pareados foram usados para comparar os valores de remoção de dentina entre os sistemas de NiTi e a modalidade de imagem, respectivamente. Os testes de Mann-Whitney e Wilcoxon foram utilizados para comparar os resultados referentes às porcentagens críticas de dentina remanescente de acordo com a escala adotada (<0,5 mm, 0,5-1 mm e >1 mm)¹³, dependendo do sistema de NiTi e da modalidade de imagem, respectivamente. Todas as análises estatísticas foram realizadas utilizando o software SPSS (versão 24.0, IBM Corp., Armonk, NY, EUA), com nível de significância estabelecido em 5% ($\alpha = 0,05$).

PUBLICAÇÃO 5

O delineamento metodológico da publicação 5 está representado na **Figura 16**.

Figura 16 – Fluxograma representando de maneira abrangente a estrutura do estudo, englobando os instrumentos, os métodos de análise e as variáveis de interesse



Fonte: Elaboração própria.

Seleção dos dentes

Antes do início deste estudo, foi obtida a aprovação do comitê de ética em pesquisa da instituição (protocolo nº 41916720.7.0000.5416). Para a investigação, foram selecionados dezesseis molares superiores humanos que apresentavam dois canais distintos na raiz méso-vestibular (MV1 e MV2), conforme a classificação de Vertucci tipo IV⁸. Os dentes incluídos no estudo deveriam ter formação apical completa, estar livres de fraturas radiculares, calcificações, reabsorções internas ou externas, e não apresentar cáries ou restaurações extensas. Além disso, todos os dentes selecionados possuíam uma curvatura radicular entre 20° e 30°, de acordo com o método de Schneider⁹, e um raio de curvatura menor que 10 mm, conforme o critério estabelecido por Pruett¹⁰. Foram excluídos dentes com destruição coronal significativa, tratamento endodôntico prévio, ápices abertos e qualquer tipo de reabsorção radicular interna ou externa. Esses critérios foram confirmados por meio de radiografias digitais das amostras e por exames de micro-CT (SkyScan 1174; Bruker-microCT), utilizando os seguintes parâmetros de aquisição: 50 kV, rotação de 180°, passo de rotação de 0,8, frame 3, filtro de alumínio de 0,5 mm, tempo de exposição de 125 ms e tamanho de voxel de 19,7 µm.

Preparo dos canais radiculares

Os acessos coronários foram realizados utilizando uma broca diamantada #1012 (Dentsply Sirona). O canal MV2 foi localizado com o uso do inserto ultrassônico E15 Finder (Helse Ultrasonic). Limas manuais tipo K C+ de tamanho #06, #08 e #10 (Dentsply Sirona) foram utilizadas para explorar os canais radiculares. O CT foi determinado quando a ponta da lima K #10 tornou-se visível no forame apical; em seguida, 1,0 mm foi subtraído dessa medida para estabelecer o CT final. Os dentes foram fixados em um suporte utilizando resina acrílica e envoltos em silicone de condensação (Zhermack SpA) para simular o ligamento periodontal. Todas as etapas experimentais foram conduzidas por um único especialista em endodontia altamente experiente, utilizando um microscópio cirúrgico com aumento de 13X (DF Vasconcellos). O preparo dos canais radiculares foi realizado utilizando o sistema rotatório de NiTi ProDesign Logic 2 (Easy Equipamentos Odontológicos), seguindo estritamente as recomendações do fabricante.

Preparo dos canais radiculares MV1 (n = 16): Os canais radiculares MV1 foram preparados sequencialmente utilizando os instrumentos 25/.01, 15/.03, 25/.03 e 30/.03

em cinemática rotatória. O instrumento 25/.01 foi utilizado a uma velocidade de 350 rpm com um torque de 1 Ncm, enquanto o instrumento 15/.03 foi operado na mesma velocidade, mas com um torque de 2 Ncm. Os instrumentos 25/.03 e 30/.03 foram utilizados a 600 rpm com um torque de 2 Ncm.

Preparo dos canais radiculares MV2 (n = 16): Os canais radiculares MV2 foram preparados sequencialmente usando os instrumentos 25/.01, 15/.03 e 25/.03, seguindo as mesmas especificações de cinemática, velocidade e torque previamente descritas para esses instrumentos.

Todos os instrumentos foram inseridos nos canais radiculares utilizando movimentos de entrada e retirada até o CT, acionados pelo motor elétrico X-Smart Plus (Dentsply Sirona). O protocolo de irrigação para todas as amostras foi padronizado, envolvendo a aplicação de 5,0 mL de NaOCl a 2,5% (Ciclo Farma) após o uso de cada instrumento. Isso foi realizado com o uso de uma seringa de 5 mL (Ultradent Products) com uma agulha 30-G Navitip (Ultradent Products), posicionada 2 mm aquém do CT, com movimentos de vai e vem, e fluxo e aspiração contínuos. A irrigação final consistiu em 5 mL de NaOCl a 2,5%, seguida de 2,5 mL de EDTA a 17% (Biodynamics) e 5 mL de solução salina em cada canal radicular. As amostras foram aspiradas com pontas capilares (Dentsply Sirona) e secas com cones de papel absorvente (Dentsply Sirona), de acordo com o diâmetro de dilatação apical de cada canal radicular.

Obturação dos canais radiculares

Todos os canais radiculares foram obturados utilizando a técnica de cone único com o cimento AH Plus Jet. Cones de guta-percha, nos tamanhos 25/.03 e 30/.03 (Easy Equipamentos Odontológicos), foram selecionados com base no tamanho da ponta e na conicidade utilizando um perfilômetro (Projetor de Perfil Nikon modelo 6C-2). Radiografias digitais nas direções vestibulo-lingual e méso-distal confirmaram a adaptação adequada dos cones de guta-percha em cada canal. O cimento AH Plus Jet foi aplicado utilizando uma espiral lentulo (#30 ou #25, Dentsply Sirona) conectada a um motor de baixa rotação (Micromotor N270 e contra-ângulo), posicionada 2 mm aquém do CT nos canais MV1 e MV2, respectivamente. Além disso, uma lima K pré-curvada (#30 para os canais MV1 ou #25 para os canais MV2) foi utilizada para levar o cimento até o CT antes da inserção do cone de guta-percha. Os canais MV1 foram obturados com cones de guta-percha 30/.03 revestidos com cimento e inseridos até o

CT, enquanto os canais MV2 foram obturados com cones 25/.03 seguindo o mesmo protocolo. O excesso de guta-percha no terço cervical foi removido e compactado verticalmente com um compactador Paiva #2 (Golgran). Radiografias digitais finais nas direções méso-distal e vestibulo-lingual garantiram a ausência de espaços vazios e a uniformidade das obturações. Os canais radiculares foram restaurados com Coltosol (Vigodent) e armazenados a 37°C com 95% de umidade relativa por uma semana para permitir a completa presa do cimento obturador.

Retratamento dos canais radiculares

Imagens de micro-CT foram utilizadas para medir a espessura da dentina (em mm) antes e depois do preparo do canal radicular nas zonas de segurança e perigo de cada canal MV1 e MV2. Além disso, o volume de material obturador (em mm³) foi avaliado utilizando o software CTAn (Bruker-microCT) após a obturação dos canais radiculares, a fim de garantir uma distribuição homogênea das amostras para os procedimentos de retratamento endodôntico. Esses dois fatores foram considerados para assegurar que os grupos experimentais fossem comparáveis durante o retratamento endodôntico.

Após a remoção das restaurações temporárias, o mesmo especialista que preparou e obturou todos os canais radiculares realizou os procedimentos de retratamento utilizando um microscópio cirúrgico com aumento de 13X (DF Vasconcellos). Os canais radiculares foram aleatoriamente distribuídos nos seguintes grupos:

Retratamento dos canais radiculares MV1 com o sistema Logic 2 (n = 8): Os instrumentos Logic 2, nos tamanhos 30/0,05, 35/0,05 e 40/0,05, foram utilizados sequencialmente. Cada instrumento foi acionado pelo motor elétrico X-Smart Plus em modo rotatório a 600 rpm com torque de 3 Ncm, realizando movimentos de entrada e retirada até o CT.

Retratamento dos canais radiculares MV1 com o sistema Reciproc Blue R40 (n = 8): Os instrumentos Reciproc Blue R40 (40/0,06) foram utilizados em movimento recíprocante, acionados pelo motor X-Smart Plus na função “Reciproc All”, conforme as instruções do fabricante. Cada instrumento foi gradualmente inserido no canal, realizando movimentos de entrada e retirada nos três terços radiculares (cervical, médio e apical) até o CT.

Retratamento dos canais radiculares MV2 com o sistema Logic 2 (n = 8): Os instrumentos Logic 2, nos tamanhos 25/0,05, 30/0,05 e 35/0,05, foram utilizados em sequência. Cada instrumento foi acionado pelo motor X-Smart Plus em cinemática rotatória, operando a 600 rpm com torque de 3 Ncm, realizando movimentos de entrada e retirada até o CT.

Retratamento dos canais radiculares MV2 com o sistema WaveOne Gold Medium (n = 8): Os instrumentos WaveOne Gold Medium (35/0,06) foram utilizados em movimento recíprocante, acionados pelo motor X-Smart Plus na função “WaveOne”, conforme recomendado pelo fabricante. Cada instrumento foi gradualmente inserido no canal, com movimentos de entrada e retirada nos terços cervical, médio e apical até o CT.

Durante o retratamento, o protocolo de irrigação para todos os grupos experimentais seguiu os critérios previamente estabelecidos na etapa de preparo do canal radicular.

Aquisição das imagens por micro-CT

Todos os dentes foram escaneados antes e após o retratamento endodôntico usando um sistema de micro-CT (SkyScan 1174; Bruker-microCT). As configurações de escaneamento foram 50 kV, 800 mA, passo de rotação de 0,8°, filtro de alumínio de 0,5 mm e tamanho de voxel de 19,7 µm.

Aquisição das imagens por TCFC

Um modelo antropomórfico foi criado utilizando um crânio humano seco e uma mandíbula totalmente dentada, ambos cobertos com o material Mix-D para simular a atenuação dos raios-X, imitando de forma bastante fiel as características dos tecidos moles humanos¹. Além disso, um modelo de língua foi confeccionado e colocado em sua posição anatômica dentro do modelo. Este modelo antropomórfico completo foi utilizado para adquirir as imagens de TCFC neste estudo. O primeiro molar superior esquerdo foi cuidadosamente extraído, e os molares superiores previamente selecionados foram individualmente posicionados no alvéolo correspondente para a obtenção das imagens de TCFC. Para garantir um posicionamento consistente dos dentes durante as aquisições dos exames de TCFC realizados antes e após o retratamento endodôntico, guias de silicone personalizadas foram confeccionadas para cada dente utilizando silicone de condensação ZetaPlus (Zhermack SpA). Todos

os exames de TCFC foram realizados utilizando o dispositivo VeraView X800 (J Morita), com parâmetros ajustados para 5 mA, 70 kVp, FOV de 40 × 40 mm e um tamanho de voxel de 0,08 mm. Todos os exames de TCFC adquiridos foram, então, exportados no formato DICOM.

Avaliação das Imagens de Micro-CT

As imagens de micro-CT foram reconstruídas usando o software NRecon (Bruker-microCT). As imagens obtidas antes e após o retratamento endodôntico foram alinhadas geometricamente por meio da superposição dos exames de micro-CT utilizando a função "3D registration" no software Data Viewer (Bruker-microCT). A análise quantitativa das imagens foi realizada com o software CTAn (Bruker-microCT), e modelos tridimensionais foram gerados posteriormente com o software CTVox (Bruker-microCT).

Os volumes dos canais radiculares e do material obturador remanescente foram quantificados após o retratamento endodôntico. A faixa de tons de cinza para identificar cada objeto de interesse foi determinada utilizando um limiar adaptativo com base em um histograma de densidade. Para calcular o percentual de material obturador remanescente, aplicou-se a seguinte fórmula: material obturador após o retratamento × 100 / material obturador antes do retratamento¹⁴. Essa avaliação foi realizada para todo o canal radicular, bem como para os terços cervical, médio e apical dos canais MV1 e MV2.

Para avaliar o transporte e a centralização no terço apical, imagens axiais superpostas obtidas antes e após o retratamento endodôntico foram cuidadosamente analisadas usando o software CTAn (Bruker-microCT). O transporte do canal radicular foi calculado de acordo com a metodologia descrita em um estudo anterior¹¹. Seis regiões distintas dentro do terço apical dos canais MV1 e MV2 foram medidas usando imagens axiais processadas pelo software CTAn (Bruker-microCT), e os valores médios aritméticos foram calculados para cada região. As pontuações de centralização foram atribuídas em uma escala de 0 a 1, onde valores próximos a 1 indicavam centralização ideal, e aqueles mais próximos de 0 sugeriam resultados menos favoráveis. Para as medições de transporte, valores menores indicavam mínima desvio da trajetória original do canal.

A espessura da dentina foi avaliada a 1, 2, 3 e 4 mm abaixo do nível da furca nos canais MV1 e MV2, tanto antes quanto após o retratamento endodôntico com

vários sistemas de NiTi. Um operador experiente em análise de imagens de micro-CT realizou essas medições usando reconstruções axiais de cada amostra no software CTAn (Bruker-microCT). As medições abrangeram desde o perímetro externo dos canais MV1 e MV2 até a superfície externa da raiz mésio-vestibular, cobrindo tanto a zona de perigo quanto a zona de segurança. As medições das imagens de micro-CT serviram como padrão de referência para comparação com aqueles obtidos nos exames de TCFC. Após um período de 4 semanas, 30% das amostras foram selecionadas aleatoriamente, e o mesmo operador repetiu as medições para avaliar a confiabilidade intraexaminador.

Avaliação das Imagens de TCFC

O software e-Vol DX foi utilizado para medir a espessura da dentina nas imagens de TCFC. Isso foi realizado em um monitor LED colorido de 25 polegadas com resolução de 2560 x 1080 pixels. O ambiente de avaliação de imagens foi mantido escuro e sem ruídos para garantir condições ideais. Ajustes no brilho, contraste e zoom da imagem foram realizados conforme necessário, com um limite de 10 exames de TCFC avaliados por sessão para evitar fadiga visual no examinador. Inicialmente, os exames de TCFC foram realinhados para garantir que as reconstruções axiais, sagitais e coronais estivessem devidamente alinhadas com o longo eixo de cada canal radicular. Um examinador treinado e calibrado, experiente no uso do software e-Vol DX, realizou as medições da espessura da dentina nos canais MV1 e MV2 a 1, 2, 3 e 4 mm abaixo do nível da furca, utilizando as imagens axiais dos exames de TCFC. Essas medições foram feitas pelo mesmo examinador antes e após o retratamento endodôntico. Para avaliar a concordância intraexaminador, 30% das amostras foram selecionadas aleatoriamente para reavaliação pelo mesmo examinador após 30 dias.

Para ambas as modalidades de imagem utilizadas neste estudo, uma espessura de dentina inferior a 0,5 mm após o retratamento endodôntico foi considerada indicativa de remoção excessiva em todas as regiões analisadas¹².

Análise Estatística

O ICC foi utilizado para avaliar a consistência intraoperador para cada modalidade de imagem (micro-CT e TCFC). A normalidade dos dados foi verificada utilizando o teste de Shapiro-Wilk. Uma ANOVA multivariada foi realizada para comparar a espessura da dentina antes e depois do preparo dos canais radiculares

MV1 e MV2, conforme medido pelo Micro-CT, considerando o canal MV1 e MV2, superfície radicular e nível da furca. O teste de Mann-Whitney foi utilizado para comparar os parâmetros do Micro-CT entre os diferentes sistemas de NiTi, enquanto os testes t não pareado e pareado avaliaram as diferenças na remoção de dentina após o retratamento entre os sistemas de NiTi e as modalidades de imagem, respectivamente. Os testes de Mann-Whitney e Wilcoxon foram aplicados para comparar as porcentagens de dentina remanescente crítica (<0,5 mm, 0,5-1 mm e >1 mm)¹³ com base no sistema de NiTi e na modalidade de imagem, respectivamente. Todas as análises estatísticas foram realizadas utilizando o software SPSS (versão 24.0, IBM Corp., Armonk, NY, EUA), com um nível de significância estabelecido em 5% ($\alpha = 0,05$).

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ANEXO A – CERTIFICADO DO COMITÊ DE ÉTICA

Projeto de Pesquisa aprovado pelo Comitê de ética em pesquisa em seres humanos da Universidade Católica de Leuven – KU Leuven **(Publicações 1 e 2)**.

Número do protocolo: S67798



Leuven, 27 Jul 2023



Ethics Committee
Research UZ/KU Leuven
Herestraat 49
B 3000 Leuven (Belgium)

prof. dr. Reinhilde Jacobs
MKA

Email : ec@uzleuven.be

Our reference:
S67798

EudraCT-nr:

Belg. Regnr:

Artificial Intelligence (AI)-based root canal segmentation for endodontics.

Dear colleague

The Ethics Committee Research (EC Research) of University Hospitals Leuven (UZ Leuven) has examined and discussed the above mentioned dossier at its meeting of 08 May 2023.

EC Research has no objection to the project provided that the data is managed confidentially and in compliance with the Belgian legislation on privacy.

EC Research emphasizes the responsibility of the PI/promotor of this study concerning the privacy of the person/patient data in contact with patients, or when accessing patient data, including the correct implementation thereof by coworkers and students. The PI/promotor is responsible for the implementation of the project proposal in accordance with applicable laws and regulations including, but not limited to, the EU regulation 2016/679 (General Data Protection Regulation), the Belgian Law on patients' rights of 22/8/2002, and the policy of the institution where the research will be carried out.

EC refers to the ICH/GCP guidelines on its website, and confirms that a GCP-training is required from each investigator. It is the responsibility of the principal investigator that each member of the study team has a valid GCP-certificate.

This project does not fall within the scope of the Law of 7/5/2004.

EC Research requires that the head/staff of the clinical department or the responsible care program are informed about and concur with this study; this is the PI's responsibility.

For the assessment of this dossier, documents/answers submitted on 18 Apr 2023, 21 Jun 2023, 19 Jul 2023 and 26 Jul 2023 have been taken into account.

S67798

1 / 3

This letter concerns:

Protocol:
v3 – Date 19/07/2023
GDPR questionnaire:
dd 18Apr2023

EC Research confirms working in accordance with the ICH-GCP principles (International Conference on Harmonization Guidelines on Good Clinical Practice), the latest version of the Declaration of Helsinki, the Oviedo Convention on Human Rights and Biomedicine and applicable laws and regulations.

EC Research confirms that - in case of conflict of interest - involved members do not take part in the vote concerning the study.

List of members: see appendix.

Points of concern: (if applicable)

The conformity of translated documents compared to the Dutch documents, is the responsibility of the sponsor.

Provided that there is a Clinical Trial Agreement, the study can only start when the Clinical Trial Agreement has been approved and signed by the CEO of UZ Leuven (and/or by an authorized representative of KU Leuven R&D).

Please take into account the regulations of the hospital concerning tissue management and the regulations of the law of December 19, 2008.

This advice of EC Research does not imply that she will assume responsibility for the planned study. You will remain responsible for the study. In addition, you should ensure that your opinion as an involved researcher is reproduced in publications, reports for the government, etc. which are the result of this study.

We request you to inform us if the study will not be initiated, or when it will be closed or prematurely ended (stating the reason).

Yours sincerely,

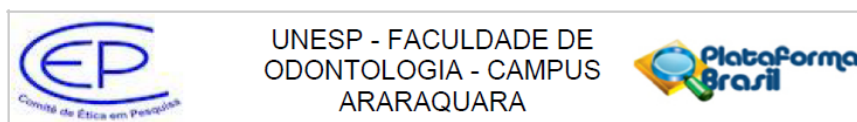
Prof. Dr. Minne Casteels
Chair
Ethics Committee Research UZ Leuven

List of members EC Research UZ/KU Leuven on 08 May 2023:

Chair	prof. dr. Maria-Reinilde Casteels	Clinical Pharmacology
Vice chair	prof. dr. Dominique Bullens	Paediatrics
	De heer Aemout De Raemaeker	Medical Legislation alternate
	De heer Jean-Jacques Derèze	Medical Legislation alternate
	De heer Mathijs Swaak	Healthy volunteer repres.
	Mevr. Angélique Rézer	Medical Legislation alternate
	Mevr. Annick Vanclooster	Nurse
	Mevr. Katelijne Van Overwalle	Pt representative (alternate)
	Mevr. Lia De Wilde	Pt representative (alternate)
	Mevr. Marilien Vandeputte	Nurse
	Mevr. Michèle Dekervel	Medical Legislation alternate
	Mevr. Teresia De Fraye	Pt representative
	Mevr. Veerle Vanparys	Pharmacist (alternate)
	dr. Kristel Van Landuyt	Rheumatology
	dr. Lut De Groot	General Practitioner
	dr. Marleen Renard	Paediatrics
	dr. Walter Janssens	Clinical Pharmacology
	prof. André Loeckx	Pt representative (alternate)
	prof. Ben Van Calster	Statistics
	prof. Guy Bosmans	Clin. Psychology (alternate)
	prof. Pascal Borry	Ethics
	prof. Rik Gosselink	Revalidation
	prof. dr. Anne Smits	Paediatrics
	prof. dr. Anne Uytendaele	Paediatrics
	prof. dr. Ariel Alonso	Statistics (alternate)
	prof. dr. Bart Van der Schueren	Endocrinology / Pharmacology
	prof. dr. Frank Van Calenbergh	Neurosurgery
	prof. dr. Gregor Verhoef	Haematology
	prof. dr. Jan Verhaegen	Laboratory Medicine
	prof. dr. Jan de Hoon	Clinical Pharmacology
	prof. dr. Karin Sipido	Experimental Cardiology
	prof. dr. Koen Luyckx	Clin. Psychology (alternate)
	prof. dr. Laura Van Gerven	ORL
	prof. dr. Maria Schetz	Intensive care
	prof. dr. Peter Sinnaeve	Cardiology
	prof. dr. Simon Brumagne	Physiotherapy
	prof. dr. Xavier Bossuyt	Immunology
	prof. dr. apr. Erwin Dreesen	Pharmacist (alternate)

ANEXO B – CERTIFICADO DO COMITÊ DE ÉTICA

Projeto de Pesquisa aprovado pelo Comitê de ética em pesquisa em seres humanos – CEP da Faculdade de Odontologia de Araraquara – FOAr, UNESP (**Publicações 3, 4 e 5**). CAAE:41916720.7.0000.5416



PARECER CONSUBSTANCIADO DO CEP

DADOS DO PROJETO DE PESQUISA

Título da Pesquisa: Avaliação comparativa entre micro-CT e TCFC empregando o software e-Vol DX na análise de obturação em canais ovais e espessura dentinária em canais MV1 e MV2 de molares superiores após preparo e retratamento

Pesquisador: Mario Tanomaru Filho

Área Temática:

Versão: 1

CAAE: 41916720.7.0000.5416

Instituição Proponente: Faculdade de Odontologia de Araraquara - UNESP

Patrocinador Principal: FUND COORD DE APERFEICOAMENTO DE PESSOAL DE NIVEL SUP

DADOS DO PARECER

Número do Parecer: 4.538.911

Apresentação do Projeto:

A tomografia computadorizada de feixe conico (TCFC) e os softwares de análises apresentam grande evolução. O objetivo deste estudo será avaliar a qualidade de obtenção e espessura dentinária após preparo do canal radicular e retratamento por meio de TCFC utilizando o software de análise e-Vol DX (CDT Software, Bauru, SP, Brasil) em comparação a microtomografia computadorizada (micro-CT). Para realização deste projeto, serão utilizados dentes humanos extraídos provenientes do Banco de Dentes da Faculdade de Odontologia de Araraquara (FOAr-UNESP). Subprojeto 1: Será avaliado a qualidade do preenchimento do canal radicular usando incisivos centrais inferiores ovais humanos extraídos (n=20) selecionados por análise radiográfica e micro-CT. Os canais serão distribuídos aleatoriamente e obturados pela técnica de cone único com os cimentos AH Plus ou Bio-C Sealer (n=10). Subprojeto 2: Serão selecionados 24 primeiros molares superiores humanos extraídos com dois canais distintos na raiz mesio-vestibular, MV1 e MV2. Os canais radiculares serão preparados por ProDesign Logic/ProDesign Logic 2 ou sistema recíprocante WaveOne Gold. Subprojeto 3: Os canais MV1 e MV2 serão obturados pela técnica de cone único com o cimento AH Plus. Os canais MV1 e MV2 serão retratados pelo sistema ProDesign Logic RT e preparo adicional será realizado com ProDesign Logic. Ampliação apical nos canais MV1 será realizada por ProDesign Logic 40.05 e 50.01 e nos canais MV2 por ProDesign Logic 2 35.05 e 40.01. Serão avaliadas a qualidade do preenchimento do canal radicular e a espessura dentinária

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Bairro: CENTRO

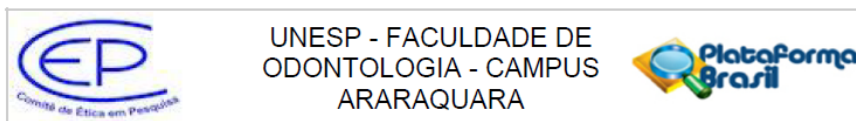
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UF: SP

Município: ARARAQUARA

Telefone: (16)3301-6459

E-mail: cep@foar.unesp.br



Continuação do Parecer: 4.538.911

após o preparo e após ampliação apical depois do retratamento nos canais MV1 e MV2 dos molares superiores por TCFC/e-Vol DX e por micro-CT como padrão ouro de referência. Os resultados obtidos serão submetidos aos testes estatísticos adequados com nível de significância de 5%.

Objetivo da Pesquisa:

Objetivo Primário:

Avaliar a obturação de canais radiculares ovais e a espessura dentinária após preparo e ampliação apical depois do retratamento em canais MV1 e MV2 de molares superiores utilizando TCFC/e-Vol DX em comparação com micro-CT.

Objetivo Secundário:

1. Avaliar a qualidade de obturação em canais ovais obturados por cimentos endodônticos com diferentes valores de radiopacidade (AH Plus e Bio- C Sealer). 2. Avaliar a espessura dentinária em canais MV1 e MV2 de molares superiores após o preparo com sistemas rotatórios (ProDesign Logic e ProDesign Logic 2) ou sistema recíprocante (WaveOne Gold). 3. Avaliar a espessura dentinária em canais MV1 e MV2 de molares superiores após ampliação apical depois do retratamento com sistemas rotatórios (ProDesign Logic e ProDesign Logic 2).

Avaliação dos Riscos e Benefícios:

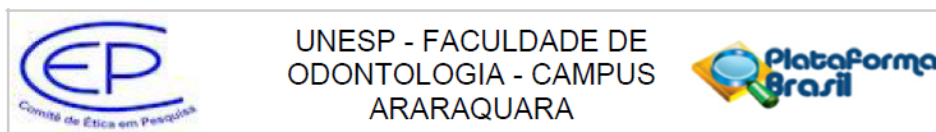
Riscos:

Os riscos envolvem os pesquisadores que serão submetidos à radiação uma vez que durante a seleção dos dentes será necessário realizar tomadas radiográficas para padronizar os espécimes, dessa maneira, será utilizado um sistema radiográfico digital (menor tempo de exposição) com utilização de uma caixa de chumbo que evitara a propagação da radiação e os envolvidos utilizarão avental de borracha plumbífero. No laboratório de Pesquisa Endodôntica (Centro de confecção de amostras), os profissionais envolvidos farão uso de EPIs indicados quanto ao Mapa de Risco de cada ambiente.

Benefícios:

A análise da obturação do canal radicular e espessura dentinária após preparo e retratamento por meio de imagens tomográficas utilizando o software e-Vol DX pode trazer grande contribuição para o planejamento correto do tratamento endodôntico. Favorecendo o planejamento clínico ou mesmo a pesquisa científica empregando imagens tomográficas.

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Continuação do Parecer: 4.538.911

Comentários e Considerações sobre a Pesquisa:

Estudo nacional, prospectivo, laboratorial, de caráter acadêmico (realizado para obtenção de título de Doutor), com patrocínio da CAPES. Serão utilizados 44 dentes humanos extraídos fornecidos pelo Banco de Dentes da FOAr. Previsão de início e término: 01/03/2021 e 15/08/2023.

Considerações sobre os Termos de apresentação obrigatória:

Todos os documentos necessário foram apresentados.

1. Folha de rosto;
2. Autorização de uso do Laboratório de Pesquisa onde será desenvolvida a pesquisa emitida pelo responsável pelo laboratório;
3. Autorização dos responsáveis pelos equipamentos que serão utilizados para o desenvolvimento da pesquisa (Micro tomógrafo e Tomógrafo Computadorizado);
4. Declaração de doação dos dentes emitida pelo responsável pelo Banco de Dentes;
5. Declaração de devolução da sobra dos dentes ao Banco de Dentes emitida pelo responsável pela pesquisa;
6. Declaração de não ressarcimento;
7. Solicitação de dispensa do TCLE;
8. Termo de Compromisso em cumprir o Regimento Interno do CEP, bem como a Resolução CNS 466/12;
9. Projeto de Pesquisa;
10. Cronograma de execução do projeto (incluído no protocolo de pesquisa);
11. Orçamento da pesquisa (incluído no protocolo de pesquisa).

Recomendações:

Vide campo "Conclusões ou Pendências e Lista de Inadequações".

Conclusões ou Pendências e Lista de Inadequações:

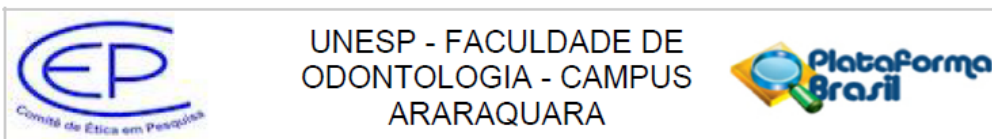
Sem pendências ou necessidade de adequações.

Considerações Finais a critério do CEP:

Protocolo APROVADO em reunião de 11 de fevereiro de 2021.

O pesquisador deverá encaminhar relatórios parciais a cada 01 (um) ano até o prazo final da pesquisa, quando deverá encaminhar o relatório final.

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Continuação do Parecer: 4.538.911

Este parecer foi elaborado baseado nos documentos abaixo relacionados:

Tipo Documento	Arquivo	Postagem	Autor	Situação
Informações Básicas do Projeto	PB_INFORMAÇÕES BÁSICAS_DO_PROJETO_1671146.pdf	11/01/2021 13:42:21		Aceito
Outros	termo_de_compromisso_.pdf	11/01/2021 13:41:48	Mario Tanomaru Filho	Aceito
Projeto Detalhado / Brochura Investigador	projeto_de_pesquisa_airton_.pdf	11/01/2021 13:40:38	Mario Tanomaru Filho	Aceito
Outros	detalhamento_de_despesas_do_projeto_.pdf	04/12/2020 16:16:38	Mario Tanomaru Filho	Aceito
Outros	autorizacao_laboratorio_pesquisa_endodontia_.pdf	04/12/2020 16:14:22	Mario Tanomaru Filho	Aceito
Outros	declaracao_de_devolucao_ao_cep_.pdf	04/12/2020 16:13:09	Mario Tanomaru Filho	Aceito
Outros	declaracao_ao_comite_de_etica_.pdf	04/12/2020 16:11:06	Mario Tanomaru Filho	Aceito
Outros	declaracao_de_nao_ressarcimento_.pdf	04/12/2020 16:08:33	Mario Tanomaru Filho	Aceito
Outros	autorizacao_tcfc_.pdf	04/12/2020 16:05:57	Mario Tanomaru Filho	Aceito
Outros	autorizacao_micro_ct_.pdf	04/12/2020 16:04:55	Mario Tanomaru Filho	Aceito
Orçamento	orcamento_detalhado_.pdf	04/12/2020 16:02:32	Mario Tanomaru Filho	Aceito
TCLE / Termos de Assentimento / Justificativa de Ausência	solicitacao_de_despensa_do_termo_de_consentimento_.pdf	04/12/2020 15:55:13	Mario Tanomaru Filho	Aceito
Folha de Rosto	folha_de_rosto.pdf	04/12/2020 15:51:38	Mario Tanomaru Filho	Aceito

Situação do Parecer:

Aprovado

Necessita Apreciação da CONEP:

Não

ARARAQUARA, 12 de Fevereiro de 2021

Assinado por:
Andréa Gonçalves
 (Coordenador(a))

Endereço: HUMAITA 1680

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ANEXO C – CONFIRMAÇÃO DO RECEBIMENTO DA REVISÃO 1 (R1) DA PUBLICAÇÃO 1 NO PERIÓDICO INTERNATIONAL ENDODONTIC JOURNAL



Airton Oliveira Santos Junior <airtonosj@gmail.com>

Submission Received by International Endodontic Journal

1 mensagem

International Endodontic Journal <onbehalf@manuscriptcentral.com>

24 de junho de 2024 às 08:21

Responder a: iej.office@wiley.com

Para: rocharlesf@gmail.com

Cc: airtonosj@gmail.com, rocharlesf@gmail.com, tanomaru@uol.com.br, tanomaru@foar.unesp.br, reinhilde.jacobs@ki.se

24-Jun-2024

Dear Mr. Fontenele,

Your submission entitled "A novel artificial intelligence-powered tool for automated root canal segmentation in single-rooted teeth on cone-beam computed tomography has been received by the editorial office of International Endodontic Journal

Your manuscript ID is IEJ-24-00097.R1.

You can check on your submission at any time by going to its page in Wiley's Research Exchange submission portal using this link:

<https://wiley.atyponrex.com/submissionBoard/1/924a513e-78ed-4fce-9109-6c88aefb2b16/current>

If you used ScholarOne directly for your submission, you will not have a link to Wiley's Research Exchange submission portal. Instead, your submission can be checked through the ScholarOne Author Center.

If you DISAGREE with being listed as a co-author, please contact us at:

iej.office@wiley.com

This journal offers a number of license options for published papers; information about this is available here: <https://authorservices.wiley.com/author-resources/Journal-Authors/licensing/index.html>. The submitting author has confirmed that all co-authors have the necessary rights to grant in the submission, including in light of each co-author's funder policies. If any author's funder has a policy that restricts which kinds of license they can sign, for example if the funder is a member of Coalition S, please make sure the submitting author is aware.

Thank you for submitting to International Endodontic Journal.

Sincerely,

The Editorial Staff of International Endodontic Journal

ANEXO D – CONFIRMAÇÃO DO STATUS DE REVISÃO 1 (R1) DA PUBLICAÇÃO 2 NO PERIÓDICO SCIENTIFIC REPORTS



Airton Oliveira Santos Junior <airtonosj@gmail.com>

Fwd: Fw: Scientific Reports: Decision letter for SREP-24-02338

Rochales Fontenele <rocharlesf@gmail.com>
Para: Airton Oliveira Santos Junior <airtonosj@gmail.com>

8 de agosto de 2024 às 05:08

----- Forwarded message -----

De: Reinhilde Jacobs <reinhilde.jacobs@kuleuven.be>
Date: qui., 8 de ago. de 2024 às 09:50
Subject: Fw: Scientific Reports: Decision letter for SREP-24-02338
To: Rochales Fontenele <rocharlesf@gmail.com>

From: scientificreports@nature.com <scientificreports@nature.com>
Sent: 08 August 2024 08:16
To: Reinhilde Jacobs <reinhilde.jacobs@kuleuven.be>
Subject: Scientific Reports: Decision letter for SREP-24-02338

** Please ensure you delete the link to your author homepage in this e-mail if you wish to forward it to your coauthors **

Dear Professor Jacobs,

Your manuscript entitled "Progress in Endodontics: An Unique AI-Based Tool for Automated Segmentation of Pulp Cavity Structures in Bi-Rooted Premolar on CBCT" has now been reviewed and the reviewer comments are appended below. You will see that, while they find your work of interest, they have raised points that need to be addressed by a major revision.

We therefore invite you to revise and resubmit your manuscript, taking into account the points raised. At the same time, we ask that you ensure your manuscript complies with our format requirements explained in full at: <https://www.nature.com/srep/author-instructions/submission-guidelines>

Please note a recent change to our competing interests policy: specifically, the definition of 'competing interests' has broadened to include financial AND non-financial interests (details and guidelines at <https://www.nature.com/srep/journal-policies/editorial-policies#competing>). When submitting your revised paper, please can you ensure this statement refers to 'competing interests' and, if applicable, also list any non-financial competing interests as outlined in our editorial policies? Please note that the Competing Interests statement on the system must match the Competing Interests statement provided in the article file.

Please use the following link to submit a revised paper and a point-by-point response to any issues raised by our referees and editors. Our [guide](#) to writing a response to the reviewers' comments provides advice for maximising its effectiveness.

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(Direitos de publicação reservados ao autor)

Araraquara, 30 de setembro de 2024.

Airton Oliveira Santos Júnior