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Application of X-ray Microtomography in Dental Science

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Abstract: This study delves into the application of X-ray microtomography (microCT) in dental sciences, displaying its ability to provide detailed and non-destructive three-dimensional images of dental structures. Two primary studies were conducted: the first study examined the formation of dentinal cracks after root canal instrumentation in lower molars using different mechanized systems and evaluated the presence of debris after instrumentation. The second study assessed the removability of bioceramic cement combined with gutta-percha in lower premolars and quantified the remaining material after re-instrumentation of the canals. The results demonstrated that microCT is an essential tool for identifying cracks with micrometric precision and quickly quantifying debris and remaining obturation materials, underscoring its effectiveness in dental diagnosis and research. The research highlights the potential of microCT to enhance clinical outcomes in dentistry, significantly contributing to the development of new treatment techniques and materials. It suggests that this technology will become increasingly accessible and widely adopted.

Keywords: X-ray, Microtomography, three-dimensional imaging, dental science.

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Aplicação da Microtomografia de Raios X na Ciência Odontológica

Resumo: Este estudo explora em profundidade a aplicação da microtomografia computadorizada por raios X (microCT) nas ciências odontológicas, evidenciando sua capacidade de fornecer imagens tridimensionais detalhadas e não destrutivas das estruturas dentárias. Dois estudos principais foram realizados: o primeiro estudo investigou a formação de trincas dentinárias após a instrumentação dos canais radiculares em molares inferiores, utilizando diferentes sistemas mecanizados e, também avaliou a presença de detritos após a instrumentação. O segundo estudo analisou a capacidade de remoção de cimento biocerâmico combinado com guta-percha em pré-molares inferiores e quantificou o material remanescente após a re-instrumentação dos canais. Os resultados demonstraram que a microCT é uma ferramenta essencial para identificar trincas com precisão micrométrica e para quantificar rapidamente detritos e materiais obturadores remanescentes, reforçando sua eficácia tanto no diagnóstico quanto na pesquisa odontológica. A pesquisa destaca o potencial da microCT para melhorar os resultados clínicos em odontologia, contribuindo significativamente para o desenvolvimento de novas técnicas e materiais de tratamento, além de sugerir que essa tecnologia se tornará cada vez mais acessível e amplamente utilizada.

Palavras-chave: raios x, ciências odontológicas, microtomografia, imagens 3D.

1. INTRODUCTION

X-ray microtomography (microCT) is a sophisticated three-dimensional imaging technique extensively utilized across various scientific disciplines. In dental science, it plays a pivotal and innovative role, bridging the gap between advanced imaging technology and a profound understanding of dental structures. MicroCT is widely regarded as the gold standard technique due to its capability to deliver highly detailed images, enabling precise analysis of internal structures without requiring sample destruction. This attribute is particularly valuable in dental research, where analyzing complex structures is essential [1-3].

The physical principles underlying microCT are based on the attenuation of X-ray radiation by matter. The resulting image of an object's cross-section is a quantitative map of the linear attenuation coefficient at each point in the plane. This coefficient reflects the local ratio of X-ray interaction during scanning, encompassing both scattering and absorption of the incident radiation. Consequently, microCT is an indispensable tool for examining dense and heterogeneous materials, such as dental tissues, where high resolution is crucial for identifying small structural variations [4, 5]. Additionally, microCT facilitates high-resolution imaging of intricate areas, such as dentin and enamel, which are of paramount importance in dentistry [6-8]. The scanning process involving the rotation of the object under an X-ray beam, allows for volumetric reconstruction of the analyzed structures, enabling detailed studies of the interfaces and integrity of dental materials, such as cement and fillings [9]. These capabilities render microCT essential for research and clinical applications in dentistry, driving advancements in diagnostic and treatment techniques, as well as the validation of new materials and methodologies [10-14].

Moreover, when compared to traditional imaging techniques like conventional radiography or CT scans, microCT offers superior resolution, allowing for the detection of finer details that are often imperceptible with other methods. However, this increased precision comes with challenges, such as higher costs and longer processing times, which may limit its widespread adoption in routine clinical settings. Despite these challenges, the versatility of microCT continues to expand with technological innovations, such as enhanced image resolution and integration with other imaging modalities. These advancements promise to cement further the role of microCT in cutting-edge dental research and practice. For example, recent studies have employed microCT to investigate the progression of carious lesions [15], assess the success of dental implants [16, 17], and explore the mineralization patterns in enamel [7, 18]. Such applications emphasize the potential of microCT not only as a diagnostic tool but also as a critical instrument for the development of new dental materials and techniques.

In this context, the objective of this study was to harness the precision of microCT to address the specific challenges of dental science. The aim was to drive significant advances in understanding, diagnosing, and treating dental conditions, thereby contributing to the continuous improvement of dental practice. The primary focus of this work is on the application and effectiveness of the microCT technique in dental research. Emphasis is placed on demonstrating the capability of microCT as a tool for advancing our understanding of dental treatments, rather than evaluating the performance of the materials used.

The first study utilized the microCT technique to evaluate the incidence of crack formation in the root canals of lower molars following instrumentation with various mechanized systems. Additionally, it assessed the presence of debris left in the root canals after instrumentation. The second study employed microCT to examine the retrievability of canal fillings made with bioceramic cement combined with gutta-percha in lower premolars, estimating the amount of material removed from the canals after re-instrumentation.

2. MATERIALS AND METHODS

The microCT system used in both studies was the Skyscan 1173, manufactured by Bruker. The samples were scanned with an effective pixel size of 20 μm, a current of 114 μA, and a voltage of 70 kV. Projections were obtained over 360º with an angular step of 0.5º. To reduce the contribution of low-energy photons from the X-ray beam, an aluminum filter (1.0 mm thick) was used. For the pre-instrumentation data acquisition (projections), the samples were kept at room temperature for 2 hours before analysis for drying, to remove any signs of moisture, as they can interfere with the analyses.

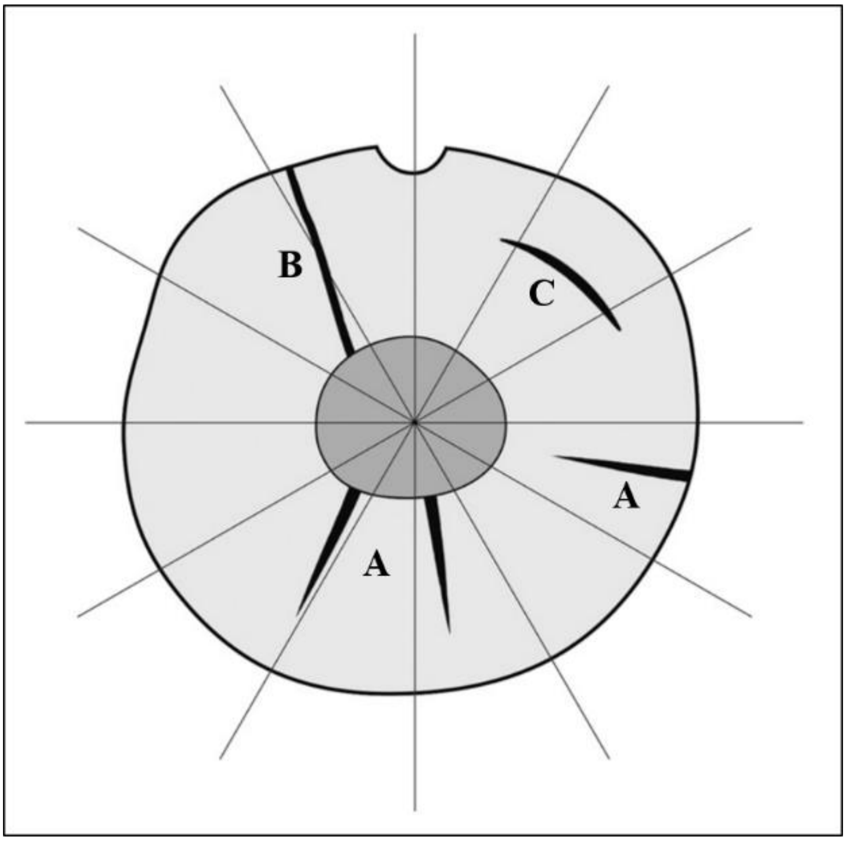
After the acquisition, the images of the teeth were reconstructed using the NRecon software version 1.7.5.1 (Bruker-microCT).

Afterward, the images obtained pre- and post-instrumentation were registered, leaving them in the same position through the 3D registration tool of DataViewer version 1.5.6.2 (Bruker-microCT). For this, the image of the previous phase was selected as the reference and the current phase as the target and they were adjusted in the X, Y, and Z coordinates, as well as their respective angles.

For the first study, 43 lower molars were scanned pre- and post-instrumentation. To standardize the definition of dentin cracks, a classification of these cracks into three categories was established as shown in Figure 1[19].

- ✓ **A – Incomplete crack**: a line that extends from the dentinal wall of the root canal without reaching the external surface of the root or a line that extends from the external surface of the root and does not reach the lumen of the root canal.
- ✓ **B – Complete crack**: a line that extends from the dentinal wall of the root canal to the external surface of the root.
- ✓ **C – Other cracks**: All other cracks (lines) that do not reach any surface of the root or extend on the surface of the dentin but do not reach the canal wall.

Figure 1: Schematic drawing of the dentin cracks evaluated in the first study [19].

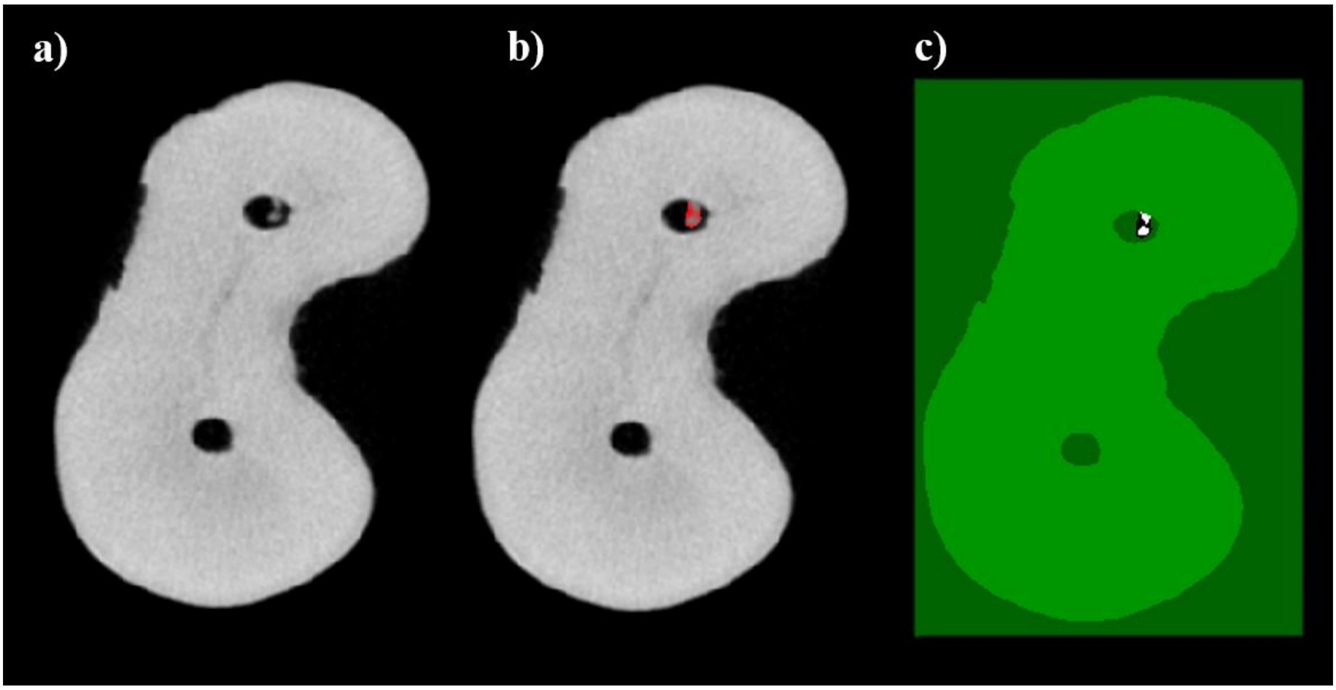


The identification of cracks was performed using the DataViewer program, and the linear (2D) measurements of crack length were made using the ISee software version 1.10.2 (BAN).

In the assessment of post-procedural debris within the canal, debris is defined as any dentin particles remaining after the procedure, and it was quantified using CTAN software version 1.18.9.0 (Bruker-microCT). This process involved the isolation and separate evaluation of each canal in the tooth. The region of interest (ROI) was determined, referring to the selected area in a single cross-sectional image. The volume of interest (VOI) was then defined as the integration of all ROIs across the selected image levels, representing the subvolume of the dataset within which procedures such as model construction and morphometric calculations would be performed. Subsequently, debris were binarized using the global method; in this method, a fixed range of grayscale values is set for solid pixels (white), while pixels outside this range are designated as space pixels (black), as shown in Figure 2.

The quantitative analysis was conducted using the software's three-dimensional analysis tool. The study aimed to evaluate crack formation and debris presence post-instrumentation along the entire length of the canals. A comparison of different mechanized systems was made based on the incidence of new cracks and amount of residual debris following instrumentation.

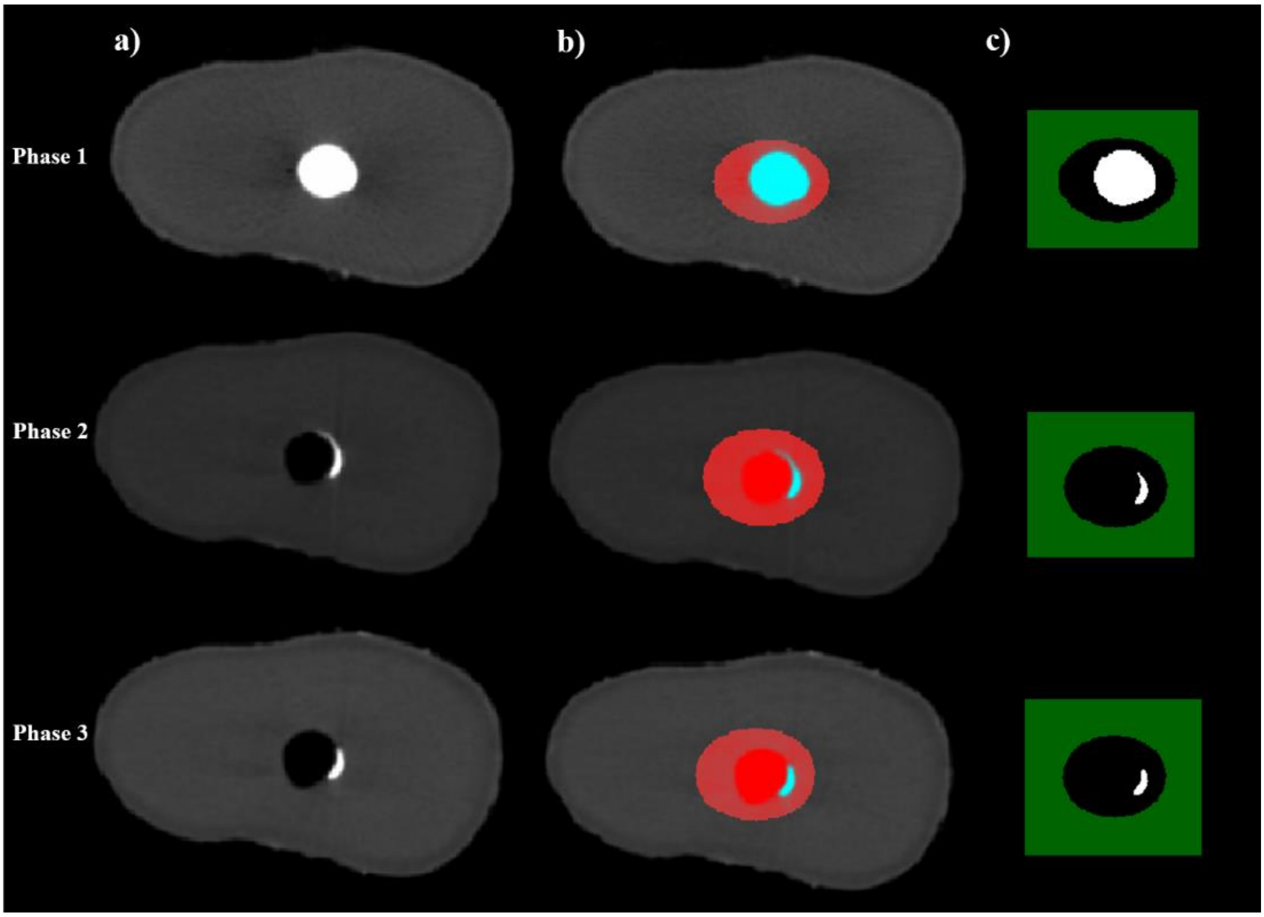
Figure 2: Steps of the quantification process:(a) original slice, (b) round ROI, and (c) binarized slice (the white color represents the debris).



In the second study, 70 lower premolars were scanned in three phases: pre-instrumentation, post-instrumentation, and a third phase after complementary instrumentation (retreatment). The primary objective was to evaluate the removability of bioceramic cement combined with gutta-percha from the premolars, and to quantify the residual material after re-instrumentation. The quantification of the cement volume in the canal was accomplished using the CTAN software. This process involved initially defining the region of interest, followed by image binarization (using a global method). The total volume of the obturation material was then determined using the software's three-dimensional analysis tool, with this process repeated for each of the three phases, as shown in Figure 3.

The amount of material removed after each instrumentation phase was calculated throughout the entire canal, and the efficacy of the retreatment procedure, using various approaches, was assessed based on the reduction in the remaining obturation material.

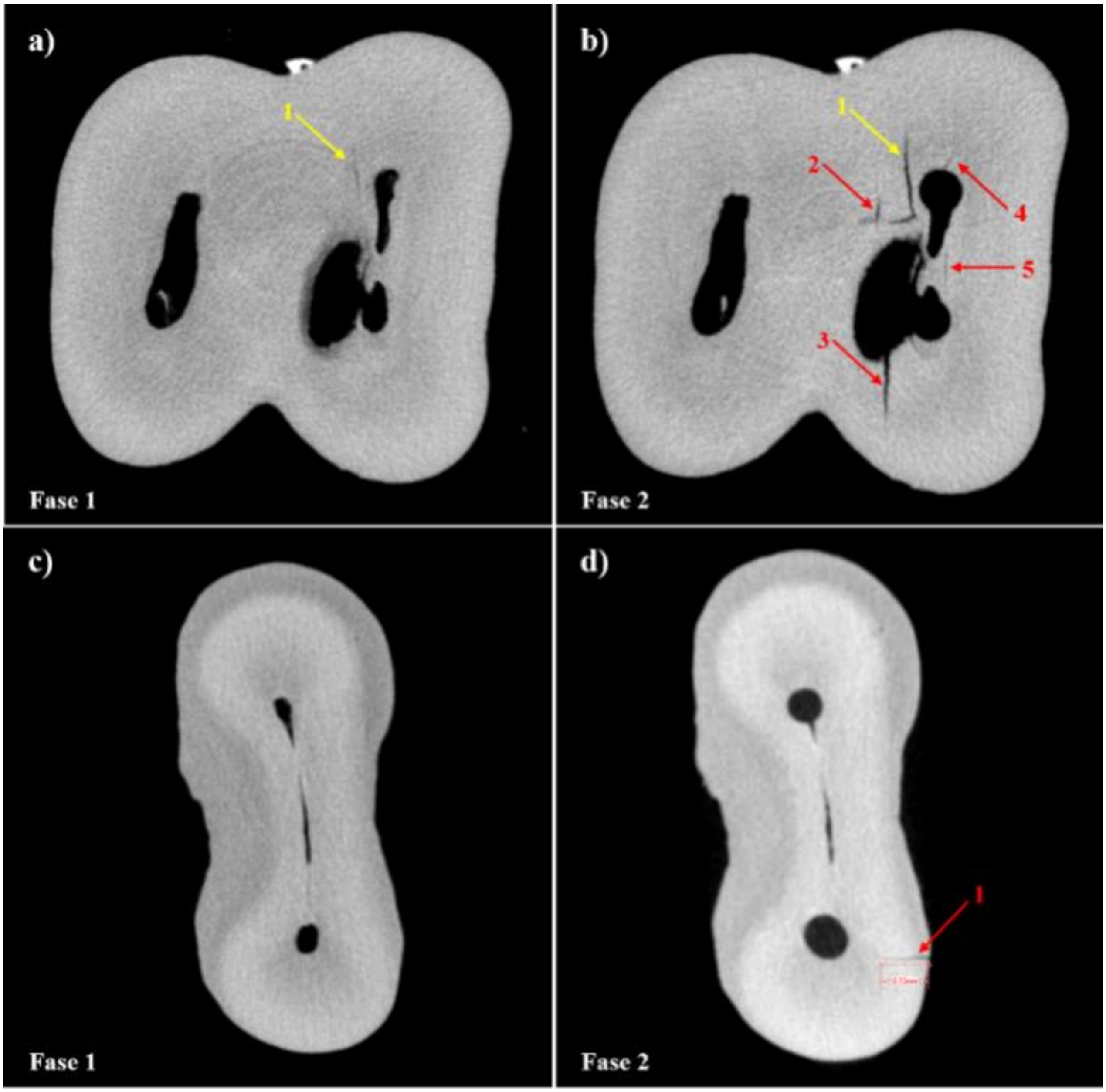
Figure 3: Steps of the quantification process for the 3 phases: (a) original slice, (b) round ROI, and (c) binarized slice (the white color represents the materials and the residual materials).



3. RESULTS AND DISCUSSIONS

The results of the first study showed that after instrumentation, cracks appeared in approximately 23% of the analyzed teeth and approximately 7% showed an increase in existing cracks. The minimum crack size observed (2D measurement) was approximately 0.25 mm. All cracks found were in categories A and C; no category B cracks were observed in any sample, as shown in Figure 4.

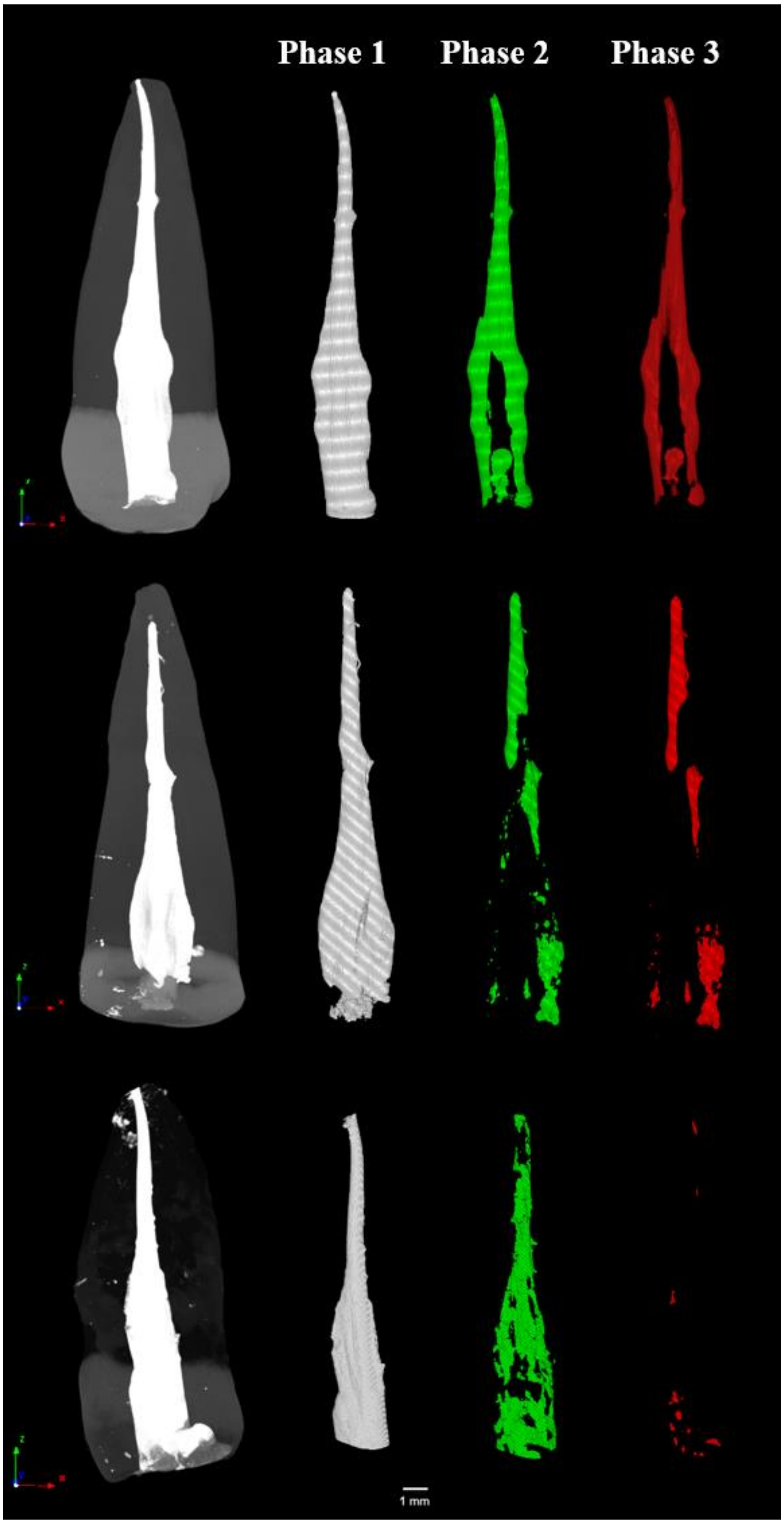
Figure 4: Examples of cracks found in the samples: a) and b) Arrow 1 highlights the increase in an existing crack (category C); arrows 2 and 5 indicate new cracks in category C and arrows 3 and 4 indicate cracks in category A. c) and d) Emergence of a crack (category A) after instrumentation with a length of 0.72 mm.



Within the limitations of this study, new cracks may appear during instrumentation, with no significant differences between the instruments tested. Approximately 95% of the lower molar canals exhibited debris following instrumentation. However, the maximum percentage of any canal occupied by debris did not exceed 2.8%. This remaining debris may negatively affect dentin treatment as it may be contaminated with microorganisms that will continue to develop inside the canals, compromising the treatment's effectiveness.

The findings from the second study revealed that, on average, 81% of the material was extracted from the canals after the initial instrumentation, and over 88% was removed after the second, the type of cement used had no impact on the volume of the remaining material. The percentage of material removed ranged from 41.3% to 99.6%, between phase 1 and phase 3, with a standard deviation of 10.6. While significant removal occurred in most cases, complete clearance of the canals was not always achieved. The main goal of root canal retreatment is to ensure the complete removal of filling materials, as well as debris and microorganisms, through adequate cleaning of the root canal system. Therefore, inadequate or insufficient removal of these elements could influence treatment outcomes, since the presence of root canal filling may hinder the contact between the irrigation solutions and persistent microorganisms. Figure 5 presents the 3D models showing the filling material in the three phases of the study for three different samples.

Figure 5: Example of 3 samples, filling material filling the canal in the first stage (phase 1), remaining filling material after the first instrumentation (phase 2), and remaining filling material after complementary instrumentation (phase 3).



4. CONCLUSIONS

The results of this study demonstrated the benefits of applying microCT in dental research, particularly in non-destructive studies. The ability of microCT to identify dentinal cracks with micrometric precision and to quickly quantify debris and remaining obturation materials in root canals underscores its effectiveness in both diagnosis and research. These findings not only confirm microCT as a valuable tool for dental diagnosis but also suggest that it could be crucial for the development of new treatment techniques and materials.

The application of microCT offers significant potential to improve clinical outcomes in dentistry, enabling a more detailed analysis of the consequences of different instrumentation and obturation methods. With the continuous evolution of technology, it is expected that microCT will become increasingly more accessible and widely used, contributing to the advancement of dental practice and scientific research.

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CONFLICT OF INTEREST

We have no conflicts of interest to disclose.

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