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Micro-Computed Tomography Applications in Dentistry

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Abstract

Micro-computed tomography (MCT) encompasses two primary scanning options: *ex-vivo* and *in-vivo* imaging. *Ex-vivo* scanning involves the examination of extracted teeth or dental specimens, allowing for detailed analyses of the microarchitecture of mineralized tissue. By analyzing the microarchitecture of dental tissues, MCT can provide valuable information about bone density, porosity, and microstructural changes, contributing to a better understanding of disease progression and treatment outcomes. Moreover, MCT facilitates the quantification of dental parameters, such as bone volume, trabecular thickness, and connectivity density, which are crucial for evaluating the efficacy of dental interventions. This present study aims to comprehensively review and explore the applications of MCT in dentistry and highlight its potential in advancing research and clinical practice. The results depicted that the quantitative approach of MCT enhances the precision and reliability of dental research. Researchers and clinicians can make evidence-based decisions regarding treatment strategies and patient management, relying on quantifiable data provided by MCT. The applications of MCT in dentistry extend beyond research, with potential clinical implications in fields such as dental implantology and endodontics. MCT is expected to play an increasingly significant role in enhancing our understanding of dental pathologies, improving treatment outcomes, and ultimately, benefiting patient care in the field of dentistry.

Keywords

Clinical Practice, Dentistry, *Ex-Vivo* Scanning, Micro-Computed Tomography

1. Introduction

Micro-computed tomography (MCT) is a digital imaging technique with three-dimensional higher resolution images used in dentistry to minimize chances of damage to samples leading to improved quality and safety of specimens and results [1]. Dental caries is a common dental disease that causes damage to the hard dental tissues due to acid diffusion interaction with hydroxyapatite in the presence of bacterial species such as "*Streptococcus mutans*" [2]. The worldwide prevalence of dental caries in permanent teeth was reported at 2.3 billion in 2017 [3]. To reverse the damage caused to dental tissue due to carries, there are still no effective methods available to completely regenerate tissue or enamel techniques probably because of a partial understanding of the fine structure remineralization process and estimation of enamel course through the statistical model in dental tissues [4]. The micro to Nanoscale visualization is required to identify progression in dental caries. MCT provides physical object cross-sectional visualization through X-rays which are later processed through software to create three-dimensional images or models [5]. MCT plays here critical role in the three-dimensional (3D) segmentation and assessment of millimetre size view on sub-micron resolution, especially for carious inter-rods and rods phases [6].

The MCT consists of an X-ray tube of 90 to 150 kVA, computer computer-operated CCD camera an electric motor to convert data from X-rays to visual, a collimator and filter, an intensifier apparatus for images, a computer, and a specimen stand. MCT consists of *ex-vivo* and *in-vivo* scanning as two options [7].

This comprehensive review explores the promising applications of MCT in dentistry, offering valuable insights for both researchers and dental practitioners. MCT, with its *ex-vivo* and *in-vivo* imaging options, unveils the intricate micro-architecture of dental tissues, shedding light on bone density, porosity, and microstructural changes. It goes beyond the surface by quantifying vital dental parameters, enhancing the precision and reliability of research. This quantitative approach not only aids researchers in evidence-based decision-making but also holds clinical potential, particularly in dental implantology and endodontics. As the dental community seeks to improve patient care and understand pathologies more deeply, MCT emerges as a powerful tool for achieving these goals. If you are curious about how cutting-edge technology is revolutionizing dentistry and improving treatment outcomes, this article is a must-read. The evidence presented in this article is of high quality, as it explores the scientific and clinical applications of MCT in dentistry, emphasizing its potential impact on both research and clinical practice.

2. Materials and Methods

A literature review was conducted using the following search terms: "Micro-Computed Tomography in Dentistry," "MCT applications in dental research," and "MCT in dental clinical practice." The process of data acquisition was performed using multiple databases, including PubMed, MEDLINE, Google Scholar, and relevant dental journals. No date limits were imposed during the search to ensure a comprehensive review. The literature examined in this review consisted of high-quality research studies, systematic reviews, and meta-analyses, published in reputable dental and medical journals. The majority of the included articles were based on well-designed experimental and clinical studies, providing robust evidence. The research process, depicted in Figure 1, intuitively outlines the systematic steps undertaken during the literature review, showcasing the approach used for data acquisition, analysis, and synthesis of findings from the reviewed literature.

3. Micro Computed Tomography in Endodontics

3.1. Assessment of Root Canal Morphology

An indispensable requirement of endodontic surgery and root canal treatment involves sufficient understanding and precise characterization of the anatomy of the root canal. Cone beam computed tomography (CBCT) and MCT use a coding system to identify the configuration of a root canal, tooth notation, dental anomalies, and several roots [8]. A research study estimated the dentin amount removed, and the increase in root canal volume through the determination of the alterations with the use of (XP-endo sharper (XP), Wave one Gold (WG), TRUShape (TS), TruNatomy (TN) and Reciproc Blue (RB) in the root canal structure and anatomy through MCT pre and post molar screening and reported similar effectivity with TN and XP, and RB and WG [9]. The morphological alterations in several teeth have limited detectability through conventional radiographs. In such conditions, the morphological features complex analysis could be performed through MCT. A study used MCT to monitor maxillary second premolar root canal morphology with the frequency of single root detection which came out to be higher (67%) than two roots (30%) and three roots (3%).

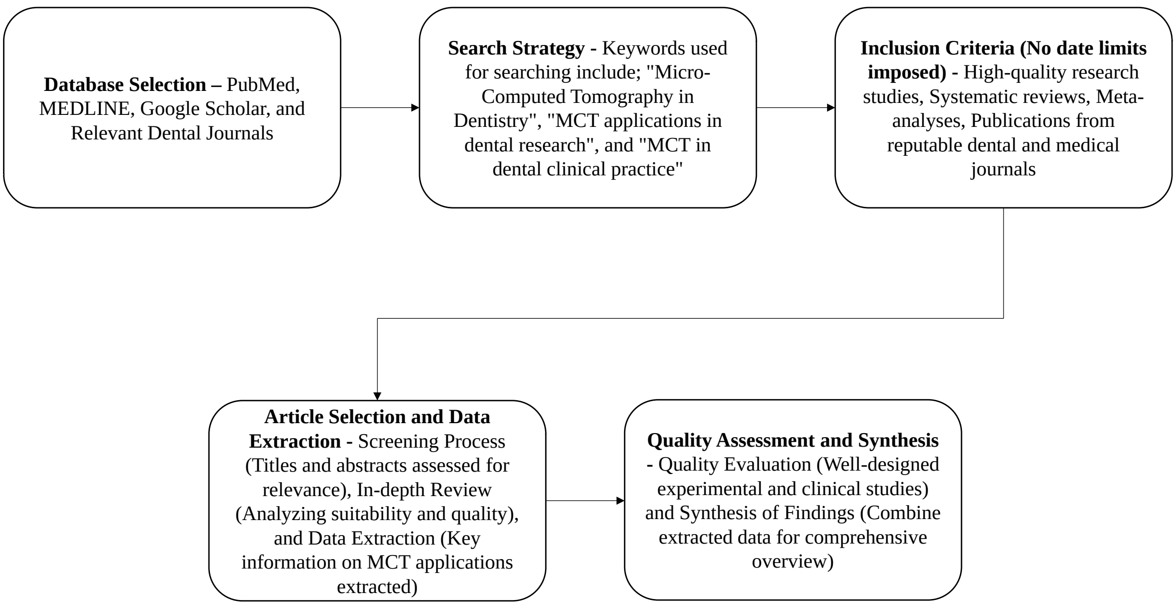

Figure 1. Research process.

Concerning canal assessment, two canals were reported in 65%, a single canal in 30%, and three canals in 5%. Studies with MCT use also concluded no dentinal micro-fissures determination on the tooth surface, if it has not experienced root canal treatment however the fissures existent on the tooth surface subsequently root canal preparation [7].

Esentürk *et al.* [10] examined the MCT of root canal preparation with the use of endodontic conventional files and (one shape, Revo-S) rotary files of young permanent and primary molar teeth. The MCT showed that Revo-S rotary file instrumentation significantly improved root canal surface area and volume ($p < 0.001$). A significant reduction in apical transport was observed in primary molars in comparison to permanent teeth ($p < 0.001$). The study recommended the use of rotary files as an alternative with the existence of un-instrumented areas in both permanent and primary teeth (**Table 1**).

Table 1. Micro-computed tomography application in different studies.

Author	Year	Sample Examined	Technology	Comparison Technology	Important Findings
Besnard *et al.* [6]	2021	Healthy carious and non-carious human dental enamel	Synchrotron X-ray MCT	Optical microscopy, electron microscopy (ion beam scanning), and X-ray conventional tomography	Clear contrast was obtained with Synchrotron X-ray MCT. Improved quantification of lesion depth function through volume fraction of demineralized content, voids cross-sectional area estimation, and aspect ratio achieved through D and 2D image segmentation. Within the same lesion, a transition between type 1 and type 2 lesions was identified.
Bollmann *et al.* [14]	2022	Transferability from tablets to oral films of X-ray MCT virtual matrice to be used in validation concept	X-ray micro-computed tomography	Confocal Raman microscopy	The obtained images confirmed the transferability of the validation concept. The combination of X-ray MCT and Raman microscopy figured out artifacts in images due to the presence of air bubbles in oral films. Therefore, the final raw images were with artifacts and the film virtual matrix did not be used in silico calculations as no real oral film representation was found.
Esentürk *et al.* [10]	2020	Root canal morphology	Micro-computed tomography	Rotary and conventional files in the young permanent and primary teeth	The MCT showed that Revo-S rotary file instrumentation significantly improved root canal surface area and volume ($p < 0.001$). A significant reduction in apical transport was observed in primary molars in comparison to permanent teeth ($p < 0.001$).
Colombo *et al.* [14]	2019	archaeological teeth mineral matrix	Micro-computed tomography		Through the IGD mineral matrix, vitamin D deficiency was detected in the archaeological samples under environmental and dietary habits.
Aktuna Belgın *et al.* [15]	2019	dentin and enamel	Micro-computed tomography	Periapical radiographs	Measurement of enamel and dental thickness accuracy and reliability through analysis of intra and inter-observation.

3.2. Improved Quantification of Lesion Depth Function

Besnard *et al.* [6] examined demineralization through a 3-dimensional analysis of human enamel in carious and non-carious dental samples with 325 nm voxel size with (815.4 × 815.4 × 685.4 μm^3) as total volume. The study used "Synchrotron X-ray MCT" to examine enamel sub-micron details in the inter-rod and rod regions. The comparison of results with an optical microscope, conventional X-ray, and ion-electron microscopy showed improved clear contrast images with Synchrotron X-ray MCT. The study also reported improved quantification of lesion depth function through volume fraction of demineralized content, voids cross-sectional area estimation, and aspect ratio achieved through 3D and 2D image segmentation. Within the same lesion, a transition between type 1 and type 2 lesions was identified, whilst the type 1 etching pattern was predominant in overall carious enamel. The post-treatment apical periodontitis assessment with MCT and CBCT validated in terms of tooth location, radiolucent lesions size, and determination of the quality of filling to examine root apexes after microsurgery of endodontic showed a fair level of agreement between MCT and CBCT (procedural errors) to satisfactory level (filling density). This indicates that MCT provides improved procedural error evaluation [11]. The maxilla microarchitecture trabecular assessment by CBCT and MCT-*ex-vivo* that trabecular numbers were higher with MCT images. The results also showed improved agreement between MCT and CBCT in bone and total volume (ICC: 0.421) and anisotropy degree (ICC: 0.439) ($p < 0.01$) [12].

3.3. Transferability of Validation Concept with MCT

Bollmann *et al.* [13] examine in silico tools to monitor the validity of quality assessment parameters of dissolution etc. through the examination of more than thirty million virtual matrices. The obtained images confirmed the transferability of the validation concept. The combination of X-ray MCT and Raman microscopy figured out artifacts in images due to the presence of air bubbles in oral films. Therefore, the final raw images were with artifacts and the film virtual matrix did not be used in silico calculations as no real oral film representation was found. Through the raw image representation, pathways were identified in image processing.

3.4. Detection of Vitamin D Deficiency in Archaeological Samples

A study by Colombo *et al.* [14] for the first time examines the presence of vitamin D deficiency associated with mineral pathological defects (interglobular dentine IGD) through MCT in three medieval cases of the mineral matrix. The X-ray technique of MCT is considered safe in archaeological findings as it demonstrates no damage to ancient preserved DNA or material in the investigation. IGD detection can be done in 3D through MCT as it is a non-destructive technique and analyses tooth microstructure.

3.5. Measurement of Enamel and Dental Thickness Accuracy and Reliability

MCT id recently been extensively used in prosthetic and restorative dentistry to examine restoration adoptions. Aktuna Belgın *et al.* [15] used 15 first premolars (maxillary) and maximum cervical crown, dentin, and enamel thickness was measured through MCT and periapical radiographs. Results were compared using the "Image J" software version and results demonstrated more than 0.95 intraclass correlation coefficients (ICC) through intra and inter-observation analysis. The results showed a statistically significant difference between the results of MCT and periapical radiographs. The highest R-value of 0.962 was shown by MCT with the least error indicative of the high accuracy of MCT. Resin-based restorative materials' mechanical properties are influenced by gaps, voids, or bubbles due to the presence of fatigue load and durability compromise. This results in clinical failure or fracture. Demirel *et al.* [16] used a "Filtek one BulkFill" resin composite which results in less production of internal voids in comparison to a conventional paste-like flowable resin composite. Another study examined different bulk-filled premolar restorations either with or without linear consisting of glass ionomer resin-modified cement to examine gap formation volume [17]. The thickness of the cement adhesive and seal margin are important factors for the successful utilization of restorative materials such as ceramic. Various computer-added software was used to measure inlay marginal adaptation and internal fit through the use of MCT. In this condition, the non-standardized portions of MCT must be kept in mind to avoid the non-standardization of specimen statistical results [18]. MCT and OCT are expensive procedures with the requirement of technical-specific instruments and statistical software for 2D and 3D assessment of the images. The limitation of MCT is that its ability to examine the oral cavity requires further examination. It is an expensive but non-destructive technique that protects the sample and displays extensive sample-associated information [19].

3.6. Assessment of Mini-Screws Implantation Location

Mini-implant advancements for orthodontic procedures, the implants help in the anchorage and the basis of desired tooth movement deprived of the implant was very challenging. The maxillary mini screw-type implants are placed between the first molar and premolar in the interalveolar segment of the arch. However, the placement of the implant can cause injury to related structures like the maxillary sinus and adjacent tooth roots. So, a detailed evaluation of anatomical structures is necessary for implant placement. So, the micro-CT can be used as an essential tool for the evaluation of the position of mini-implant placement. The evaluation by CT works on the digital image software. The software is specially designed to measure the difference between two lines [20].

3.7. Assessment of Micro-Leakage

The assessment of microleakage in class II cavity through comparison between pre-heated, flowable, and micro-hybrid resin composites through MCT has al-ways been the topic of debate [21]. MCT examines the anatomy of the complex internal tooth to assess the distance between anatomical components and thickness before the surgery. It also determines root fractures, dent alveolar, and maxillofacial accurate identification [22].

3.8. Role in Maxillofacial Surgery

MCT imagining role in maxillofacial surgery is evaluated among 28 patients through the determination of pre and post-surgical differences in the treatment of facial asymmetry due to "condylar hyperplasia" through MCT quantitative and semi-quantitative examination of the structure of bone. The study also reported no significant difference among condylar hyperplasia types ($p > 0.05$) [23]. Additionally, MCT was used to examine histological differences due to calcium hydroxide extrusion in endodontic events. This mandibular canal CH extrusions cause injury of the alveolar inferior nerve, detected through MCT at 1200 ms and 2.5 micrometers. The alterations in the nerve structure were effectively examined through MCT [24].

3.9. Role in Dental Implant

The treatment success in dental implants is measured through the assessment of implant stability based on bone-implant interface mechanical properties and fixation quality. A study utilized MCT for the assessment of dental and titanium-based orthopedic implants through silica-based ceramics at 14- and 28-day gaps. The MCT examination showed no significant difference in biomedical application with silica and titanium-based implants [25]. Another study examined marginal fit prosthesis through MCT, triple scan method, optical coherence tomography, and silicone replica technique, and a significant difference was reported in internal and marginal fit based on the used method [26].

4. Conclusion

MCT is an emerging technology with statistical software utilization to obtain high-resolution and accurate images of endodontic samples without destroying to sample. The limitations of MCT being expensive technology, involvement of skilled professionals and recent software, large file volume, and time involved in reconstruction and scanning could be overcome through scientific continues to research. However, the reliability of results and standardization of systemic parameters and samples overcome these limitations in patient dental care.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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