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Micro-computed tomography in preventive and restorative dental research: A review

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ABSTRACT

Purpose: The use of micro-computed tomography (micro-CT) scans in biomedical and dental research is growing rapidly. This study aimed to explore the scientific literature on approaches and applications of micro-CT in restorative dentistry.

Materials and Methods: An electronic search of publications from January 2009 to March 2021 was conducted using ScienceDirect, PubMed, and Google Scholar. The search included only English-language articles. Therefore, only studies that addressed recent advances and the potential uses of micro-CT in restorative and preventive dentistry were selected.

Results: Micro-CT is a tool that enables 3-dimensional imaging on a small scale with very high resolution. In this method, there is no need for sample preparation or slicing. Therefore, it is possible to examine the internal structure of tissue and the internal adaptation of materials to surfaces without destroying them. Due to these advantages, micro-CT has been recommended as a standard imaging tool in dental research for many applications such as tissue engineering, endodontics, restorative dentistry, and research on the mineral density of hard tissues and bone growth. However, the high costs of micro-CT, the time necessary for scanning and reconstruction, computer expertise requirements, and the enormous volume of information are drawbacks.

Conclusion: The potential of micro-CT as an emerging, accurate, non-destructive approach is clear, and the valuable research findings reported in the literature provide an impetus for researchers to perform future studies focusing on employing this method in dental research. ***(Imaging Sci Dent 2021; 51: 341-50)***

KEY WORDS: X-Ray Microtomography; Dentistry, Operative; Review Literature

Introduction

After the invention of X-rays in 1895 by Wilhelm Roentgen, it was hypothesized that X-rays could be used to diagnose some common conditions, such as fractures and foreign objects, and visualize the body's internal structures in a non-invasive way. Decades later, after a wider recognition of the importance of this technology, X-ray images became an integral part of routine patient care.[1,2]

Allan Cormack and Godfrey Hounsfield developed computer-assisted tomography in 1970, for which they received the Nobel Prize in Physiology or Medicine. In the late 1970s, computed tomography (CT) entered into widespread use in clinical settings.[3] CT is a 3-dimensional (3D) imaging method that produces 3D images composed of 2-dimensional (2D) projections. It involves obtaining X-ray projection images from many angles of view around an axis through an object. Then, it applies a tomographic reconstruction algorithm to produce a group of thin tomographic images of continual transaxial slices through the object. The transaxial images are made up of volume elements termed voxels. An object is usually scanned by rotating it around a vertical axis within a system comprising a stationary X-ray source and an X-ray imaging array.[3,4] Three levels of microscopic CT are defined based on their spatial resolution: mini-CT, micro-CT, and nano-CT. However, "micro-CT" is used as a generic term for all of them.[4]

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Micro-CT is a high-resolution type of CT. Lee Feldkamp developed the first micro-CT system in the early 1980s to evaluate structural defects in ceramic materials. Early micro-CT scanners were not widely available.[5] Compact commercial systems rapidly became essential components of academic and industrial research laboratories for various investigations and applications, with the potential of becoming a convincing substitute for histological sectioning.[6]

Micro-CT equipment consists of various essential components, including a 90-150 kVA X-ray tube, a filter and collimator, a computer-controlled electric motor, a CCD camera for translating X-ray image data, an image intensifier apparatus, a specimen stand, and a computer.[1,3] The 2 main types of micro-CT scans are *in vivo* and *ex vivo* scans. An object is placed on a stationary platform with an X-ray tube and an optical X-ray detector spins around it for *in vivo* scans. Instead, for *ex vivo* scanning, an object is placed on a rotating platform with the X-ray tube and the optical X-ray detector is in a fixed position.[7] Although rotating object scanners produce ultra-high-resolution images, they are not technically suitable for small-animal imaging (Fig. 1).[8]

An electric rotation stage is employed to specifically monitor the amount of sample rotation relative to the optical X-ray detector and X-ray tube to scan the sample for *ex vivo* micro-CT. The overall motion of the micro-CT scanner is regulated by a computer. Three-dimensional images are reconstructed using lead shielding, which protects the operators during the scanning procedure.[7] Clinical CT scanners typically produce images composed of 1 mm^3 voxels, while micro-CT systems have a much better spatial resolution. The voxel range of micro-CT (5-50 μm) is nearly 1 million times smaller in volume than the CT voxels. Thus, micro-CT is expected to have better diagnostic accuracy.[5,9]

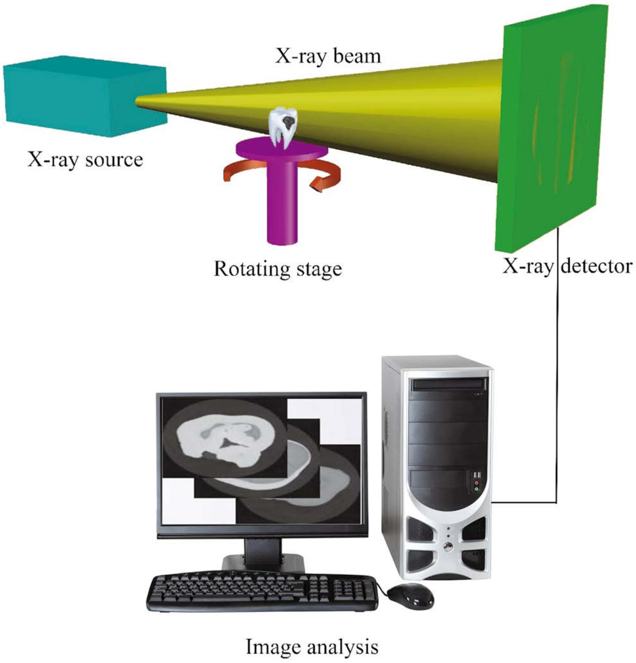

Fig. 1. Schematic representation of micro-computed tomography imaging.

Micro-CT provides many advantages in comparison with other methods, but it also has some restrictions. The advantage of these systems is convenient in-depth exploration of the X-ray imaging modality due to its narrow, monochromatic X-ray with high flux.[4] In contrast to microscopic methods, micro-CT is a nondestructive approach, meaning that the internal properties of the same sample can be tested several times, and samples remain intact for further biological and mechanical testing.[5] Another benefit of micro-CT is the possibility of multiple scanning and image processing using specific software. Sample preparation for micro-CT is not an issue, unlike when other destructive methods are used. The overall advantages of micro-CT facilitate more precise measurements.[1]

Some limitations of micro-CT relate to the scanning and reconstruction processing time, the high costs of this technique, and the necessity of computer expertise.[1,10] The image file sizes are large (around 3 GB). As a result, data acquisition can be a problem when it is necessary to store and retrieve large volumes of files.[11] The radiation dose from micro-CT scans is also sufficient to impact experimental outcomes by provoking changes in the immune response and other biological pathways. Although these changes usually are not lethal,[12] the high radiation dose prevents the use of micro-CT in clinical settings.[1,6]

In recent years, the utility of micro-CT has increased in experimental and preclinical bone and dental studies due to the broad range of technological advances in X-ray sources and X-ray imaging arrays.[4] Micro-CT systems provide an opportunity to analyze microstructures, defects, and differences in density and morphology. Several types of samples - encompassing mineralized hard tissues, soft tissues, and solid or liquid materials - can be examined using micro-CT.[5,10]

For more than 2 decades, cone-beam computed tomography (CBCT) has been routinely used in clinical settings in dentistry. CBCT was developed as a method of gathering images more quickly, at a lower radiation dose and a lower cost.[13] Compared to CBCT, micro-CT has smaller voxel sizes and a longer exposure, enabling the detection of more subtle and smaller changes.[14] Quantitative gray value measurements in CBCT, in contrast to micro-CT, are unreliable and therefore should generally be avoided. Because of the geometry of the beam and flat-panel detectors, artifacts, and variation in scanning circumstances, CBCT-based density measurements are inevitably erroneous.[15] Therefore, micro-CT images are anticipated to have higher accuracy for diagnostic measurements to detect carious lesions, periodontal disease, root resorption, and intra-operative imaging than CBCT images.[10]

The areas of implementation of micro-CT include biomedical and bioengineering applications and tissue engineering. Micro-CT has also facilitated dental research in various fields, such as endodontic studies of changes in bone structure and inflammatory root resorption due to bacterial infection of the dental apex, the evaluation of implants and surrounding bone, analyses of the growth and development of craniofacial bones, and studies investigating tooth-restoration interfaces.[1,10,16]

The purpose of this review article was not to cover all areas of micro-CT in dentistry, as this would not be possible within a single review, but to focus on the potential applications of micro-CT in preventive, diagnostic, and restorative dental research. This review addressed micro-CT approaches for the quantitative evaluation of tooth or dental material structures in recent research.

Remineralizing potential of tooth lesions under different treatment modalities

Several indirect methods have been introduced to estimate the mineral content of dental structures, such as optical coherence tomography (as a modality to measure optical properties),[17] microhardness,[18] and nanoindentation.[19] Direct approaches to measuring mineral content include transverse microradiography and micro-CT. CT is a nondestructive method of 3D tissue reconstruction for biological systems, whereas the traditional gold-standard method of transverse microradiography is destructive and time-consuming. Micro-CT has recently been used for quantitative research on dental hard tissue structures, and good agreement has been found with transverse microradiography in evaluations of mineral loss and the depth of lesions.[20]

The mineral density profiles obtained by micro-CT analyses furnish spatial insights into mineral distribution and can be utilized to monitor alterations in the mineral content of dental hard tissues, including enamel and dentin lesions.[19]

Bagheri et al.[19] used micro-CT to analyze the influence of surface impregnation of bovine enamel by leucine-rich amelogenin peptide (LRAP) on the remineralization capability of eroded lesions. They found that LRAP exerted a regulatory effect on the pattern of remineralization *in vitro*, improving lesion depth and mineral loss of the enamel lesions in a dose-dependent manner. In a similar study, Bächli et al.[21] examined the ability of dentin matrix proteins and enamel matrix derivatives to remineralize experimentally produced dentin lesions.

Neve et al.[22] promoted artificial dentin lesions in a multispecies biofilm model. After establishing caries lesions, they subjected washed samples to several bioactive types of cements, such as Biodentine^{TM}, conventional glass ionomer cement, mineral trioxide aggregate, and Portland cement. Mineral density changes were then calculated using micro-CT and reported in comparison with zinc-oxide eugenol (ZOE) and control groups.

Zan et al.[23] investigated remineralization in 3 types of restorations by means of micro-CT at the root dentin around the restorative materials after a period of cariogenic challenge.[23]

In the study of Liu et al.,[24] tooth blocks were randomly allocated to 4 groups (silver or potassium fluoride solutions, silver nitrate solution, and deionized water), and then were immersed in a buffered demineralization solution at pH 4.4. Mean lesion depth was measured by micro-CT. Another study recommended the adjunctive application of silver diamine fluoride with fluoride toothpaste for the remineralization of incipient caries lesions on smooth tooth surfaces based on the results of a micro-CT study on lesion depth and mineral density.[25]

Occlusal and proximal caries detection

Dentists usually diagnose caries primarily by a visual examination and bitewing radiography. Other clinical caries detection techniques have been proposed to provide objective measurements, such as the DIAGNOdent Pen (LF pen, Kavo, Biberach, Germany) and CarieScan PRO (CarieScan Ltd, Scotland, UK). The first relies on laser fluorescence, and the latter is based on electrical impedance spectroscopy.[26]

Histological slicing has been traditionally considered the gold-standard method for determining the depth of caries in *in vitro* studies to validate clinical methods. However, some parts of the specimen may be lost due to the thickness of the blade during the histological slicing procedure. In addition, the limited capability of a microscope to visualize damaged tissue should not be ignored.[27]

In recent years, a substantial emphasis has been placed on new methods for caries detection to investigate the depth of caries. The micro-CT technology does not destroy specimens and can evaluate nearly 1000 dental sections simultaneously. Thus, micro-CT was considered the gold standard in recent studies.[27-30] However, this method is not feasible in routine clinical practice because a long time is needed to scan, reconstruct and measure images, and micro-CT also requires a high dose of radiation.[27]

Lederer et al.[31] investigated the validity of bitewing radiography and near-infrared reflection to detect caries and compared them with micro-CT as a reference standard. In their study, near-infrared reflection was not found to be suitable for the reliable detection of proximal caries lesions. Micro-CT is a reliable and alternative nondestructive method compared with histology for the validation of caries detection methods.[6]

Evaluation of tooth structure mineral density

The density of minerals plays an essential role in providing the mechanical properties of enamel and dentin. Several studies have described the local mechanical properties of some areas of the tooth; however, it is necessary to examine the tooth's entire structure, from the crown to the apex, as a macrostructure from a mechanical point of view.[32]

Hayashi-Sakai et al.[32] examined mineral density distribution patterns in permanent and deciduous tooth structures to obtain a standard mineral density value for each type of tooth using micro-CT. They found that the mineral density of permanent enamel for each tooth gradually decreased towards the cementoenamel junction, and the mineral density of dentin in permanent teeth was lower than the density distribution of enamel in all areas.

Djomehri et al.[33] investigated various dental tissues, including normal, hypomineralized, and hypermineralized carious dentin, normal cementum, and cementum affected by periodontitis. They measured mineral density variations obtained from micro-CT in conjunction with elemental mapping obtained from X-ray fluorescence microscopy in the related tissues to obtain insights into normal and pathologic biomineralization processes.

Evaluation of thickness

Enamel thickness has long been important in anthropological studies and studies of human evolution due to its phylogenetic value.[5,34] Enamel thickness was also thought to be important in interpreting occlusal loading regimens, as well as in the presentation of chronic diseases such as metabolic disorders or developmental defects (e.g., enamel hypoplasia) in the evolutionary history of humans.[34]

Several methods exist for measuring the thickness of tooth enamel, including preparation of physical sections of the tooth, which has been widely used in a number of studies. However, the destructive nature of this approach prompted an ongoing debate regarding whether or not to cut teeth into thin sections, especially in scarce or extinct fossil samples. Other problems with this method, such as sample orientation, may cause some of the data to be less than ideal. Recent research has also used CT to quantify enamel thickness.[1] The use of micro-CT systems has become an effective and non-destructive method for measuring the thickness of tooth enamel.

Micro-CT provides optimal sensitivity in measuring the thickness of tooth enamel, while also not causing irreparable damage to specimens. Using this method, in addition to quantifying the thickness of the enamel, the volume of tooth enamel, dentin, and pulp can also be determined.[1,35] Some studies have employed this method to measure the crown thickness and cement space at different points.[36]

Biofilm formation

Recently, a method to identify low X-ray absorption materials was developed and used successfully to identify "artificial" dental biofilms created around the tooth surface.[37] Dual-energy micro-CT can detect delicate changes in the attenuation coefficient of an object utilizing 2 image stacks taken after data acquisition at 2 different input energies.

Pires et al.[37] employed saliva specimens from a patient with a carious lesion as a natural source of bacteria to induce artificial caries in sound dentin. They then quantified biofilm formation using a novel dual-energy micro-CT method and characterized the demineralization potential of the formed biofilm in the sound dentin *in vitro*.

Evaluation of polymerization shrinkage and stress

Current dental resin composites have become popular due to increasing esthetic demands and are preferred over amalgam for direct restorations. These materials undergo volume loss when they are polymerized. Polymerization shrinkage generates stresses that have a major impact on the marginal integrity of resin-based restorations, causing debonding from the surrounding tooth structure, and hence, gap formation. Several techniques have been introduced to evaluate polymerization shrinkage by measuring linear and volume changes. High-resolution microtomography is a non-contact method that can be employed to obtain actual

3D information from the cavity during polymerization.[38]

Some researchers added radiopaque zirconia fillers to experimental resin composites as markers to monitor polymerization shrinkage in bonded and unbonded class I cavities. Filler movement was investigated using micro-CT imaging.[39-41] The idea of tracing radiopaque fillers in a resin composite using micro-CT was suggested by Cho et al.,[41] who showed that boundary conditions and cavity depth affect the amount and direction of polymerization shrinkage. In their study, unbonded cavities presented free and higher deformation than bonded cavities, in contrast to the findings reported by Chiang et al.[40] An examination of the displacement vectors revealed that the filler's movement was towards the light curing source, except for the upper region of the bonded cavities, where the displacement vectors were oriented inward to the bottom of the cavities. The shrinkage effects of polymerization were more noticeable in the deepest section of the cavity.[41]

Polymerization shrinkage was measured differently by micro-CT in other studies.[42,43] Kamalak et al.[43] measured polymerization shrinkage by means of micro-CT as the ratio of the total volume of the composite resin before curing to the total volume of the composite resin after curing. Another study used a superimposition tool to evaluate volume changes of composite resin before and after curing with different irradiance modes of a light-curing unit. The results of that study did not confirm the effect of varying curing modes of the same light-curing unit on volumetric shrinkage.[42]

Evaluation of marginal and internal adaptation of restorative materials

Defects such as voids, gaps, and bubbles can reduce the mechanical properties of resin-based materials. Although the structure of the restorative material may initially have appropriate mechanical properties, defects can reduce the performance of the restorations under fatigue load and decrease the durability of the restorative material, leading to fractures and clinical failure.

Void formation can occur as a result of the viscosity of the material, the diameter of the applicator tip, and trapping of air inside the bulk composite during the manufacturing process or between the layers of a resin composite in the incremental method.[44] Oglakci et al.[45] evaluated gap formation volume using micro-CT in premolars restored with different bulk-fill composites, with and without a resin-modified glass-ionomer cement as liner. In the study by Demirel et al.[44] on void formation in class II restorations, a paste-like bulk-fill resin composite, Filtek One BulkFill, produced fewer internal voids than conventional flowable and paste-like resin composites. The most void formation was found in the group that received a layer of 1-mm conventional flowable restorative followed by conventional paste, like a restorative. The group that received 4 mm of Sonicfill SDR flowable bulk-fill resin composite followed by a paste-like resin composite also showed high void formation. The porous structure of the material, lower filler content, and chemical composition of the resin matrix may have a substantial impact on the material's microporosity and contribute to higher void formation. Some researchers have also investigated internal and marginal adaptation after curing of different adhesive restorative materials.[16,46-48]

Since the success of ceramic restorations is influenced by factors such as the margin seal and the thickness of the cement adhesive, Bayrak et al.[49] measured the internal fit and marginal adaptation of inlays designed by various computer-aided design software programs. They also emphasized that non-standardized sections in the micro-CT system due to the non-standardization of specimens could significantly impact the statistical results.

Evaluation of microleakage

The marginal adaptation of dental restorations discussed in the last section is of considerable importance in the longevity of the treatment. It has been demonstrated that structural defects at the bonding interface, as well as the action of polymerization shrinkage, can play a role in disturbing marginal adaptation. This leads to marginal staining and increases the risk of postoperative sensitivity and recurrent caries.[50-52]

Microleakage is defined as the clinically undetectable percolation of substances, such as fluids (most commonly saliva), bacteria, bacterial byproducts, and different molecules and ions, between a restorative material and cavity wall of the tooth.[52] A variety of *in vitro* methods have been suggested to image and measure microleakage. These methods include compressed air, electrochemical approaches, neutron activation analysis, reversible radioactive adsorption, radioisotopes, bacterial infiltration, scanning electron microscopy, and the dye-penetration method. Of these methods, the dye-penetration method is most widely used, but micro-CT has been introduced as the most recent method of microleakage assessment.[52-54]

The dye-penetration method entails immersion of a restored tooth in a dye solution. Then, it is necessary to cut through the restoration and assess the leakage that is visually detectable on the section under a microscope. The extent of leakage may be estimated quantitatively using a length scale. Nevertheless, leakage is often evaluated more subjectively using a system with a range of values for leakage as graded by an operator. Moreover, the major drawback of this method is that the results provide 2D images and do not take the whole tooth-restoration interface into account. In addition, dye leakage in different sections taken from other areas of the restoration varies considerably.[52]

Like the compressed air method, some other methods can produce results that reveal the entire tooth-restoration interface, although it is not possible to discern the path and location of the leakage, which is needed to determine the mechanism and cause of microleakage.[52]

To overcome all these shortcomings, micro-CT has recently been suggested to evaluate microleakage and restorations' internal and external adaptation. Micro-CT allows an accurate analysis without sectioning the samples due to the capacity of X-rays to penetrate the sample. In addition, regardless of the shape or dimensions of the sample, micro-CT makes it possible to examine the internal aspects predictably and reliably. Using micro-CT, 3D microleakage analysis is possible, as well as repeated evaluations over time.[46,55] Therefore, micro-CT is now used in various studies to evaluate microleakage.

Zhao et al.[52] evaluated the efficacy of micro-CT in detecting marginal leakage in class V restorations and reported that the accuracy of microleakage detection by micro-CT was comparable to that of the conventional microscope method in the dentin region. However, due to the lower radiopacity contrast of the silver nitrate in the enamel, it had less accuracy in the enamel area.

Tuwirqi et al.[56] used micro-CT to assess the penetration depth and microleakage of ICON resin infiltrant and conventional sealant in pits and fissures. They found that ICON revealed less microleakage and more penetration than conventional sealants. Two different techniques for bulk-fill resin composite in class II restorations were compared by Tosco et al.[54] using micro-CT, and the authors concluded that the observed microleakage was closely related to the positioning technique of the resin composite.

Bonding to cementum/dentin is considered a challenge in restorative dentistry due to the nature of the substrate. The study performed by Zavattini et al.[46] on class II cavities with micro-hybrid, flowable, and preheated composite resins showed that the majority of the microleakage detected by CT scans and an $AgNO_3$ tracer occurred at the cementum/dentin margin rather than at the enamel. They reported that the use of a flowable material should be avoided in the dentin/cementum margin and suggested lining the cavity with preheated composite-based material to reduce the incidence of microleakage.

Vohra et al.[57] compared the marginal integrity of ceramic crowns luted with bioactive and resin cements using micro-CT. The study's findings indicated that bioactive cements could provide an adhesive interface with less volumetric microleakage, better adhesion, and comparable bond strength compared with resin luting agents.

Endodontic studies

Micro-CT is also becoming increasingly important in the evaluation of root canal systems. Thirteen years after the development of micro-CT technology, the use of micro-CT was proposed for endodontic research in the field of dentistry.[58] Since then, researchers have explored the use of micro-CT in root canal systems. However, no comprehensive, detailed review of micro-CT applications in the area of restorative dentistry has yet been published, although this article attempted to supplement that gap in the present section. The following is a brief overview of the important applications of micro-CT in endodontic studies. Micro-CT allows the development of color-coded 3D models of root canals utilizing co-registered datasets from before and after preparation and high-accuracy image registration software. Endodontic research can now be conducted precisely and non-invasively thanks to the availability of micro-CT systems. A micro-CT scan can provide extensive information; slices can be reconstructed in any plane, and data can be depicted as 2D or rendered 3D images. Internal and external anatomy may be seen at the same time or separately. Images can be graded on both a qualitative and quantitative basis. Analyses of root canal morphology,[59,60] cracks,[61,62] and the shaping,[63] cleaning,[64] and filling abilities[65-67] of different systems have been conducted using this technique. Table 1 presents a summary of the information discussed in this article.

Discussion

This review article presented examples of micro-CT applications in dental research, focusing on restorative, diagnostic, and preventive dentistry. Micro-CT is now being used extensively in experimental restorative dentistry, as it can create detailed instructive images of teeth and dental materials.

Although micro-CT is not suitable for clinical use, it has become a powerful tool for experimental and preclinical research in the last decade because it provides a non-invasive, reproducible, and accurate technique for the qualitative and

Table 1. Application of micro-computed tomography in recent studies

Field of measurement	Procedure/substrate
Remineralizing potential following treatment modalities	· Effect of leucine-rich amelogenin peptide on eroded lesions in bovine enamel[19] · Effect of dentin matrix proteins and enamel matrix derivatives on dentin lesions[21] · Effect of several bioactive cements on carious dentin[22] · Impact of adhesive/composite or resin-modified glass ionomer cement restorative materials around bovine root dentin following cariogenic challenge[23] · Impact of silver or potassium fluoride solutions and silver nitrate solution on enamel following demineralization solution[24] · Effect of silver diamine fluoride and fluoride toothpaste on incipient caries lesions[25]
Occlusal and proximal caries detection	· Validity determination of bitewing radiography and visual examinations with micro-CT for occlusal caries[27] · Validity determination of digital radiography and visual examinations with micro-CT for occlusal caries[29] · Validity determination of bitewing radiography and near-infrared reflection with micro-CT for proximal caries[31]
Tooth structure mineral density	· Mineral density changes of permanent and deciduous teeth[32] · Mineral density changes in normal and diseased tissue affected by periodontitis or caries[33]
Evaluation of thickness	· Determination of enamel thickness[34] · Validity determination of optical coherence tomography with micro-CT for remaining dentin thickness[35] · Measurements of crown thickness and cement space under monolithic zirconia crowns[36]
Biofilm formation	· Quantification of biofilm formation on dentin and its demineralization potential after a cariogenic approach[37]
Polymerization shrinkage and stress	· Addition of traceable glass beads to monitor polymerization shrinkage of composite in cylindric cavity with or without an adhesive[39,40] · Addition of radiopaque fillers to monitor polymerization shrinkage of composite in class I cavity with or without an adhesive[41] · Ratio of the total volume of the composite before curing compared to after curing[43] · Use of a superimposition tool to evaluate volume changes of composite before and after curing[42]
Marginal and internal adaptation	· Adaptation of a nanocomposite resin with and without using Biodentine or resin-modified glass ionomer for pulp protection[16] · Gap formation under different bulk-fill composites compared to conventional composite, with or without capping[44] · Gap formation under different bulk-fill/conventional composites, with and without resin-modified glass cement liner[45,48] · Adaptation of composite resins bonded using different adhesive strategies after thermo-mechanical load cycling[47] · Adaptation of inlays designed by various computer-aided design software programs[49] · Adaptation of lithium disilicate and zirconia crowns made by different manufacturing systems[51]
Evaluation of microleakage	· Comparison of microleakage among micro-hybrid, flowable, and preheated composite resins in class II cavities[46] · Marginal leakage detection of class V restorations[52] · Comparison of the effect of direct and indirect bonding techniques on microleakage under orthodontic brackets[53] · Comparison of microleakage in different positioning techniques for bulk-fill in class II restorations[54] · Validation of a 3-dimensional protocol for assessment of microleakage class II cavities using regular and flowable bulk-fill composites[55] · Evaluation of penetration depth and microleakage of ICON resin infiltrant versus conventional sealant in pits and fissures[56] · Marginal integrity of ceramic crowns luted with bioactive and resin cements[57]
Analysis of root canal morphology	· Analysis of different teeth with complex anatomy[60] · Comparison of the accuracy of micro-CT and cone-beam computed tomography in detecting accessory canals in primary molars[59]
Evaluation of cracks	· Development of a method to produce a comprehensive finite element tooth model using data retrieved from micro-CT[61] · Measurements of crack depth using cone-beam computed tomography and panoramic radiography and validation of the measurements by micro-CT[62]

Table 1. Continued

Field of measurement	Procedure/substrate
Evaluation of root canal preparation	· Shaping abilities of 3 nickel-titanium rotary files in 3-dimensionally-printed mandibular molars[63]
Evaluation of cleaning of root canal	· Introduction of a validated approach for differentiating between debris and dentin tissue following instrumentation[64]
Evaluation of filling of root canal	· Filling ability and sealer apical extrusion of a sealer injection system compared to a conventional obturation system[65] · Impact of various test model sizes on the flow and volumetric filling of endodontic materials[66] · Evaluation of the void of root canal filling over time in the single gutta-percha cone technique using calcium silicate sealer[67]

Micro-CT: micro-computed tomography

quantitative assessment of teeth and dental materials. Dedicated software to extract data on the mineral density of tooth structure and tooth-restoration interfaces can collect a substantial quantity of information from scans that would be impossible to obtain using traditional methods. Data can be shown in 2D or 3D renderings, and slices can be produced in any plane. Micro-CT has also been considered as the gold standard in recent studies to determine the validity of other caries detection methods. Moreover, dual-energy micro-CT has been used to identify low X-ray absorption materials such as dental biofilms.

Furthermore, several studies have used micro-CT to measure polymerization shrinkage in different ways. A few examples include tracing radiopaque fillers before and after polymerization, volumetric measurement of composite bulk before and after polymerization, and the use of superimposition tools.

The prospect of using micro-CT as an emerging, accurate, and non-destructive method is obvious, and the promising results obtained in extant studies encourage researchers to conduct more studies on this method in dental research. It is expected that additional milestones will be reached in dental research using this method. However, the high cost of micro-CT, the time required for scanning and reconstruction, the need for computer expertise, and the large volume of files are disadvantages that limit its use in some cases. Moreover, the role of standardization of samples and system parameters cannot be ignored in achieving reliable results.

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