IDR International Dental Research

Review Article

The use of micro-computed tomography in dental applications

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Received: 5 March 2019
Accepted: 24 July 2019

Access Online

DOI:
10.5577/intdentres.2019.vol9.no2.7

Abstract

Together with developments in digital imaging systems, there has been increasing use of micro-computed tomography (μCT) in many areas, primarily in dentistry. As this method allows 3-dimensional images to be taken providing safe and high quality results, without damaging the samples being examined, it is often preferred. Consequently, it has become possible to record rapid progression in endodontic studies in particular and to research and easily compare several techniques. Furthermore, this method can be used in tissue engineering, forming data for FEM analysis, the growth and development of craniofacial bones, imaging bone structure, and in the evaluation of implants and surrounding bone in root tip surgery, to determine mineral concentration in the teeth and to measure the thickness of enamel.
The aim of this review was to focus on the areas of use of μCT in dentistry and state the advantages.

Keywords: Micro-computed tomography, X-ray micro-CT, dental application, three-dimensional imaging

How to cite this article: Erpaçal B, Adıgüzel Ö, Cangül S. The use of micro-computed tomography in dental applications. Int Dent Res 2019;9(2):78-91.

Introduction

With the invention of x-rays by Wilhelm Roentgen in 1895, technology allowing the imaging of internal body structures with non-invasive methods led to a revolution in diagnostic medicine (1). Micro-computed tomography (μCT) was developed by Jim Elliott in the 1980s and started to be used to obtain slices from samples in experimental endodontic studies in 1999 (2).

Computed tomography (CT) takes images of the body in the form of slices 1-2mm in thickness. When more slices are taken from the sample, in other words, as the slice thickness decreases, the image resolution increases. Thus more information about the sample is obtained. Therefore, the use of μCT devices was introduced with slice thickness stated in micrometers. Slices obtained from the sample on these devices are 5-50μm in thickness (2). The voxel range of μCTs is approximately 1 million times smaller volumetrically compared to the range on normal tomography. While the small voxel range provides very good cross-sectional resolution, it also provides the possibility of more detailed examination (3).

One of the two basic differences between CT and μCT is the size of the light source, which is 1mm in CT and 5-10μm in μCT. The smaller light source provides a reduction in the penumbra and a sharper image. The second difference is that while the light source revolves around the patient to form the image in CT, it is revolved around the object itself in μCT. When the light source is stable, mechanical vibration is reduced and the resolution of the image is increased (4). The most important advantage of μCT is that samples can be repeatedly examined without distortion due to the 3D imaging technology with high resolution (5). CT is extremely sensitive in linear measurements and determines bone density with accurate results. Moreover, grey tones have shown a low correlation with bone density measured with μCT and histological analysis. In a previous study of jawbones, no difference was found between regions in the grey tones measured with CT, whereas the bone density difference in μCT and histological analysis was found to be significant (6).

μCT scanners can now be accessed easily and have become basic components of current academic and industrial research laboratories. Using these scanners, mineralised tissues such as teeth and bones, and biomaterial scaffolds such as ceramics and polymers can be directly examined. In addition, soft tissues with higher intensity than infiltrated or surrounding tissue, such as lungs with perfusion, can be imaged with a contrast dye (2, 7, 8). The use of gold, iodine and silver probes allows the examination of non-mineralised tissues in these devices which do not have high soft tissue contrast. In addition to the imaging of bone tissues, composite materials and soft tissues, μCT is also used in the examination of metals and alloys (3).

Many samples, either solid or liquid, can be analysed using μCT. These devices are currently used in many different areas such as biomedical research, the development and production of pharmaceutical drugs, botany, zoology, geology, construction, mining, metallurgy, electronic components, composite materials and paper production (3).

Today, it has emerged as one of the non-destructive 3D analytical techniques in hard tissue research and has been used in a variety of dentistry fields, including caries research (9).

Micro-CT offers many advantages compared to other methods, but has some limitations. Scanning electron microscopy, stereomicroscopy and confocal laser microscopy can be used for superficial analysis, but do not provide 3D images without the need to cut samples. In contrast to these microscopic methods, the micro-CT allows the same sample to be used for different tests without destroying the sample. Other advantages of micro-CT are the possibility of repeated scanning and manipulation of the image using specific software. On the other hand, micro-CT is impossible to use for in vivo studies due to the radiation level (10).

The basic equipment constituting the micro-ct device; It consists of a 90-150 kVA X-ray tube, a CCD camera that translates X-ray image data, a computer-controlled electric motor, image intensifier apparatus and finally a computer for digitally collecting and controlling the image. Micro-CT's working principle is X-ray microfocal spot and high-resolution detectors that rotate around the object to be imaged to obtain a 3-dimensional image of the object. In the images obtained, 3D modeling is created by means of related programs in computer environment. The sample to be imaged is placed in a rotating housing, the system acquiring multiple X-ray shadow transition images of this material from different angles. Then, using these images, the cross-sectional images of the object are reconstructed to form a three-dimensional model (Fig. 1) (3).

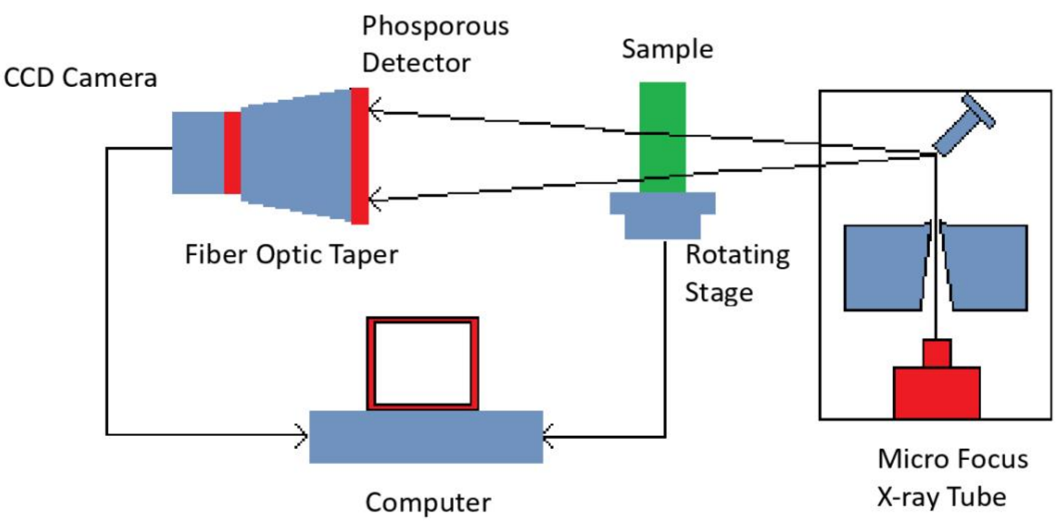

Figure 1. Schematic representation of μCT imaging

Advantages of using micro-CT

Micro-CT allows imaging of both mineralized hard tissues and soft tissues and materials (2,3). The most important advantage is that the samples used are not damaged and the measurements can be repeated (5). It provides highly accurate three-dimensional images of samples.

The use of micro-CT in comparative research can also provide insight into the relative superiority of existing treatment techniques and the emergence of best practices and clinical treatment guidelines. It can also help develop new educational approaches for dental students at all educational levels (11). Animal in vivo studies have shown that micro-CT imaging is a rapid, reproducible and noninvasive method that produces comparable results to histological methods (12).

Micro-CT imaging does not physically damage the sample; this is possible with repeated scans, which allow comparison of the same sample before or after the experiments. The difficulty of obtaining the sample used is no problem when using this method instead of other destructive methods (13). In addition, XMT aims to create a 3D dataset representing radiopacity at each point of a sample, and analysis of this 3D dataset allows reconstruction of volumetric data (14). The creation of such data sets is not possible by conventional methods. Since XMT produces a complete 3D X-ray attenuation map of the scanned object, 3D information is not compressed into two dimensions. That is, the image obtained is a real representation without overlap, as in intraoral radiographs (9).

Disadvantages of using micro-CT

Scanning and reconstruction in Micro-CT technology takes a relatively long time and requires computer expertise and is expensive compared to other methods. In addition, high radiation doses prevent the use of micro-CT in clinical settings (11).

The commercially available desktop XMT systems use polychromatic X-ray sources, which scan with loss of information due to beam hardening. It is possible that the scatter in the projection area causes a higher brightness around the edge of the cross-sectional image of the object (cupping artifacts) (9).

Use of micro-CT in dentistry

μCT is used in many areas of dentistry and research on these subjects is increasing. Areas of use for this imaging method include tissue engineering, identifying real data for FEM analysis, determining mineral concentration in the teeth, and in anthropological studies to measure the thickness of enamel, the structure and development of craniofacial bones, and in the evaluation of implants and surrounding bone in endodontic studies.

The greater ease provided by this method in endodontic studies in particular allows identification of the morpholıgy of the root canals, preparation can be checked, fillings can be evaluated and examinations can be done after the treatment (2, 15) (Fig. 2).

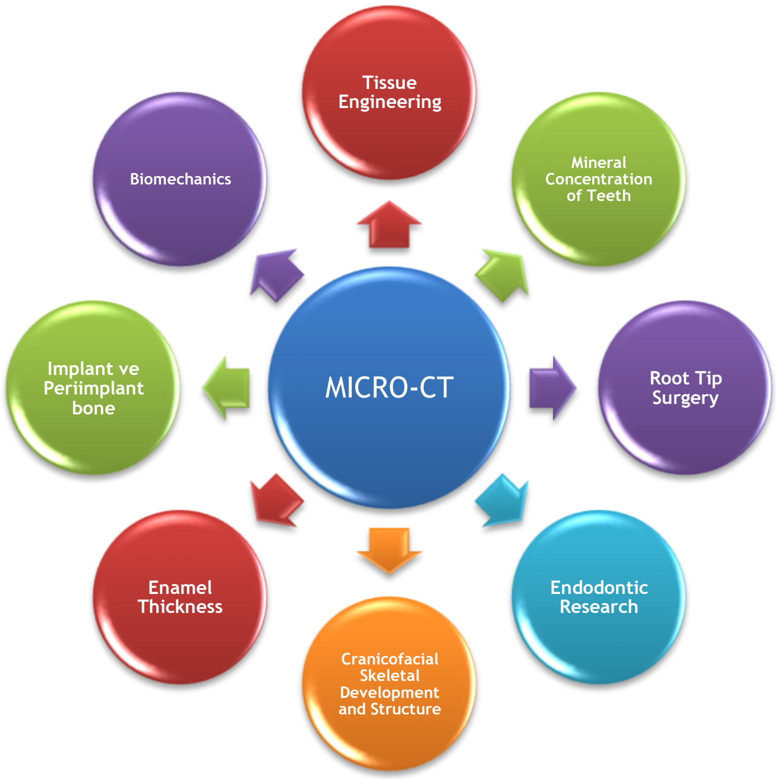

Figure 2. Uses of μCT in dentistry

1. Tissue engineering

The aim of tissue engineering studies is to produce biosynthetic organs in the laboratory to replace diseased or dead tissues (16). In recent years, µCT has been used in studies of structure scaffolds for tissue engineering, basically used to characterise the structure scaffold architecture, the disruption of the in-vitro structure scaffold and bone growth in polymeric and calcium phosphate structure scaffolds. When the destruction of the structure scaffolding is examined, it shows the site where materials have been completely lost, which can be used for evaluation of the structural changes during the destruction. In other words, it can be used in studies of acquired tissues and in the determination of lost tissues (17, 18).

In the treatment of alveolar cleft, µCT comparisons have been made of ε-caprolactone, which is the gold standard, autogenous graft and tricalcium phosphate polymer added to newly-enriched collagen. It has been shown that autogenous graft has the best ossification, and the newly developed materials have the results closest to this group. Thus, it has been concluded that tricalcium phosphate polymer added to collagen could be used as tissue scaffold (19).

2. Finite Element Method (FEM) analysis data

In recent years, finite element modelling (FEM) has become a technique that is widely used for the analysis of biomechanical and physical events together. µCT scanners can be used to form finite element models of small objects such as teeth, implants and dental restorations. Thus, the stress distribution of both teeth and bones can be more successfully reproduced (1, 5).

3. Growth and development of craniofacial bones

Imaging with µCT can be used for the evaluation of the growth and development of craniofacial bones. The unique properties and broader utility of this method have enabled it to become a new gold standard technique for the measurement of bone structure (1, 8).

µCT imaging has been used for the evaluation of alveolar bone remodelling, changes in the thickness of periodontal ligament, and changes in cortical and trabecular bone in rodent jaws. There are studies that have analysed the amount of destruction in the periapical bone using this method. The effect of different substances in the treatment of apical periodontitis has also been researched with this method in experimental animal models (4, 20). Although histological studies are the gold standard in the evaluation of periapical lesions, equivalent results with the use of µCT in the evaluation of periapical bone destruction have been reported in literature (21).

However, there is limited information in current literature on the subject of the analysis of images for the evaluation of periapical lesions and the standardisation of significant parameters such as data collection and re-structuring. There are limitations that could lead to incorrect measurements of the area or volume of peripheral lesions. According to some studies, although clear images have been obtained, changes have been seen in the lesion dimensions. Moreover, areas have been encountered in the related regions which are not a part of the periapical lesion (22). These results have demonstrated the need for a standard methodology in µCT analysis, and this procedure has been defined as usually insufficient. Currently, the resolution limit of in vivo µCT is not sufficient for measurement of the bone microstructure and vascular network. There is a need for in vivo scanning technologies to be developed to overcome this problem (20).

4. Determination of mineral concentration in teeth

The mineral concentration of dental tissues can be measured with chemical analysis or contact microradiography methods. However, these methods are time-consuming procedures and cause irreversible damage to the tissues. With the application of µCT, mineral concentration can be determined with a sensitive measurement without damaging the tissues. As the slice thickness in this application depends on the size of the x-ray bundle, finer slices can be obtained than in other methods (Fig. 3) (1, 23).

The mineralisation process of tooth enamel can be used to develop biomimetic approaches for the repair of lost enamel tissue. There are studies that have applied mechanical mapping of incisor teeth using µCT and in this way new images have been revealed for the full understanding of enamel maturation and mineralisation (24). Previous studies have reported the efficacy of different treatments and materials by measuring the change in mineral concentration following the application of materials to demineralised teeth to aid remineralisation (25,26).

Determination of mineral density profiles based on changes in X-ray attenuation is the principle of this method and requires calibration and image processing procedures for better image and reproducible measurements. With this method, 3D reconstruction is also possible and allows visualization of the internal structures of tooth decay. With advances in computer technology, a variety of applications such as automatic caries assessment algorithms are being studied (9).

Conventional gold standard in caries research in vitro is the histological evaluation of dental sections by expert examination or transverse microradiography. Both of these methods require tooth segmentation (9) (27). Since XMT provides a complete 3D construction of the scanned object, the information is not compressed into two dimensions. These advantages have made XMT more popular for measuring in vitro demineralization. Because radiopacity corresponds well to the mineral density in the teeth, XMT is well suited to detect demineralization properties of caries lesions (28).

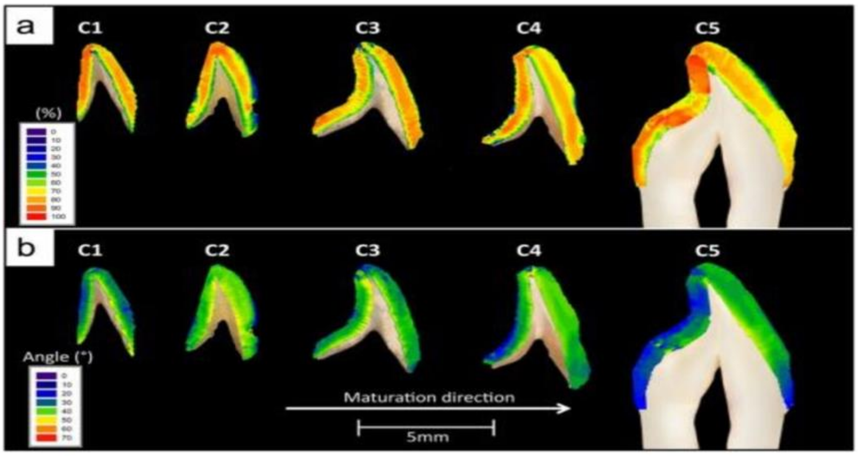

Figure 3. Mineral density display with µCT (25)

5. Measurement of enamel thickness

The determination of enamel thickness is a frequently used method in anthropological studies. One of the measurement methods is the taking of a slice, and this is frequently criticised as it causes irreversible damage to the samples. As the cutting of fossils results in loss of samples there is a need for the development of a new technique in this area. Although the use of CT for this purpose was desired, as the images obtained are of insufficient quality because of low resolution, CT use has been abandoned. While µCT provides results of the desired sensitivity in the measurement of enamel thickness, it is also a method that does not cause irreversible damage to the samples. With this method, it is not only possible to determine enamel thickness, but also the volumes of enamel, dentin and pulp (1, 4, 5). In studies that have been conducted to compare µCT and the method of taking slices, the reliability of µCT has been confirmed. However, it is not a reliable method for the differentiation of dental tissues showing over-mineralisation. It may also be seen to be insufficient in conditions where the enamel thickness remains <100µm (29).

6. Endodontic studies

Recent technological developments in the imaging of the anatomy of teeth have led to the successful use of different imaging methods. As these methods are non-invasive, they allow samples to be used for other purposes or the control of advanced treatment procedures and results (30). However, conventional clinical radiography only produces a 2-dimensional record rather than 3D information from a radiograph of a tooth. In traditional CT, thick slices are taken, which reduces the resolution and the image quality remains insufficient. However, from a µCT scan a great amount of information can be obtained, slices can be recreated in any plane and the data can be shown as 2D or 3D images. The internal and external anatomy can be shown at the same time or separately, and images can be evaluated qualitatively and quantitatively (1).

The development of µCT has become important in the imaging of hard tissues in endodontics. As it allows 3D images to be taken, this technique, which can be applied both quantitatively and qualitatively, allows evaluation of the root canal system (30) (Fig. 4).

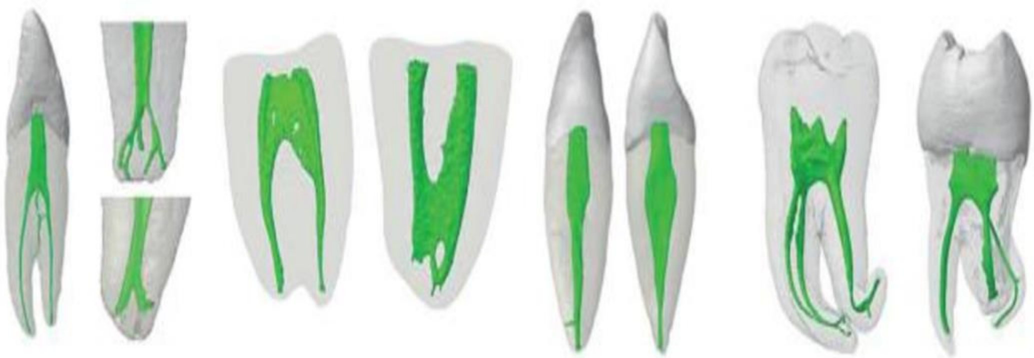

Figure 4. Visualization of root canals with µCT (31)

7. The use of micro-computed tomography in different areas of dentistry

7.1. Endodontic applications

Endodontic treatment involves several steps that determine the success of the treatment. Cleaning and shaping procedures are implemented to prevent microbial infection from the root canal system. This stage of treatment is carried out manually or with rotary instruments using irrigation solutions. After the reduction of microorganisms from the root canal system, a blocking agent is used to completely fill the cleaned area and prevent leakage. Various studies have been conducted to analyze the ability of the materials and techniques. However, there are limitations to the methods used. Microcomputer tomography has greatly improved the perspective of endodontic research. This technology has been widely applied to assess anatomy, techniques, and materials related to endodontic treatment (10).

7.1.1. Analysis of root canal morphology

To provide successful root canal treatment, it is mandatory to comprehensively understand the complex internal anatomy of the teeth. In several teeth there are irregularities such as lateral canals, apical branching, isthmuses and C-shaped canals (2, 32). Previous studies have been effective in developing the understanding of the structure of C-shaped canals. Further studies would be useful for the morphological examination of teeth showing developmental dental anomalies. In brief, it can be predicted that imaging with μCT could be a useful method for advanced analysis of root canal morphology in experimental endodontics (Fig. 5) (4, 33).

In a study that used μCT to investigate the root canal morphology of maxillary second premolars, a single root was found most commonly (67%), followed by 2 roots (30%) and 3 roots (3%). In the canal morphology, while 65% contained 2 canals, the presence of a single canal was observed in 30% and 3 canals in 5% (35). In a similar study, all canals in canine teeth with a single canal were classified as Vertucci Type I. Lateral canals were confirmed in the roots of 42.4%, and there was observed to be a wide variation in different root levels of canal morphology (35).

In a study that used μCT on fresh cadaver teeth, no dentinal micro-fissures were determined in any teeth that had not undergone endodontic treatment (36). In another similar study, the presence of micro-fissures was shown in several samples (1.54%) which had not undergone root canal preparation. It was also reported that post-space preparation increased the number of micro-fissures independently of the technique used. It was concluded that ParaPost XT Drills caused the formation of the maximum micro-fissures followed by Peeso Reemar and K files (37).

7.1.2. Evaluation of root canal preparation

Successful endodontic treatments are dependent on several factors, the most important of which is the stage of canal preparation. Initial preparation made in the best way is important for the efficacy of all the subsequent procedures, including mechanical debridement (1). As a result of imaging with μCT, it is possible to evaluate changes in the surfaces of the root canal exposed to instrumentation, the transportation formed, canal volume, canal width, volume of dentin removed, and changes occurring before and after preparation (2, 5). Just as the effect of different canal instruments on preparation can be evaluated with this method, changes may be revealed which occur as a result of the use of the same type of files of different diameters. There are also studies that have included comparisons of the effect of files and different canal filling materials for re-treatment (4).

Figure 5. Imaging of root canals with micro-CT (11)

Previous studies have shown that the root canal walls were not completely touched by any of the systems evaluated with µCT (31). According to recent studies, Reciproc Blue (RPCB), XP-endo Shaper (XPS) and Wave One Gold (WOG) did not cause the formation of new dentinal micro-fissures or increase existing dentinal micro-fissures (38). A study used µCT to compare the ability of 4 instrumentation systems in shaping curved molar root canals. The results showed that the shaping capabilities were similar, including Reciproc, but the ProTaper Next and Wave One Gold systems created a more rounded canal morphology than the ProDesign logic system (39).

In another µCT study, BioRace (BR), ProTaper NEXT (PTN) and Genius (GN) systems were seen to be effective at the same level, and each was seen to have successfully shaped the curve of the root canals without any significant errors in shaping or any unwanted changes in the root canals (31). When TruShape and Vortex Blue systems were compared in oval-shaped canals using µCT, both showed similar performance during preparation, but a more developed surface was seen to have been obtained with TruShape (32).

In another study with µCT, it was seen that the use of an electronic apex locator could determine apical narrowing but led to over-estimation of the working length (33).

7.1.3. Irrigation and the accumulation of hard tissue debris

During instrumentation, hard tissue debris has been seen to fill gaps extending as far as the branching and indentations in the root canal. To determine the areas where debris has adhered, voxels have been determined with µCT which show soft tissue before preparation with the appearance of air or fluid, but radio-opacity after the procedure. Thus the accumulation of hard tissue debris can be encountered, and the effect on this accumulation of the type of irrigation solution and the methods applied can be determined (34). However, a disadvantage of the method is that necrotic tissues are not seen with soft tissue debris. Furthermore, as hard tissue debris presents an appearance similar to that of dentin, voxels circulating with debris again after removal from the canal wall during preparation cannot be differentiated (35). While these methods cannot determine the chemical effects of irrigation solution on the root canal, there are studies that have used contrast dye to visualise the areas that have been reached (4), although a previous study found the role of irrigation solutions in re-treatment to be debatable (36).

In a study that examined hard tissue accumulation during root canal instrumentation with µCT, 29.2±14.5% of the original canal volume was seen to be filled with debris in selected canal segments. 2D reconstructions of µCT images demonstrated hard tissue accumulations that had accumulated in the whole canal system. It was concluded that the existing method is suitable for the quantitative comparison of different instrumentation and irrigation regimens in dentin debris accumulation (37).

µCT was used in a study that compared the efficacy of removing calcium hydroxide (CH) in the root canal with CanalBrush, Vibringe, laser-activated irrigation (LAI), conventional syringe irrigation (CSI), XP-endo Finisher and passive ultrasonic irrigation (PUI). It was concluded that activation with different devices of sodium hypochloride solution contributed to the removal of CH in the apical and mid-sections of the canal, and that better results were obtained with PUI and LAI methods in the mid and apical thirds of the canal, respectively (38).

7.1.4. Evaluation of the filling of the root canal

To be able to consider endodontic treatment successful, a 3D canal filling is required which shows homogenous adaptation to all gaps, completely closing the root canal with no leakage (4, 5). Any potential microleakage between the canal filling material and the dentin or in gaps which could not be homogenously filled has a negative effect on treatment success. µCTis currently the best method which can be used in microleakage studies (5). When histological slices have been compared with the µCT method for the investigation of gaps remaining in root canal fillings, a strong correlation has been found. In addition, filling material reaching isthmus regions and branching has been able to be determined with this method. By processing on the computer after obtaining images with µCT, gaps can be stained with canal paste at different intensities, gutta percha or with different colours or become transparent (39) (Fig. 6).

In a previous study, µCT and nano-CT were used for quantitative analysis in the investigation of gaps remaining in different root canal fillings. In all the tested materials, the least gap was seen in the apical third. In addition, nano-CT imaging was seen to be more sensitive in the determination of the rate of gaps (40). In a study that compared the techniques of cold lateral compaction (CLC), continuous wave condensation (CWC), single core (SC), and sealer-only buckfill (SoB), it was concluded that no technique filled the gaps completely and CWC technology was the most successful (41). Using µCT, another study evaluated the frequency of dentinal micro-fissures following root canal procedures in mandibular molars with GuttaCore (GC), cold lateral compaction (CLC), and warm vertical compaction (WVC) techniques and it was seen that none of the techniques triggered the development of new micro-fissures (42). In dental models simulating internal root resorption (IRR), evaluation was made with µCT of the obturation quality of mineral trioxide aggregate (MTA) and Biodentine, which had been placed with manual condensation or indirect ultrasonic activation techniques. No significant difference was observed between the groups in respect of filling materials. It was concluded that obstruction of the apical region in teeth with IRR is difficult, regardless of the type of material and placement technique (43).

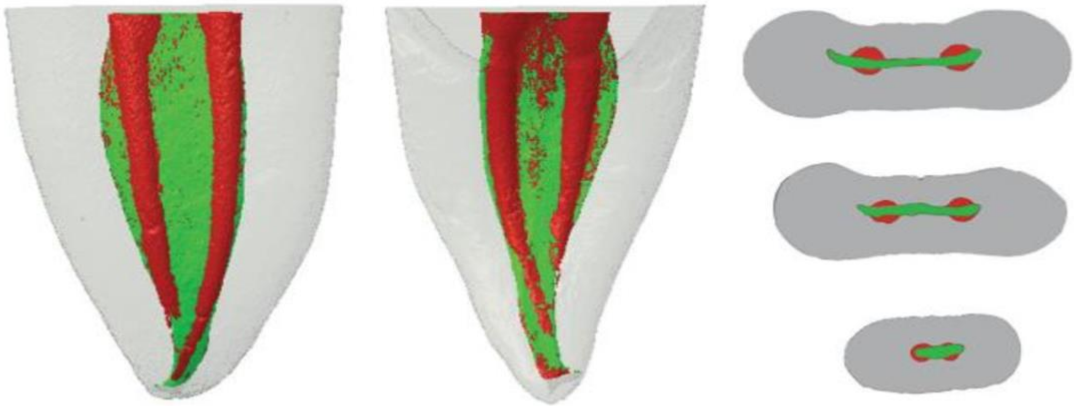

Figure 6. Visualization of root canal filling with µCT (11)

7.1.5. Evaluation of filling material remaining in the root canal after repeated treatment procedures

Epidemiological studies have shown that >40% of root-filled teeth in a population with periradicular radiolucence were consistent with endodontic infection (44). In the majority of cases, the preferred treatment was ortograde emptying of the root canal system. The root canal cavity is disinfected with the aim of creating more favourable conditions for periradicular healing. Therefore, it is necessary to remove the existing root canal filling. As µCT is a non-destructive imaging method, it is the most appropriate method for evaluation of the gradual widening of the canal area during removal (2, 45). In this way, 3D evaluation of the amount of dentin removed and the canal volume can be made, and the efficacy of the instrument used for removal of the filling material from the canal (5).

Comparisons of methods used for removal of root canal filling were made in a study using µCT, and it was reported that while the applications of different protocols were effective, none of the methods completely removed the filling material. There was seen to be wider preparation than previous treatments and less material remained with hybrid methods. According to another study, when additional preparation was made using XP-Endo Finisher after the use of ProTaper Universal Retreatment system and F3 ProTaper devices, the efficacy of removal of filling material from root canals was increased (46).

In another study that used µCT imaging, more material was removed using XP-Endo Finisher R device to remove filling remnants from oval-shaped canals than with passive ultrasonic irrigation. It was concluded that none of the additional approaches completely rinsed the root filling material from oval-shaped canals (47). In another study, XP-Endo Finisher and XP-Endo Finisher R were evaluated with µCT to be equally effective in the removal of old filling material from smooth oval-shaped canals. However, it was concluded that neither of the instruments could completely remove all the remaining filling material (48).

7.2. Orthodontic studies

µCT is used in orthodontics to evaluate bone development in the region and to determine changes in the bone during tooth movement (49, 50). Animal models are widely used to examine orthodontic tooth movement (OTM), which is the result of specific bone modelling in the region under pressure. Measurement of change in the alveolar bone around a tooth is a basic requirement to understand the orthodontic mechanism. In a study conducted on rats, it was concluded that µCT could be used to accurately measure dynamic alveolar bone changes during OTM (50). The vitality of skeletal anchorage and the effect on inter-radicular bone volume during low-force OTM can be determined with this method (51). There are also studies that have determined the effect of drugs on tooth movement using µCT (52).

7.3. Periodontological - Surgical operations

µCT has been shown to be the most cited technique for assessing bone mass and morphology in animal models (53). Especially in dentistry, this method is extremely useful for examining human jawbone associated with different conditions and diseases, as well as evaluating changes made when bone lesions develop or are referred to surgical procedures (54,55). For bone tissue analysis, sample preparation and stabilization of the sample holder within the µCT unit should be standardized (56).

µCT imaging was applied in a study to investigate the specific morphological properties of alveolar bone and to make comparisons with the femoral bone in rats. It was determined that the alveolar bone showed specific morphological properties of being compact, wider and having extremely mineralised trabeculae, compared to the spongeous distal femur (57).

In another rat model study using µCT that examined alveolar bone healing following the extraction of upper incisor teeth, it was observed that the morphometric parameters of bone volume and trabecular thickness gradually increased over time. Finally, there was seen to be a gradual decrease in porosity in the trabecular space and in the total bone. Appropriate morphometric properties in the newly-formed bone were shown qualitatively and quantitatively with µCT (58).

In another experimental study, rats were examined with µCT to reveal the effect on bone repair of a high-refined carbohydrate diet. The results showed horizontal alveolar bone loss and disruption in trabecular bone. A high-carbohydrate diet was seen to impair the bone regeneration process and this was supported by bone loss (59) (Figure 7).

In a rat model of hyperocclusion, µCT was used to measure changes in bone mineral density. This method was proved to be beneficial for further investigation of bone changes in other periodontal disease research areas (60).

To compare the differences between Enterococcus faecalis (Ef) and Porphyromonas gingivalis (Pg)-origin chronic apical periodontitis (CAP), 3D µCT analysis was made of periapical sclerotic changes and inflammatory root resorption (IRR). It was reported that Pg had caused more severe alveolar bone destruction than Ef and had caused IRR. In addition, the mandible was found to be more susceptible to CAP in respect of micro-structural changes in the maxilla and trabecular bone (61).

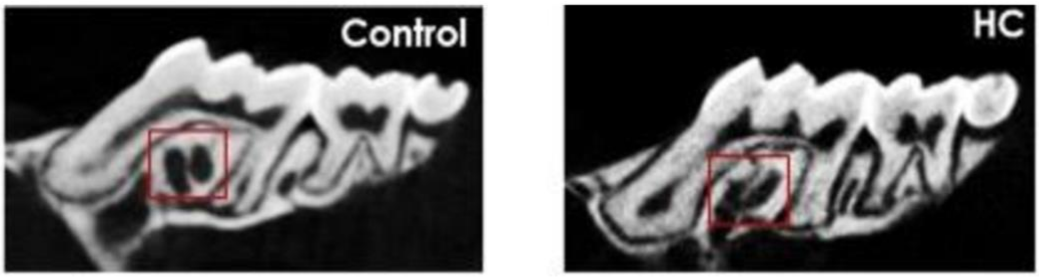

Figure 7. µCT images of alveolar bone and teeth (59)

7.3.1. Evaluation of the implant and surrounding bone

Implant stability is one of the important factors providing successful osseointegration, and is necessary for the long-term success of the treatment. Osseointegration is measured as the amount of bone in direct contact with the implant, known as bone-implant contact (BIC). There are several methods that can evaluate implant stability. Histology and backscatter scanning electron microscope (bSEM) is the current gold standard method for measuring BIC, but as histological methods are invasive, the use of radiographs has been found to be more practical (62, 63). µCT is a non-destructive, rapid method giving reliable results, which can be used in the evaluation of implants and the surrounding bone. It can be used in the measurement of parameters of bone volume, bone surface, trabecular thickness, trabecular separation and the bonding capability of the bone. This method allows non-destructive 3D evaluation of samples containing the implant, and the implant interface can be visualised in detail (2, 64). Thus, the bone tissue close to the implant surface can be examined at a thickness of several microns and the implant osteointegration can be evaluated quantitatively and qualitatively (65) (Figure 8). However, in comparisons of µCT with bSEM and histology in animal models, conflicting results have been obtained in respect of BIC evaluation (63). When the osteointegration of titanium implants has been examined with µCT, a remodelling model parallel to bone formation and bone-implant interface has been revealed (66).

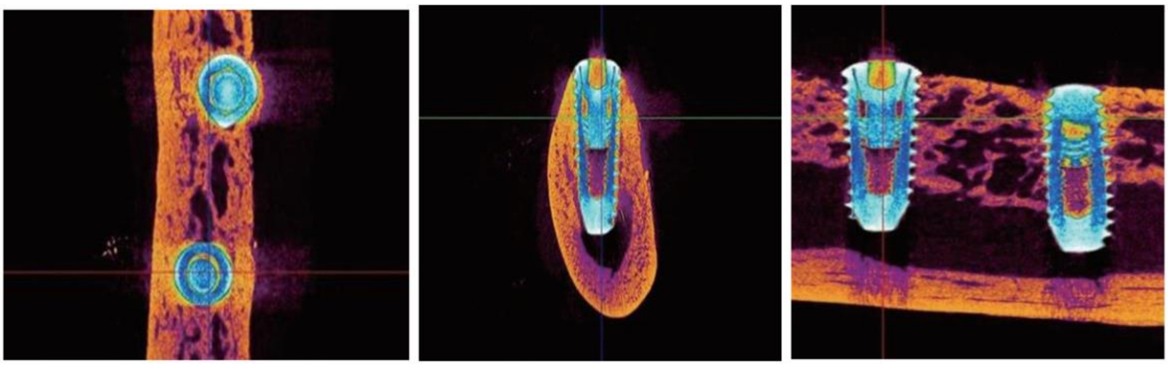

Figure 8. Evaluation of bone around the implant (69)

In a previous rabbit model study, histological methods and µCT were used for the evaluation of implant distortion and new bone formation. The findings showed that µCT was non-traumatic and provided quantitative definitive data in vivo, and was therefore valuable for the investigation of implants and new bone formation (67).

In a rat model study conducted in 2012, differences in implant composition and geometry were seen to lead to different artefact designs. It was concluded that it could be used only as a guide for the prediction of implant fixation and it should not be over-interpreted as BIC measuremnt (68). There is a need to establish a protocol to provide measurements made close to the implant and to optimise the parameters of µCT imaging. According to the reported findings, the advanced imaging capability of new-generation scanners has reduced the inclusion of metal artefact regions to the extent of allowing BIC evaluation. In conclusion, it was shown that with optimisation of the scanning parameters, the use of µCT to measure the BIC amount was sufficient to be able to reduce metal-origin traces (63).

In a study that employed µCT to evaluate the effect on inner and outer marginal compatibility of different production methods of metal crown with single implant support, it was seen that the production method had a direct effect on marginal compatibility between prosthesis and implant. The best results were determined for crowns manufactured using CAD/CAM processes (70).

In a canine study to evaluate the effect of different abutment configurations on soft and hard tissue healing, examinations were made with µCT and histological methods. It was seen that the design of the transmucosal component could affect the peri-implant biological width. From the results it was understood that the peri-implant biological width of the straight and wide outflow profile had caused apical displacement and greater bone loss (71).

In another canine study conducted using µCT, comparisons were made of the effects on two-layer biological bone augmentation (BBA) technique treatment of dehiscence type defects formed in the bone around the implant. The results showed that the BBA technique including mechanical support for the long-term care of the xenogenic bone could be useful for the treatment of defects around the implant (69).

A study that compared titanium and zirconium dental implants was designed to examine the reaction of bone tissue to new zirconium implants with a modified surface. Similar osseointegration properties were shown by the modified surface zirconium implants as in the titanium implants. These results are promising for the future use of zirconium implants in dental applications. According to the µCT findings of a rat model study, bone loss percentages were determined to be significantly higher than periodontitis in peri-implantitis (Fig. 9) (72,73).

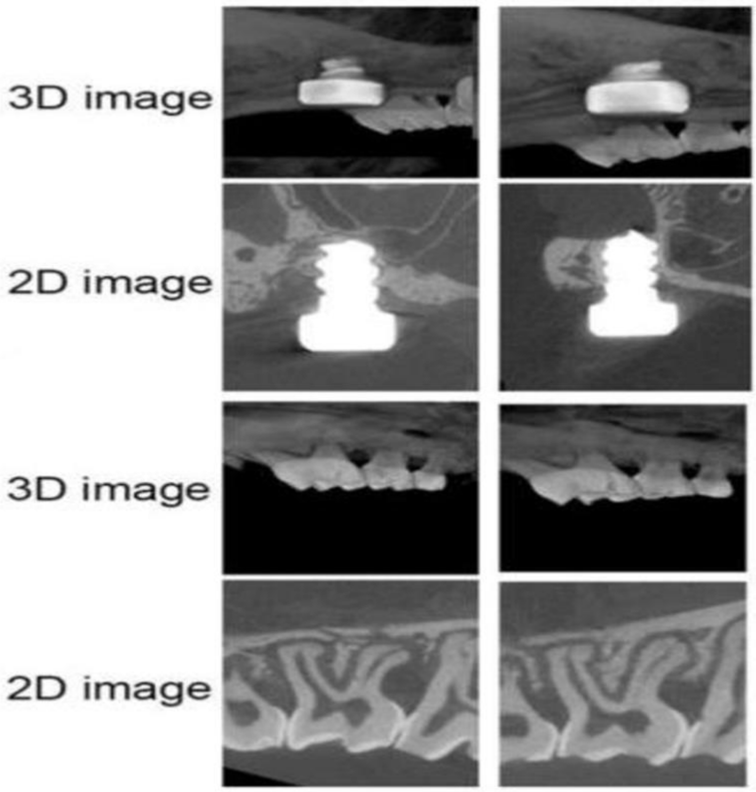

Figure 9. µCT image of peri-implantitis and periodontitis in rats (72)

7.4. Restorative Treatment Applications

In a study that used a commercial μCT system (micro-CT 20) for quantitative analysis of mineral concentration in human enamel and dentin, the device was observed to be able to determine a higher mineral content in enamel and dentin from the outside to the inner tissue. When the data obtained were compared with findings in literature, it was concluded that μCT was highly appropriate for the measurement of the mineral content of teeth. However, it was shown to be necessary to take the limited voltage rate of the system into consideration and to limit the thickness of the sample evaluated to 6 mm (74).

For the characterisation of the mineral distribution pattern of fissural enamel lesions and to measure mineral density, μCT has been shown to be effective for non-destructive evaluation and provides a high-resolution approach. Using this method, it may be possible to establish an approach that could form the basis of the repair and remineralisation of fissural enamel lesions (75).

μCT was used to compare tooth mineral density (TMD) in different lesion types in hypomineralised first permanent molars and in unaffected enamel. Brown-coloured lesions were found to have the lowest TMD and yellow/cream lesions were more mineralised. The TMD in white lesions was determined to be similar to that of unaffected enamel (76).

μCT was applied in a study that measured dentin mineral concentration (DMC) in traditionally restored teeth compared to those where atraumatic restorative treatment (ART), conventional restorative treatment (CRT) and ultra conservative treatment (UCT) protocols were used. The mean DMC below the restorations in the ART protocol group and the mean DMC of the cavities applied with UCT were found to be statistically significantly higher than that of the untreated cavities. A hypermineralised area was observed in the dentin below the ART restorations (77). In a study that examined the remineralisation potential of arginine (Arg) in NaF toothpaste, mineral density was evaluated with μCT. With the addition of 2% arginine to NaF toothpaste, the remineralisation of lesions similar to enamel caries was observed to significantly increase (78).

Teeth were scanned with μCT before and after the application of Carisol and Papacarie, to compare dentin mineral density (DMD) and removed tissue (RT) volume. It was observed that Papacarie resulted in higher DMD, a greater volume of dentin and less RT compared to Carisol (79).

The μCT technique has been more effective for evaluating the marginal adaptation and the tooth-adhesive-composite interface and it is possible to obtain real and non-destructive 3D information from composite restored cavity during polymerization (Fig.10) (80).

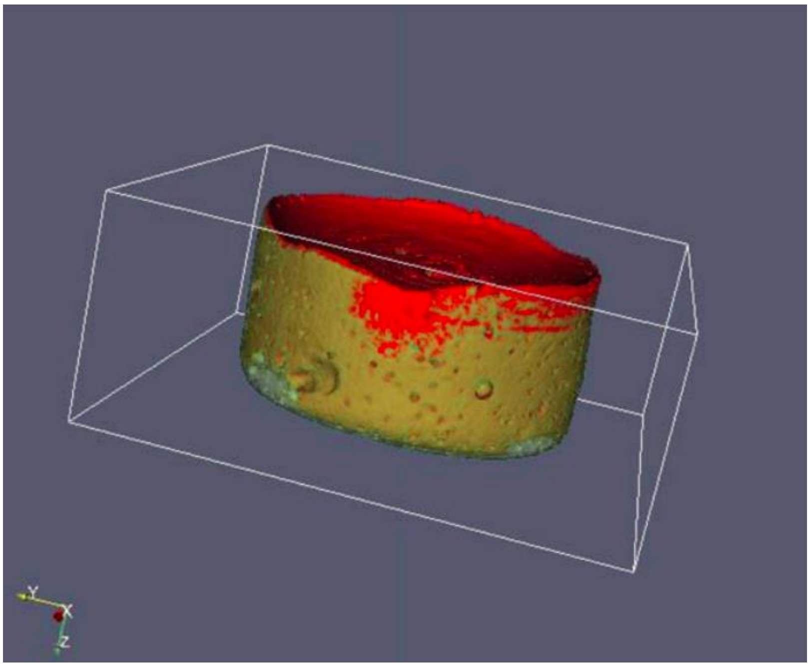

Figure 10. 3D superimposed image of the bonded composite filling restoration before (semitransparent green) and after (red) light-curing (80)

Casein phosphopeptide-amorphous calcium phosphate (CPP-ACP) was applied to teeth treated with hydrogen peroxide as a bleaching material and μCT images were obtained before and after the procedure. The application of CPP-ACP was seen to have provided a compact structure of the enamel tooth surface throughout 7 days because of the calcium accumulation. The results demonstrated that μCT could be a useful tool in future studies related to the determination of mineralisation (81).

Conclusions

μCT is currently used in many areas, primarily in dentistry. Although there are alternative methods to this device, their use is both time-consuming and causes irreversible damage to the samples. The most important characteristic of μCT is that it can be used many times without causing any damage to the samples. The high resolution of the 3D μCT imaging method allows the examination of small details. In many studies, the results obtained with μCT imaging have been compared with histological methods, and the results have been similar. The reliability of this method has been confirmed many times with research studies.

1. Changes occurring in the bone during orthodontic tooth movement can be observed. The effects of different methods, force models or drugs used can be evaluated.
2. The morphology and mineral concentration of alveolar bone can be determined. The effect on the healing process of materials or different methods used in surgical operations can be observed.
3. The effect of all kinds of systemic activity, such as nutrition, drugs, etc, on alveolar bone can be measured.
4. The effects of all kinds of bone loss that occur (periodontitis, periapical lesions), treatment methods and treatment processes can be compared.
5. Osteointegration can be determined by evaluating implant stability, and different methods can be compared with implant materials and compositions.
6. The demineralisation rates of different lesions can be determined with the determination of the mineral concentration of teeth.
7. The effect on remineralisation of different treatment methods and different materials in enamel and dentin restorations can be compared.
8. In endodontics, detailed imaging of the root canals can be made from the determination of the canal morphology to every stage of the retreatment procedure.

By combining different methods, μCT can be safely used in in-vitro studies. It is expected that image resolution will increase even more with developments in technology, and it can therefore be predicted that μCT will be able to be used in in vivo studies in the future.

Peer-review: Externally peer-reviewed.

Author Contributions: Conception - B.E.; Design - B.E., Ö.A., S.C.; Supervision - Ö.A.; Materials - S.C., Data Collection and/or Processing- B.E., S.C.; Analysis and/or Interpretation - Ö.A., Literature Review - B.E., Ö.A., S.C.; Writer- B.E., Ö.A., S.C.; Critical Review - Ö.A.

Conflict of Interest: No conflict of interest was declared by the authors.

Financial Disclosure: The authors declared that this study has received no financial support.

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