Microcomputed tomography in Endodontics:

ABSTRACT:

In recent years, the use of micro-computed tomography (micro-CT) scans in biomedical and dental research is increasing promptly. Due to a wide range of technological developments in X-ray sources and X-ray imaging arrays, the utility of micro-CT has improved in experimental, preclinical bone and dental studies. Micro-CT systems allow researchers to analyse microstructures, differences in density and morphological changes. This review highlights the recent advances in X-ray microcomputed tomography (Micro-CT) applied in Endodontics. It summarizes Micro-CT applications in analysis of root canal morphology, evaluation of root canal preparation, irrigation and intracanal medicament extrusion, restoration of root canal and retreatment. Details of studies in each of these areas are highlighted along with the advantages of Micro-CT, and finally a summary of the future applications of Micro-CT in dental research is given.

Keywords: Endodontics; Irrigation; Root canal morphology; Retreatment; X-ray microcomputed tomography (Micro-CT).

INTRODUCTION:

The invention of X-rays by Wilhelm Roentgen in 1895, has led to a revolution in diagnostic medicine, making it possible to visualize the body’s internal structures in a non-invasive way. In the late 1970s, Allan Cormack and Godfrey Hounsfield developed computer-assisted tomography. The first high-resolution X-ray micro-computed tomographic device was constructed by Elliott and Dover, a decade after the CT scanner was designed, and the image of the shell of a Biomphalaria glabrata snail was obtained utilising a resolution of 12 µm.

Microcomputed tomography (Micro-CT or CT) systems introduced in the early 1980s were custom-built in the beginning and were not readily available. Compact commercial systems are now available, and they are quickly becoming indispensable components of many academic and research experiments.[1]A wide range of specimens may be examined directly using Micro-CT including mineralized tissues such as teeth, bone, and materials such as ceramics, polymers, biomaterial scaffolds etc. Micro-CT imaging could also be extended to soft tissues such as lungs that have been infiltrated or perfused with a contrast agent having a higher density than the surrounding tissue. With the development of Micro-CT systems, the newest generation of such systems allows for in vivo imaging of small live animals. The name "micro" is used to describe the pixel sizes of the cross sections in this new technology, which is measured in micrometres. This also indicates that the machine is designed to model smaller items and is smaller in size than the human version. MCT (micro-computed tomography) is a radiographic technique that combines thin-layer radiography (tomography) and computed image synthesis.

In dentistry, Micro-CT algorithms have also been utilised to analyse and morphometrically describe the root canal space, allowing for the assessment of basic 2D geometric metrics like area, perimeter, roundness, and major and minor diameters. MCT devices, have a resolution of 1–200µm, which helps in precise and consistent measurement of enamel thickness in teeth and tooth volumes.[2] They are currently being employed for ex vivo dental anatomy research because they can provide a complete quantitative and qualitative description of the exterior and internal anatomy of the teeth. Micro-computed tomography (µCT) combined with mathematical modelling has supplied detailed information about dentin thicknesses, canal dimensions, and curvatures quantitatively. The MCT approach involves almost no sample preparation and can image teeth in their natural state, without the need for sectioning, which can result in root material loss or artefact.[3] It is also possible to tilt and rotate the image while magnifying specific regions of interest so that the orientation of root canals within a tooth can be seen by imaging them separately or with the tooth superimposed. All of these options can be beneficial to clinicians since they can gain a better knowledge of dental anatomy. This technique has the potential to be not just a great educational tool, but also to have far-reaching clinical implications. The purpose of this article is to review recent applications of Micro-CT in Endodontic therapy.

MICRO CT SCANNING AND RECONSTRUCTION:

Micro-CT systems with micro focal spot X-ray sources can provide the volumetric pixel (Voxel) with substantially superior spatial resolution, in the range of 5–50 µm, or roughly 1,000,000 times smaller in volume than CT voxels. The high-resolution detectors can obtain 3D reconstructed pictures of samples by rotating projections via several viewing directions. The images depict spatial distribution maps of linear attenuation coefficients determined by the X-ray source's energy and the material sample's atomic composition. Because the imaging method is non-destructive, the internal features of the same sample can be studied multiple times, and samples can be used for further biological and mechanical testing after scanning.

A comprehensive three-dimensional examination of the sample can be performed using micro-computed tomography (micro-CT) and mathematical modelling. A serial reconstruction of axial cross-sections can be utilised to rebuild full 3D objects. It comprises of a single acquisition cycle followed by "off-line" reconstruction of the entire 3D object at a resolution of 1024 × 1024 for a total of 1024 layers. These are usually cone-beam reconstructions. The reconstructed three- dimensional images are observed in 0.125-1 mm slice intervals in the Coronal(X), Sagittal(Y) and Facial (Z) directions. Axial cross sections of the object, as well as a building of a 3D object's realistic perspective with the ability to "rotate" and "cut" the object model, can be displayed on the screen after the serial reconstruction. It is possible to recreate 3D objects using external software based on the reconstruction results.[4]

TRAINING AND EDUCATION:

In the realm of endodontics, educational practise is critical. Micro CT is an intriguing tool for experimental endodontology since it can provide detailed, useful images of tooth anatomy. It is the potential useful research tool as it can also help clinicians and researchers who want to learn more about dental anatomy have better preclinical training in the fundamental techniques of endodontic therapies. Micro CT has the potential to be used in preclinical student teaching for tooth morphology and endodontic procedures. The 3-D graphics assist students in visualising and comprehending the results of root canal preparation and obturation. It was thought to be useful for inexperienced students to evaluate endodontic therapy.[5]

ANALYSIS OF ROOT CANAL MORPHOLOGY:

For decades, the clearing technique was thought to be the greatest way for studying the morphology of the root canal system and its variations. The fluid materials such as molten metal, gelatine, or ink was injected which demineralizes the tooth, making it transparent. The disadvantages of this technique are injected material does not flow laterally into delicate anatomical tissues, this approach causes irreversible alterations in the tooth structure and artefacts. The introduction of the micro-CT imaging system has overcome several methodological limitations of the clearing technique, allowing the reporting of several new anatomical variations and complexities of root canal anatomy in the human dentition that were not previously classified.[6] As a result, the inclusion of these unique anatomical configurations in a future root canal classification system must be explored.

The root canal shapes can be analysed qualitatively and quantitatively using micro-CT. The ability to distinguish the dental hard tissues as transparent and the pulp chamber and root canal system as opaque in 3D morphologic properties of the root canal system aids in the differentiation of both the surface and internal morphology of a tooth. The morphological characteristics of the pulp cavity, the volume ratio at the horn, floor and overall regions of the pulp chamber and the diameters of the buccal and lingual orifices of the root canals could be measured. Some researchers discovered that triangulation methods could be used to determine the surface areas and volumes of each root canal, while model-independent approaches could be used to evaluate canal diameters and configuration.[7]

Dentists, on the other hand, frequently confront anatomically abnormal cases in clinical practise. The C-shaped canal is one of the most complicated anatomic variations of the canal system. It is most commonly observed in mandibular second molars and can provide numerous biomechanical and obturation challenges. The C-shaped canal orifice even observed under the dental operating microscope, one cannot assume that the shape will remain throughout the length of the canal. The Micro CT delivered high-resolution serial cross-sections of the root canal system over its entire length. The C-shaped canal was seen in these images to vary in shape significantly at different levels. The surface rendering process helps in 3-D reconstructed model of the C-shaped canal system which can be visualized at different angles and showed that the C-shaped canals were not found in the root's centre, but rather towards the fused root's deep groove surface. This understanding led to measurement of depth of groove and thickness of root, ratio of the groove depth to the buccal-lingual thickness of the root. It also aids in determining the location and appearance of canal orifices, cross sectional form, canal bifurcation level, and level of fusion across the whole length of the root.[8,9]

Curved canals also represent a significant challenge for clinicians, with increased risks of procedural errors such as transportation, ledge formation and perforation. The canal curvature could be measured by constructing an imaginary central axis for each canal, calculating the rate of turning of the tangent vector at a given point on the central axis, and inverting this rate to canal curvature using special mathematical modelling software.[10] Using specifically created Kappa software, recent micro-CT investigations has been done evaluating 3D curvature by linking the intersecting sites of the major and minor axes of the canal in each slice.[11]Park et al. used Kappa software with micro-CT to examine alternative canal shapes and curvatures in maxillary first molar mesiobuccal roots. These analyses provided a comprehensive and quantitative characterization of the root canal curvatures found in maxillary first molars. Root canal curvatures are most pronounced in the MB (mesiobuccal) canals, moderate in the DB (distobuccal) canals, and least in the P (palatal) canals. The curvatures increase in the apical third, particularly in MB and DB canals, and the apical curvatures increase when accessory canals are present. The detailed measurements of canal curvature in mandibular molars using micro- CT revealed that the curvatures were greater in the MB (mesiobuccal) canal than in the ML (mesiolingual), which concurs with previous studies that used radiographs. They were greatest in the apical region, followed by the coronal areas, and they were straightest in the mid-root region in mesial root of mandibular molar. This information will aid in our provision of endodontic therapy and the techniques refined in this study will abet ongoing endodontic research.[11]

Due to the position of their orifices, accessing the middle mesial root canal is challenging clinically if left untreated these canals may house bacteria, may compromise treatment success and contribute to persistent apical periodontitis. In comparison to traditional sectioning or casting processes, previous research demonstrated that the use of micro-CT technology ensured a high visibility of additional canals that were consistently smaller than the main canals at each level. Micro-CT and CBCT had a higher rate of detection of the second canal than the other diagnostic tools. Furthermore, the ability of micro-CT devices to obtain imaging projections with a larger degree rotation of the specimen (360°) than the CBCT unit (200°) allowed for the construction of more precise and detailed 3D models of the root canal region. The presence of three canals along any point of the mesial root (7.7%) of mandibular molars was found to be higher than previously detected (2.3%) rate reported by de Pablo et al. These findings along with 3- dimensional picture of mesial root canal helps in identification of additional canal and its appropriate root canal preparation in order to increase the success rate of nonsurgical endodontic procedures.[12]

The apical delta is an intricate system of spaces within the root canal that allows free passage of blood vessels and nerves from the periapical area to the pulp tissue. Its morphological feature may be depicted as a root canal dividing into three or more ramifications near the root apex, with the main canal becoming indistinguishable. The maxillary second premolars, mandibular lateral incisors, and mandibular second premolars are the most common sites for apical deltas. Tooth clearance is the most often utilised approach for assessing apical deltas. Despite this, the procedure always results in specimen destruction and is difficult to employ precisely for quantitative data collecting. Due to lack of resolution, both periapical radiography and cone-beam computed tomography (CBCT) was unable to adequately identify the apical deltas. With high resolution of micro-CT, Apical delta branches (ADB)diameter was measured which varies between apical deltas. The median diameter was 132.3μm and only 24% ADBs had a diameter more than 180 μm. It is also feasible to observe the prevalence of apical deltas in different tooth types and root formation, their number and morphology, and their vertical expansion inside the root canal system using micro–computed tomography (micro-CT).[13]

An isthmus defined as a narrow, ribbon-shaped communication between two root canals that contains pulp tissue, necrotic debris, tissue remnants, or organic substrates if left untreated will support the growth of microorganisms leading to the failure of endodontic treatment.[14] Therefore, the localization and management of the isthmus is an important factor that may improve the long-term prognosis of nonsurgical endodontic treatment. Band shaped isthmuses lie in the buccolingual direction and cannot be visualized by conventional two-dimensional radiographs. The ability of cone-beam computed tomography to reveal root canal morphology has been reported as equivocal particularly in roots with variable anatomical configurations.[6] Owing to advantage of high resolution, currently micro-CT studies are focused in analysing this anatomic variation and reported that prevalence of isthmus is high in the mesial root of the mandibular first molars, particularly at the apical third of root canal.

Micro-computed tomography (CT) has been used to diagnose or evaluate the location and extent of peri radicular lesions in recent years, in addition to evaluating cross-sections of teeth. In micro-CT once the sample is placed into the device, data acquisition is automated and requires no further operator attention. In contrast, histological preparation of the same number of samples takes approximately 2 months and requires many hours of hands-on effort by laboratory personnel. The proportion of samples cannot be quantified due to imprecise sectioning orientation, resulting in oblique rather than sagittal sections. In vivo studies of rodents, Balto and colleagues revealed that micro-CT imaging produces results that are highly correlated with histological data. The error attributable to image analysis with histological sections (4.9% of the mean for all values; range, 3.5 to 6.5%) was found greater than that attributable to the error inherent in micro-CT measurements (3.4% of the mean; range, 2. 1% to 6.4%).[15]

Quantitative analysis of micro-CT led to the measurement of residual thickness of dentin along the walls of root. [16]Dentin thickness is limited in the mesial root of mandibular first molars approximately 2 mm below the furcation due to greater concavity seen on its distal surface. They are described as danger zones because there are more prone to strip perforation during root canal shaping and post space preparation procedures. Two dimensional radiographs were not a reliable method for measuring residual thickness of tooth walls, because they showed greater thicknesses than were actually present.[17] Micro CT analysis yielded two novel findings concerning the anatomical Danger zone. First, in almost 40% of the canals, the thinnest dentine was found along the mesial root (22 percent and 18 percent of the mesiolingual and mesiobuccal canals, respectively). Second, the DZ was in the middle third of the root in terms of vertical placement in relation to the furcation area, up to 4 mm under the furcation area in only 35% of the specimens, while the majority of the samples revealed that the DZ was between 4 and 7 mm below the furcation area.(18) Lee et al. reported the thinnest root canal wall on the mesial portion of the root in between 15% and 33% of the specimens using micro-CT imaging analysis, which is consistent with the previous findings[3] This knowledge of root canal complexities is important so that instrumentation could be directed away from this risk zone towards the lateral and mesial canal walls, which have significantly increased dentin thickness.

EVALUATION OF ACCESS CAVITY & ROOT CANAL PREPARATION:

The main objective of endodontic treatment is to achieve adequate cleaning and shaping in order to eliminate bacterial infection from root canal system. To assist clinical judgments during endodontic procedures, knowledge of the dimensional variations of complicated root canal systems and adequate apical canal preparation with available instruments is required. Micro-CT can be used to evaluate the ability of endodontic instruments to clean the root canal system. The volume of pre and post instrumentation can be measured and the area cleaned by the instruments can be assessed. Previous analysis of instrumentation procedure was performed using different methods. Most recent methodologies are used in endodontic researches to evaluate the shaping procedure includes stereomicroscope, scanning electron microscope and morphometric evaluation. In all these methods, sections result in loss of specimen size. On Contrary, micro-CT allows the analysis of the complete root canal without the requirement of sectioning. Paque et al. described a technique of slice-by-slice assessment of area between the apical stop and the furcation wall. Micro CT scans of teeth performed pre and post instrumentation helps in quantitative assessment of remaining unprepared surface area and the associated morphological changes. The colour mapping technique further aids in spatial location of potentially infected dentin and its successful removal after instrumentation.[19]

Siequeira et al found that existing preparation techniques and instruments leave around 10%–50% of unprepared wall portions in narrow or circular root canals, and these percentages rise in oval/flattened canals, using (micro-CT) tests. The high prevalence of unprepared walls can be attributed to the fact that apical canal diameters vary significantly and are not always compatible with the dimensions of currently available instruments. Furthermore, constant or reciprocating rotation of instruments tends to carve spherical preparations while leaving recesses in irregular noncircular canals intact. This suggests us the need of modification in instruments include those that are adjustable or expandable and have the potential to adapt to the anatomy of the canal, using instruments of smaller diameters, importance of activation and agitation during irrigation process to optimize disinfection than use of rotary/ reciprocating instruments alone.[20]

Canal transportation is an important parameter to be evaluated mostly if root canal enlargement is followed by unnecessary dentin removal, resulting in the weakness of the tooth structure. Using micro-CT, canal transportation due to instrumentation can be assessed by connecting the centre of gravity in each cross section of the canal with an imaginary line (z-axis), through the length of the root, from the co-registered datasets before and after preparation. Then, mean transportation can be calculated by comparing the distance between the centre of gravity at each level of the root canal. They also give a thorough representation of the 3D canal architecture and surrounding root structure, canal widths, that can be used to guide instrumentation and enhance cleaning and shaping while reducing errors.[21] The smallest dimensions of canal widths were recorded as a measure of canal narrowness, which is significant in selecting the initial apical file for the apical third.  According to findings of micro-CT study by Lim and Stock, the dentine thickness should be kept between 200 and 300 µm after preparation to withstand compaction forces during obturation and avoid perforation or vertical root fracture. The "risk zone" of insufficient dentin thickness of the root canal wall should be considered when selecting great taper NiTi tools. Strip perforations would be reduced, if not eliminated, if the remaining dentin thickness in the root is known, particularly in the distal aspect of the mesial roots.

IRRIGATION:

After rotational instrumentation, some parts of the original canals were filled with a radiopaque material, confirming that hard tissue debris is formed inside the canal in the form of small dentin chips, according to a 3-dimensional (3D) investigation using high-resolution micro-CT imaging.[22] Because it allows a longitudinal observation of the same specimen during numerous experimental procedures at different time points, this non-destructive imaging technology has proven to be the gold standard method for the evaluation of accumulated hard tissue debris (AHTD) into the abnormalities of the root canal system. A recent micro-CT investigation found that increasing the size of the apical preparation lowered the overall quantity of packed debris. Previous research analysed at the elimination of AHTD only at the root level and used qualitative score-based scanning electron microscopy to assess its efficacy. Current studies use Micro CT imaging to analyse the elimination of AHTD promoted by the final irrigation treatments. When this technique is combined with image analysis, quantifiable data on dentin morphology along the entire canal may be extracted automatically, reducing human bias.[23]

Wiseman et al. conducted the first Micro-CT investigation on root canal irrigation to examine the performance of two irrigation devices Passive Ultrasonic Activation (PUI) and Endo-Activator (EV) in removing calcium hydroxide from human molar root canals. According to a recent micro- CT study, the EV system combined with PUI was the only approach capable of attaining irrigant solution penetration up to the WL as well as in the lateral canals. A protocol combining these two methods would be beneficial in terms of greater irrigant dispersion throughout the canals, resulting in a constant flow of fresh chemical irrigant. Further researches are necessary to evaluate the impact of this improved cleanliness of the root canal system performed by these final irrigation protocols on the clinical success rate of endodontic treatment.[19,24]

ESTIMATING THE FILLING OF ROOT CANAL AND RETREATMENT:

An adequate root canal filling should present higher volume of gutta-percha and a thin layer of sealer at dentin interface of root canal. The filling of the debrided root canal must adapt to the root canal space, including accessory and lateral root canals. Due to the potential of fluid infiltration and subsequent contamination of the root canal system, the presence of voids in between filling and leakage must be prevented. Numerous methods have been used to evaluate the adaptation and quality of root canal fillings like Confocal laser scanning, Stereomicroscope which requires sectioning the samples before analysis. Leakage tests were also used to analyse but the models proposed were considered unreliable and time-consuming.[25]

Micro CT is currently the most effective tool for studying microleakage in vitro and has the advantages of being quick, precise, and non-destructive. This method has also been used to determine the amount of filling material reaching the isthmus regions and branching. These areas can be visualised with varying intensities of sealer, gutta percha into different colours by processing pictures obtained with µCT on the computer. The percentage of volume of voids and gaps in the root canal can be calculated. The analyses include demarcation of voids and gaps in the two-dimensional slices and then the reconstruction in a three-dimensional image. The main advantage of micro-CT to evaluate root canal fillings is the possibility of further analysis. After study of obturation, the material can be removed using a retreatment system and the ability of retreatment techniques can also be studied.[26]

The main aim of nonsurgical root canal retreatment is to re-establish healthy periapical tissues which involves removal of the previous root canal filling material, further cleaning and shaping, and refilling. To measure the amount of filler material left after retreatment, most early laboratory-based research used destructive and two-dimensional approaches. These approaches have drawbacks makes it impossible to properly determine the volume of filler material left following retreatment. The non-destructive micro-CT methodology, on the other hand, enables for an accurate volumetric evaluation of filler materials left after various retreatment regimens, overcoming earlier methodologies' limitations. It uses visual image analysis to locate specific area of interest and the quantities can be computed using dedicated software. Micro-CT was also utilised to assess the effectiveness of instrumentation like ProTaper files and hand K-files were used to remove root fillings. The use of supplementary procedures during retreatment, such as ultrasonic tips or laser irradiation, has been shown to improve the removal of filling remnants from the root canal space using micro-CT.[27]

CONCLUSION:

Micro-CT is a non-destructive approach that has been successfully employed for the evaluation of morphological characteristics, it allows for the evaluation of consecutive steps in root canal therapy. High-resolution imaging allows for a more thorough examination of endodontic morphology as well as new information about the complex root canal system. This method has the advantage of displaying internal and exterior dental anatomy as well as the results on the quality of mechanical preparation, confirming the inability of shaping instruments to act within the anatomical complexity of the root canal. Hence it has the potential to be used in preclinical student teaching for tooth morphology and endodontic operations. Micro CT imaging is a fast, reproducible, and non-invasive technology that yields results comparable to histological sections, according to animal in vivo investigations, and 3-D analysis of micro-CT pictures has a strong correlation with 2-D cross-sections of peri-radicular lesions. Micro CT also enables for the evaluation of microstructural characteristics as well as subregional investigation of emerging lesions. Although due to its inherent limitations, it is not currently accessible for use in a daily clinical basis nevertheless, efforts are being made to build a device that will allow in vivo 3-D imaging of teeth. The influence of ageing and cementum deposition on the deviation of the main apical foramen will be determined in future micro-CT studies. With further development of Micro-CT systems, higher resolution will become available for both in vitro and in vivo studies, and it will be a powerful tool in future dental research.

LIMITATIONS:

Its clinical application is limited by

High radiation doses, long scanning times and limited specimen size.[28]

High cost and necessity of high technical knowledge.[29]

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