Microcomputed Tomography: Adding New Dimension to 3-D Imaging

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ABSTRACT

Dentistry has witnessed tremendous advances in all its branches over the past decades. With these advances, the need for more precise diagnostic tools, specially imaging methods, have become mandatory. The three-dimensional imaging has made the complex craniofacial structures more accessible for examination and accurate diagnosis. Numerous technical advancements have led to the development of innovative diagnostic modalities like CT, MRI and Ultra-Sound which revolutionized dental research. Micro computed tomography (micro CT or µ CT) is a non-destructive imaging tool which produces high resolution three dimensional (3D) images composed of two-dimensional (2D) trans axial projections or slices of a target specimen. Micro CT applications in dentistry include measurements of enamel thickness, root canal morphology, craniofacial skeletal structures, dental tissue engineering, mineral density of dental hard tissue and dental implants. Micro CT (µ CT) is a gold standard technique which act as an adjunct tool in the diagnosis. It provides high-resolution images as well as both qualitative and quantitative analysis of tooth, bone and implants. With further development, higher resolution will become for both in vitro and in vivo studies and will thus become a powerful tool in future dental research.

INTRODUCTION

A combination of complete history, clinical examination and radiological assessment helps in the accurate diagnosis and treatment planning of the patient. In the past few decades, there has been revolution in the diagnostic field[1]. Beginning with the simple intra-oral radiography technique and progressing to advanced imaging modalities like computed tomography, cone beam computed tomography, magnetic resonance imaging and ultrasound have found a place in modern dentistry. The change from analogue to digital dental radiography has made the process easier and faster including image storage, image manipulation and image retrieval easier. Three-dimensional imaging has made complex cranio-facial structures more accessible for radiological evaluation and aids in early and accurate diagnosis of deep-seated lesions[2].

Micro computed tomography (microCT or µCT) an non-destructive imaging tool which is used for production of high resolution three-dimensional (3D) images composed of two-dimensional (2D) trans-axial projections, or ‘slices’, of a target specimen. The equipment composed of major components such as: x-ray tube, radiation filter and collimator (which focuses the beam to either a fan- or cone-beam projection), specimen stand, and phosphor-detector/charge-coupled device camera[3]. It has a spatial resolution, in the range of 5 -50 μm (less than one million times), lesser in volume than conventional computed tomography voxel[4]. µCT is gold standard technique for...
numerating the bone architecture[5] Micro-computed tomography (micro-CT) has remarkable space resolution, and a shorter capture time than cone beam computed tomography (CBCT)[6] Micro CT is also used to scan various objects like bone, teeth, dental implants, textiles, concrete (dental casts) and precious metals. It discloses the details of external and internal surface of an object, which allows measurement on the 3D object[5]

### Historical Overview

In 1979 Allan Cormack and Godfrey Hounsfield, were awarded with the Nobel Prize in Physiology or Medicine for the development of computer-aided tomography. In early 1980s, LeeFeld Kamp developed the first micro CT system for the evaluation of structural defects in ceramic automotive materials and used a cone-beam x-ray source and 2D detector and the sample rotation of 360°. In 1984, Goldstein named the technique “micro computed tomography” and the first publication of micro CT analysis of bone architecture. Goldstein replicated the Feld Kamp micro CT system thus, establishing the first university micro CT system[3]

### Working Principle of Micro Ct

Micro CT uses micro focal spot X ray sources and detectors to obtain 2D images of a sample that are used to create a 3D reconstruction with high resolution which allows for projections from different orientations to produce 3D reconstructions with voxels approaching 1µm, which is approximately 1,00,000 times smaller in volume than CT voxels, giving it superior resolution to ultrasound and magnetic resonance imaging (MRI). Thus, it provides enhanced image analysis capability and the reconstruction of three-dimensional image slices in intervals of 0.125-1 mm slice in the Coronal (X), Sagittal (Y) and Facial (Z) directions[7]

The fundamental components of micro-CT instrument are (i) penetrating ionizing radiation, (ii) a sample manipulator, and (iii) a detector. X-rays generated by a micro-focus x-ray tube, uses a beam of electrons which are accelerated by a voltage of up to 240 kV and are focused onto a tungsten or similar metal target. A “shadow image,” also called a projection image or radiograph are formed on a 2D x-ray detector. Hundreds or thousands of 2D projection images are recorded during the scan process. After scanning, these images are used to reconstruct a 3D data set by making use of filtered back-projection algorithms[8]

There are in vitro and in vivo micro CT scanners. In vitro scanners, the object rotates between a static x-ray source and detector and the amount of radiation received is not a concern enabling much higher spatial resolution (30 to 1 µm) than in vivo micro CT. In case of in vivo micro CT, x-ray source and detector rotate around a static object. The spatial resolution ranges from 100 to 30 µm and produces faster images than in vitro micro CT[11]

### Applications of Micro Ct

Micro CT a powerful research tool which is mostly used for laboratory purposes for higher order of energy and finer resolution. Micro CT is a noninvasive method for 3D reconstruction. The first laboratory micro CT instruments, which were introduced in the early 1980s and could achieve a spatial resolution of ~10 µm, were typically used to image inorganic materials and the internal structures of fossils and calcified bones. The 3D volumes micro CT generates can be segmented and interrogated to provide not only useful qualitative visual information but also quantitative measurements[1]

Evaluation of bone, cartilage, and cardiovascular structures, with applications in fundamental structure-function analysis, disease, tissue engineering. In the field of dentistry has been used in various fields like endodontic research, caries research, craniofacial development as well as implants.

### Evaluation of Bone Structure

MicroCT is an essential tool for evaluating bone structure and quality. It is used to study metabolic bone diseases such as osteoporosis and also to evaluate preclinical models of disease and to test the efficacy of anti-resorptive and anabolic therapeutics, such as bisphosphonates. Micro CT evaluation of bone fragility, induced by aging or osteoporotic disease, with the use of contrast agents to detect and quantify bone microdamage. It enables high-resolution 3-D reconstruction of microstructural characteristics from trabecular architecture to cortical porosity. Age, gender and disease influence the micro structural properties of both cortical and trabecular bone, and these can be evaluated quantitatively by micro CT[5]

Bone quality involves bone mass& structural properties such as geometry, macro and micro-architecture, and tissue properties as modulus of elasticity, mineral density, collagen quality, cell and marrow behavior. Mechanical and biological behavior of bone tissue plays an important role for evaluating systemic and local conditions (diseases, therapies or lesions). This property can also contribute to better understanding of bone regenerative procedures, such as alveolar ridge and maxillary sinus augmentation procedures, bone repair and fracture healing and implant osseointegration. Micro CT has shown to be the most indicated technique for assessment of the bone mass and morphology in animal models[9]

### Evaluation of Soft Tissues

Evaluation of soft tissues by x-ray imaging requires application of radio dense contrast agents. Contrast enhanced micro CT angiography enables visualization of cardiovascular structures. Cardiac imaging with the use of coronary CT angiography provides evaluation of: (1) coronary arteries for atherosclerosis or anomalies; no coronary pathology including the great vessels, chambers, myocardium, valves, or pericardium; cardiac chamber function, including ejection fraction and chamber volumes[10] High resolution analysis of model animal vascular structures by microCT was first conducted on renal microvasculature in 1998 by Sir William Bowman. Liu et al., in 2019 reported the use of barium sulfate for the visualization of cervical spinal cord micro-vessels in rat models using 3 D reconstruction of high-resolution micro CT scanning[11]

To visualize and quantify differences in the 3D internal structure of tendons and ligaments, microCT is used to identify key geometrical differences in the arrangement of fascicles within. MicroCT approach is used to rapidly visualize (24 min per sample) relatively large tissue volumes, the damaging consequences of mechanical sectioning is also avoided. Jones and Rocha et al., in 2012 visualized and quantified differences in the 3D internal structure of tendons and ligaments, using...
Micro CT is used to identify differences in the arrangement of fascicles and tendons that were chemically fixed and stained with an iodine-based contrast agent\textsuperscript{12}.

**Diagnostic Applications**

Micro CT has better diagnostic accuracy over CBCT but is not routinely used in clinical practice due to its high radiation exposure and increased scanning time. It can be used for differentiating radicular cysts and granulomas which can be difficult with routine radiography. It can also be used to determine the mesiodistal extent of pathology like that of tumor margins and can also assess the thickness and distance between anatomical structures which helps in pre surgical assessment. It aids in the diagnosis of maxillofacial, dentalveolar and root fractures with high precision and also in 3D virtual treatment planning for orthognathic surgeries. It has also shown high correlation with histological examination for the detection of tumors like Garre’s Osteomyelitis\textsuperscript{11}. A case study conducted by Santos \textit{et al.}, in 2016 of a 26-year-old man diagnosed with complex odontoma. The specimen(approximately 30 mm × 47 mm) was obtained and sent for micro-CT evaluation. A greater amount of hyperdense material in the periphery of the lesion was observed, in addition to the density, volume, and surface area were also evaluated\textsuperscript{13}.

Micro CT is better than conventional radiography and CBCT for the detection of carious lesions, tooth resorption, periodontal diseases as well as periapical pathology. 3D images of high-resolution micro CT images helps in root canal treatment by diagnosing apical periodontitis, root fractures and variations in root canal morphology. It can also be used to assess the success outcomes of periodontal regenerative therapy.

**Caries Exploration**

Micro CT has the potential to evaluate mineral content changes in dental hard tissues.

Micro-CT is an non-destructive method and can be considered as a gold standard for caries diagnosis. It can be used to detect occlusal as well as proximal caries lesions in posterior teeth\textsuperscript{14}. The morphogenesis of carious lesions, development of demineralization and remineralization on enamel and dentin can be quantitatively and qualitatively analyzed using microCT. It is a very sensitive technique and can be used to assess mineral density of white spot lesions and dentinal caries. Micro-CTIs used to assess the mineral concentration of teeth with a very high accuracy and resolution (5-30 μm), thus used to assess mineral density changes in cases of enamel or dentin demineralization and remineralization. Thus, it has a promising potential for future assessment of caries and remineralization of the tooth. Freitas \textit{et al.}, in 2019 conducted a study on 26 extracted human primary teeth and scanned using a compact micro-CT device for detection of proximal caries\textsuperscript{15}.

**Analysis and Evaluation of Root Canal Morphology and Root Canal Preparation**

A broad understanding of the complexity of internal tooth anatomy is necessary for successful root canal treatment.

Micro CT is used for the qualitative as well as quantitative three-dimensional analysis of root canal without destroying the sample. It helps to analyze 3-D changes in a root canal before and after preparation with the help of 3D volume rendering technique such as surface area, volume, amount of dentin removed, canal thickness, curvature, canal transportation and post space preparation by 3D volumetric analysis\textsuperscript{16}.

It is also used to analyze porosities within obturation and information about the existence of voids within endodontic materials. It helps in 3D quantitative evaluation of residual filling material and the amount of dentin removed during retreatment\textsuperscript{17}.

High resolution micro CT results in better imaging of small isthmuses, inter canal connections, accessory canals, multiple apical foramen as well as complex anatomic variations such as C shaped canals. Micro CT also has the potential to analyze surface changes and development of micro cracks on radicular dentin after rotary instrumentation. Boschetti \textit{et al.} in 2017 conducted a study to evaluate the morphological features of 70 single-rooted mandibular first premolars with radicular grooves (RG) using micro-CT technology. Volume, surface area and Structure Model Index (SMI) of the canals were measured & the number of accessory canals, the dentinal thickness, and cross-sectional appearance of the canal at different root levels were also recorded\textsuperscript{18}.

**Alveolar Bone Level**

Micro-computed tomography offers significant potential for identifying mineralized structures. Micro-CT can produce 3-D images of bone, allowing for detailed analysis of 3-D bone architecture and anisotropy\textsuperscript{19}. Micro computed tomography (micro-CT) is used for evaluating trabecular bone structures. Micro-CT produces image slices at a resolution ranging from 7 and 35 μm and is typically used for analyzing the trabecular bone structures of small animals and small human biopsy specimens. Micro-CT is considered the standard for evaluating trabecular bone structure\textsuperscript{20}. The use of micro-CT assessment and associated imaging provide effective 3-D visualization and image analysis of the bone–tooth interface that accompany periodontal, craniofacial, and orthopedic investigations. Micro-CT use for preclinical application provides higher spatial resolution images than medical or dental CT for clinical assessment. Micro-CT technique provide a more accurate quantification method for 3-D assessment of bone. Micro-CT enables detailed 3-D microarchitecture. Wilensky \textit{et al.} showed that micro-CT imaging could overcome several problems of previous 2-D approaches and demonstrated the verification of the quantification of bone loss following periodontitis\textsuperscript{19}.

**Craniofacial Skeletal Development and Structure**

Micro-CT system is used in the craniofacial bone growth and repair. This imaging has facilitated 3D measurements of trabecular bone morphology such as trabecular thickness, number, bone volume, bone density. Different studies done with Micro CT on the architecture and mineralization indicated that the remodeling state of the condyle was different anteriorly and posteriorly, where more active growth took place posteriorly. Micro-CT is used measure bone level in periodontitis before and after treatment. Different studies conducted showed that periodontitis condition caused a 46% decrease in bone volume and after treatment the bone volume was 35% higher\textsuperscript{21}. A study conducted by Lee \textit{et al.}, on...
30 human cadavers of 30 scanned by high-resolution micro-CT for assessing the microstructural characteristics of trabecular bone, in order to develop a potential strategy for implant surface improvement to facilitate osseointegration[22]

Other studies done with Micro-CT for the presence of porosity of the human mandibular condyle. It is found that cortical porosity did not differ significantly between different cortical regions. Micro-CT can be used to investigate peri radicular bone destruction, 3D void volume, void surface, and void thickness of bone destruction can be analyzed. Renders et al., conducted a study on 10 right mandibular condyles. A Three-dimensional reconstruction of the cortical and trabecular bone of the condyles were obtained using a high-resolution microCT system in which the cortical cancellous network in the mandibular condyle was assessed, in order to obtain more information about the principal directions of stresses and strains during loading[23]

The unique feature and wider availability have made micro CT the new gold standard technique for quantifying bone architecture and has stimulated a rapidly growing number of new applications.

**Implants**

The measurement of stability and osseointegration of an implant is crucial to assess the treatment outcome.

Micro CT a non-invasive, precise and fast technique which provides a three-dimensional representation of bone formation in the peri implant region up to few microns. The use of micro CT in implant and peri implant involves interface osseointegration by determining parameters like bone volume, trabecular thickness, bone connectivity. With Micro CT it is possible to carry out Finite Element analysis of the bone implant system which includes the of stress concentration at the interface of bone and implant. [4]

**Tissue Engineering**

Tissue engineering is a multidisciplinary field that applies both biology and engineering to the development of viable substitutes that re-create functional, healthy tissues and organs so as to replace diseased, dying or dead tissues. Tissue engineering relating to the oral maxillofacial apparatus, hard and soft tissue defects secondary to trauma (accidents), congenital defects (cleft palate) and acquired diseases (cancer, periodontal disease). In the field of tissue engineering, scaffold material and porous architecture design plays a significant role in tissue regeneration by preserving tissue volume, providing temporary mechanical functions. Micro-CT has been used in the study of scaffolds for tissue engineering in recent years, and has mainly been used for characterizing scaffold architecture. The 3D data sets obtained using Micro-CT offers more accurate information on the structure of the sample than the 2D methods[24].

Scaffolds with complicated or detailed interior structures can be scrutinized using micro-CT, and any spatial location of the architecture can be digitally isolated out. Micro-CT employs penetrative X-rays, closed pores can be imaged. This flexibility allows the evaluation of foams, textiles and nanofiber scaffold[25].

Micro-CT is used to assess large surface area, cell attachment and proliferation. Porosity and the pore size define the surface area per volume. High porosity assists in nutrient and waste diffusion that is one of the critical factors for vascularization and tissue in growth[26].

**Advantages of Micro Ct:[1]**

- The samples are available for any additional biological or mechanical testing.
- Eliminates noise, allowing high spatial resolution (5 μm) and multiplanar reconstructions.
- Provides very high contrast resolution even higher than that of CBCT thus allowing excellent discrimination of very small differences in attenuation coefficient (< 1%).
- Aids in analyzing the 3D relationship with the anatomical structures and the data can be saved for future comparative or qualitative assessment.
- Allows imaging of both mineralized hard tissues and soft tissues and materials[27].
- The samples used are not damaged and the measurements can be repeated.

**Limitations of Micro Ct:[1]**

- There is greater complexity in equipment construction and also there is necessity for long exposure times which can pose problems with pediatric, geriatric and mentally compromised patients.
- High radiation dose and high cost of the scans.
- Scattering is seen due to metallic objects.
- Beam hardening and Cupping artifacts.

**Futuristic Approach**

**Synchrotron micro CT devices**: Synchrotron Radiation Micro-Computed Tomography (SR micro-CT) possesses significant advantages over standard micro-CT. A synchrotron source is a high-speed electron ring in which electrons are accelerated by the magnetic fields of a bending magnetor undulator. They emit electromagnetic radiation & provides a high-flux, high-intensity and monochromatic X-ray beam, allowing acquisition of quantitative high-resolution 3D images with a high signal-to-noise ratio. SR micro-CT has already been used to study trabecular micro architecture, remodeling and local mineralization[1] Larrue et al., conducted a study using 3D Synchrotron Radiation (SR) micro-CT for the evaluation of bone micro damage in human trabecular bone specimens taken from femoral heads. 3D microrrack density was found between 3.1 and 9.4/mm² & length and width of micro crack ranged respectively from 164 μm to 209 μm and 100 μm to 120 μm[28].

**Nano CT devices**

Ultra-high spatial resolution which is 'nano-CT' devices have become available as a result of the continuous technological advancements in the development of CT systems. Nano-CT systems, which generally use a nano-focal spot source (< 400 nm), have been employed to analyze cartilage and bone tissues, material quality, and imaging of vascular networks. Image resolution is mainly determined by the focal spot size of the X-ray source. A smaller focal spot size enhances the image resolution which include the sharpness and clarity by decreasing blurriness or "penumbra effect". The small focal
spot size of the nanoCT (1 micron) have the advantage with regard to clear edges and almost complete absence of noise compared to the microCT image. In addition, there is greater detection of detail, which allow for the characterization and quantification of less mineralized tissue. Nano-CT system allows clear visualization of structures on the level of cells as well as internal ultrastructure of bone trabeculae and also submicron hard tissue cracks. The device is equipped with granite base and a rotation unit, which makes it very stable during the data acquisition process. The ability of obtaining faster scans is another advantage as compared to micro-CT. Examples of Nano CT devices are Phoenix Nanotom S and Sky Scan 2011 Nano CT.

A study conducted by Huang et al[30] extracted mandibular central incisors to investigate voids in different root canal sealers using nano-CT found a significant difference between the other sealers using nano-CT. All three sealers presented with less void volume in the apical third with higher void volumes observed in the apical and coronal thirds.[30]

**CONCLUSION**

Micro-CT analysis has been proven useful in a wide variety of applications in dental research. It provides high-resolution images as well as both qualitative and quantitative analysis of tooth, bone and implants. 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. Micro CT is likely to become more applicable in clinical practice if radiation safety, cost and ease of use can be overcome. Micro and Nano CT possess a considerable room to grow in the near future which may be a quantum leap in the field of dentistry.

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