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Applications of Synchrotron radiation based micro-computed tomographic analysis in medical and dental field: A Review

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Abstract

Background: Advances in both x-ray sources and x-ray optics have dramatically improved the feasibility of these techniques in various fields such as biological research and clinical applications, including diagnostic radiography.

Aim: This review highlights the difference between the conventional micro-CT and Synchrotron radiation based micro-computed tomographic analysis along with its applications in medical and dental field.

Methods: By using specific keywords, electronic search of scientific papers was carried out on the PubMed/Medline, Scopus, and EBSCO host databases database. By pooling the extracted data from selected papers, the reviewed data was synthesized

Conclusion: This technique can be a powerful tool for investigating both hard and soft materials along with tooth related defects more effectively and quantitatively.

Keywords: Diagnostics, Synchrotron radiation.

Introduction

Since the invention of X-rays by Roentgen in 1895, technology has seen a rise in diagnostic medicine, making it possible to see the inner workings of the body non-invasively.[1] Imaging techniques such as scanning electron microscopy (SEM), magnetic resonance imaging (MRI), ultrasonography, x-ray radiography, and x-ray computed tomography (CT) have played a significant role in the development of many life science related fields, including medicine and dentistry. Many of these imaging modalities, have the ability to produce 3-D images of the object of interest.[2]

Micro computed tomography (micro-CT) is a non invasive detection tool that includes radiation and digital X-ray detectors to capture images of a sample's internal structure without damaging the sample.[3] This uses micro focal spot X-ray sources and high resolution detectors that allow projections rotated through multiple viewing directions to produce 3D reconstructed images of samples. Since the imaging process is non destructive, the internal features of the same sample may be examined many times and samples remain available after scanning for additional biological and mechanical testing.

In general, a resolution of less than 50 µm is considered micro-CT. Currently, a resolution of 10–30 µm is commonly used to scan small samples (e.g., a single tooth or animal bone).[4,5] Early Micro-CT scanners were custom-built and not widely available. Various commercial systems are now available and are rapidly becoming essential components of many academic and research laboratories. Mineralized tissues like bone, teeth and materials such as ceramics, polymers, scaffolds etc. may be examined directly using Micro-CT. Soft tissues such as lungs analysis has also become common with this technology.[6,7]

In contrast to conventional micro-CT, Synchrotron radiation based micro-computed tomographic analysis (SR-µCT) uses synchrotron generated x-rays. The narrow bandwidth of the x-ray energy permits quantitative CT imaging with high accuracy of the measured attenuation coefficients. The x-ray photon energy can be adjusted, that allows element selective imaging.[8] Another advantage is that the scans use a parallel beam geometry, that allows the reconstruction of different regions of the sample at a higher spatial resolution. Furthermore, the artefacts (beam hardening) are reduced with respect to the use of polychromatic conventional sources with an increased signal-to-noise ratio.[9] With high brilliance, coherence and energy tunability, synchrotron sources allow faster image acquisition, better sensitivity and higher resolution.[10] The purpose of this article is to review recent applications of SR-µCT in field of medical and dental research.

Thin membranes in the inner ear

Angular accelerations of the head are sensed by the membranous labyrinth in the inner ear. In a relatively short time span better contrast and less noise are achieved using synchrotron based micro-CT scanning, especially after phase retrieval.[11]

Human cochlea

The use of synchrotron radiation (SR) based X-ray imaging can potentially overcome these shortcomings of conventional micro-CT such as artefacts, noise, low contrast resolution and restriction on specimen size.[12] SR provides coherent collimated X-rays with high photon flux and highly stable sources. These high energy X-ray beams pass through dense structures easily, making inner structures visible. This method also aids in the reconstruction of the Human spiral ganglion.[13]

Craniofacial defects

This technique also overcomes the inner limitations of conventional tomographic approaches during to its increased sensitivity enabling the reconstruction of full vascularization network by contrast agents.[12,13]

Non-mineralized biological tissues

In SR-µCT, the contrast originates from the phase shift of the X-ray beam passing through the matter. This phase shift can be up to three orders of magnitude larger than attenuation explaining the highly increased contrast that has been observed with this imaging in investigating oesophagus, brain, liver, kidney, lung, cartilage and breast tissues.[14]

Analysis of the three-dimensional morphology of microcracks in human trabecular bone

Microdamage is thought to have a marked impact on bone strength and plays a major role in the repair process. This presents in the form of microcracks, whose size, morphology and localization are strongly related to the mechanical loading applied to bone.[15] Although 2D measurements can be made to three-dimensional (3D) measurements by using statistical models, these require prior knowledge and may not necessarily be valid for an individual microcrack. These should be observed, analyzed and measured in three dimensions with isotropic and with sufficient high spatial resolution.

Confocal microscopy can also produce micrometric 3D images of microdamage but with an anisotropic resolution and a small depth (typically 200 mm). Finally, contrast agents are being developed for 3D observations with standard micro-CT devices.[16] A synchrotron source 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.[17]

Alveolar support tissues

The monochromatic nature without beam-hardening artifacts could been seen. The grey values in the scans are directly related to the local tissue densities. The beam energy is low enough to allow for the visualization of soft tissues such as fibres of the periodontal ligament and blood vessels. 3D reconstruction of the alveolar bone can also be analysed.[18]

Enamel thickness and tooth measurement

Tooth enamel thickness has long been considered to be of importance in anthropological studies and the interpretation of human evolution for its purported taxonomic and phylogenetic value in human evolution. Enamel thickness is significant for the interpretation of occlusal loading regimen.

Application of SR-μCT systems has become an effective and nondestructive technique for the characterisation of DEJ and measurement of enamel thickness. It has been used to measure enamel thickness of a great variety of archaeological specimens.[19,20] Various studies indicated that Micro-CT was a reliable method and might be a useful device for measuring distances and for analysis of internal and external tooth structure. Apart from the enamel thickness, Micro-CT systems could also generate contiguous slices revealing the thickness and area of enamel, dentin, and pulp chamber accurately and reliably.[7,20]

Analysis of root canal morphology and evaluation of root canal preparation

Amongst the great variation and complexity of root canal morphology, there usually exist fins, webbing, accessory canals and multiple foramina. It is very important for an endodontist to develop a complete understanding of the 3D morphologic characteristics of root canal systems and the associated changes during root canal treatment.

The biomechanical preparation of root canals causes stress concentration in the root dentin, which creates gateway to dentinal microcracks, leading to failure of treatment .

Several researchers have used SR-μCT to generate both qualitative and quantitative outcome measures for investigations of pulp cavity and root canal During rotary and reciprocating nickel titanium (NiTi) instrumentations lead to the formation of dentine microcracks.[21] In addition root canal curvature could be measured by creating an imaginary central axis for each canal, by calculating the rate of turning of the tangent vector at a given point of the central axis, and inverting this rate to curvature of the canal by special mathematical modeling Software.[22]

Dental bur debris under dental composite restorations

Bur debris can remain within the prepared tooth structure, canal so be ingested or inhaled, and, due to their sharp edges, can become lodged in soft tissue. The sharp phase-contrast appears at the air/enamel interface, but may be significantly reduced at fragments/filling interface. This is because the density difference between air and enamel is an order of magnitude larger than that between fragments and filling. This edge-enhanced phase contrast may also affect the estimates of the small particle sizes and made the calculated volume oversized. [23]

Micro defects in Dental restoration

Quality assessment of dental restorations can be made using this phase contrast. This aids in the evaluation of Microdefects leading to microleakage and further failure of the restoration.[24,25] SR-μCT imaging also enables better visualization of gap and differentiation of materials at the tooth-restoration interface.[26]

Conclusion

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 medical and dental research.

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