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REVIEW ARTICLE

# Optical Coherence Tomography in Dentistry: An Emerging Perspective

MPV Prabhat, S Sudhakar, Karthikeya Patil, VG Mahima, K Srikrishna

## ABSTRACT

Optical coherence tomography (OCT) is a non-invasive, real time diagnostic modality that enables detection of oral lesions at an early, relatively harmless stage with improved resolution. OCT gives quantitative and qualitative information of hard and soft tissue by providing a cross-sectional 'optical biopsy' of tissue up to 3 mm in depth from the surface. In the present scenario, OCT has emerged as one of the forefront imaging modality because of the wide variety of information and the three-dimensional (3D) data it can provide. This article focuses on the basic sciences of OCT with its potential dental applications

**Keywords:** Optics, Coherence, Tomography, Optical biopsy, Non-ionizing, Real-time imaging.

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## INTRODUCTION

Optical coherence tomography (OCT) is a noninvasive and nondestructive method for imaging the microstructural details of the tissue.[1,2] OCT is comparable to ultrasound as both create a cross-sectional image by measuring the echo time delay and intensity of the reflected and backscattered wavelength.[1,3] The general principle of using reflections to create the images is the same for OCT and ultrasound but the methods for detecting these reflections are different. The use of light as the medium in OCT gives it the advantage of being noncontact for the patient, whereas ultrasound needs a coupling medium, such as water along its path between transmitter and tissue to pass the sound waves.[3] As light is faster than sound, the time delays between reflections from different layers cannot be measured directly, the differences would be on the order of femtoseconds, hence, OCT uses low-coherence interferometry to see the time difference corresponding to the distances between structures.[3] Initially, OCT was developed to image the transparent tissue, such as eye, recently it has been used to image nontransparent tissues.[4] This added advantage has been utilized in imaging the oral cavity as they have both transparent and nontransparent tissues. Moreover, oral cavity is particularly well suited for OCT imaging because they are easily accessible for interrogation by the fiber-optic OCT device.[2] OCT imaging has the potential to detect and diagnose very early stages of demineralization, remineralization, recurrent caries, restorative failures, root canals, periodontal disease, soft tissue dysplasias and precancerous lesions in real time.[1]

## HISTORICAL PERSPECTIVE

The concept of using light and optics to image biological tissues was first proposed by Duguay in 1971.[1] Fujimoto in 1989 imaged the retina of the eye using OCT.[3] Huang et al in 1991 did extensive work on the usage of OCT for imaging retina, optic nerve head structure and coronary arteries.[1-3] Fercher et al presented the first *in vivo* OCT images in 1993. In 1994, Carl Zeiss Meditec, Inc (Dublin, California) patented OCT. The first commercially available OCT, called OCT 1000, was marketed in 1996 and then OCT 2000 in the year 2000. Otis et al in 2000 proposed the OCT imaging for dental applications.[1,2] Wojtkowski et al in 2001 presented the first *in vivo* spectral-domain (SD)-OCT scans. In 2002, US Food and Drug Administration (FDA) approved the SD-OCT systems for clinical use.[3]

## PRINCIPLES AND INSTRUMENTATION

An OCT system operates on the basic principal of white light Michelson interferometry.[2,3] OCT utilizes noninvasive light and biomedical optics to provide cross-sectional 'optical biopsy' images of tissue up to 3 mm in depth, measured from the tissue surface.[1] An optical biopsy is defined as a method for imaging tissue pathology without the surgical removal of tissue, while the resultant image correlates well with that of histopathology.[1]

Otis et al in 2000 developed a dental OCT system which consists of a computer, compact diode light source, photodetector and handpiece that scans a fiber-optic cable over the oral tissues.[2] The system uses a white light fiber-optic Michelson interferometer connected to a handpiece that moves the sample arm linearly to create a tomographic scan.[5] A fiber-optic splitter separates the light from the low-coherence diode into the sample and reference arms of the interferometer. Reflections from the reference mirror and backscattered light from the sample are recombined and propagated to a photodetector.[2,5] An interferometric signal is detected only when the distance of the reference and sample arm reflections are matched with the coherence length of the source.[1] As the position of the reference mirror

is known, the location within the tissue of the reflected signal can be precisely determined.[5] Moreover, by imposing a changing optical delay in the reference arm with a scanning mirror operating at a known velocity, the axial positions of reflective signals from within the tissue being imaged can be measured with high accuracy.[1] The magnitude of reflective signals is determined by the optical scattering properties of the tissue. Thus, image contrast is determined by the optical properties of the tissue. A single interferometric signal measured at a specific point on the tissue gives the reflected boundaries across the axis of the beam.[5] Signal amplitudes are assigned a gray scale or false color value and the axial signals are serially displayed producing a composite OCT image. The OCT image thus obtained is a two-dimensional representation of the optical reflections of tissue in cross-section and the images can be viewed in real time and can be stored in a digital format.[2]

## MAIN CHARACTERISTICS OF OCT

- The wavelengths utilized in OCT imaging lies within 600 to 2,000 nm, where the main constituents of the tissue, water, pigments exhibit low absorption.[4]
- To achieve high depth resolution, the optical spectrum linewidth should be wider and the coherence length should be smaller.[4]
- A strict phase relationship is required between the interfering waves for interference to take place. This is best achieved by single scattered photons rather than multiple photons because, as the number of photons increases, the event loses the phase information.[4]
- Photodetection at the interferometer output involves multiplication of the two optical waves, therefore, the weak signal in the object arm, backscattered or transmitted through the tissue, is amplified by the strong signal in the reference arm. This explains the higher sensitivity of OCT when compared with confocal microscopy, which for instance in skin can produce images only to a depth of 0.5 mm.[4]
- OCT is built around a confocal microscope, hence, the transverse resolution is determined by diffraction.[4]
- Dental OCT imaging is considered safer as the power of the source in the current systems falls far below the American National Standards Institute (ANSI) standard for tissue damage. The ANSI threshold for skin damage using a source with a 1.3 mm wavelength is 96 mW, assuming 8 hours of continuous exposure, when compared it is thousand times less than the criterion.[2]
- Live subsurface images at near-microscopic resolution.[6]
- Instant, direct imaging of tissue morphology.[6]
- No preparation of the sample or subject.[6]
- No contact with the patient.[3]
- No ionizing radiation.[1-3,6]

## DIFFERENT OCT VERSIONS TIME DOMAIN OCT

The original OCT technology was based on time domain (TD)-OCT, where images are obtained in both the depth and lateral or angular axis.[4] Here, the path length of the reference arm is translated longitudinally thereby not only is the depth scanned, but an oscillating signal is also generated.[3] The images obtained are a series of dark and bright fringes, when the path difference lies within the coherence length of the light source.[6]

### SD-OCT or Fourier Domain OCT or Spatially Encoded Frequency Domain OCT[6]

The sepectral domain (SD) OCT works on the same principle as that of TD-OCT, however, the signal acquisition varies. The key difference here is that the reference mirror is stationary and the interference pattern is split by a grating into its frequency components and all these components are simultaneously detected by a charge-coupled device (CCD).[3,4] The CCD has an array of photodetectors, each sensitive to a range of specific frequencies corresponding to a certain depth of the tissue.[3] This method enables much faster acquisition times, resulting in a large increase in the amount of data that can be obtained during a given scan.[7] However, the acquisition speed of the signal is limited by the CCD array and spectrometer resolution limits can result in image drop-off, depending on imaging depth resulting in a reduction in both resolution and sensitivity with increasing depth in the scan window.[3]

### En-Face OCT or Full-Field OCT[6]

En-face OCT is a type of OCT based on white-light interference microscopy. It is an alternative method to conventional OCT and provides ultrahigh resolution images in three-dimension (3D) using a simple halogen lamp instead of a complex laser-based source. Here, the tomographic images are obtained in the en-face (transverse) orientation by a combination of interferometric images recorded in parallel by a detector array, such as a CCD camera.[6]

### Swept source OCT or Time Encoded Frequency Domain OCT

Swept source (SS)-OCT is a hybrid of TD-OCT and SD-OCT which provide faster acquisition of images.[6] SS-OCT uses a single tunable laser source instead of broad-bandwidth light source used in SD-OCT.[4] This laser can quickly scan through the range of relevant frequencies and thus the

reflectance of this tuned beam can then be detected by a single photodetector, which is much faster than a CCD array used in SD-OCT. Because of this, imaging can have a much higher scan density with transverse oversampling resulting in effectively improved transverse resolutions. This could be very relevant to visualizing fine transverse details, such as axons, blood vessels and individual cells.

### Functional OCT

Functional OCT provides depth resolved information of reflectivity, phase and polarization of the backscattered signal.[4] Here, the signals obtained are characteristic of functional changes of the tissue or the organ involved, which usually precede morphological changes and thereby helps in early diagnosis. Polarization-sensitive (PS)-OCT, spectrometric OCT, differential absorption OCT and Doppler OCT are the examples of functional OCT.[4]

### Polarization-Sensitive OCT

PS-OCT can detect and quantify the polarization properties of the tissue by analyzing changes in the polarization state of the backscattered probe light beam.[4] The information provided by polarization-sensitive OCT images can be used to identify birefringent structural constituents in the target tissue. Thus, the images obtained can be related to a change in the structure, functionality or integrity of the target. For instance, thermal injury denatures collagen in skin and polarization-sensitive OCT can sense these changes in the collagen.[4]

### Differential Absorption OCT

In differential absorption OCT, the system uses two channels, each operating on a different wavelength. One wavelength is chosen close to the absorption peak of the constituent to be measured while the other for low absorption.[4]

### Doppler OCT

Doppler OCT is used for monitoring or measurement of biological fluids. The image obtained is based on the depth resolved profile of the flow velocity in the vessel, with the resolution determined by the coherence length of the source.[4]

## DIFFERENT SCANNING PROCEDURES IN OCT IMAGING

### A-Scan

A-scan, also called as axial scan, is obtained by focusing the light beam to a point on the surface of the sample under test and recombining the reflected light with the reference. The information thus obtained corresponds to the depth of the tissue which is determined by the optical reflectance of the tissue.[3,4]

### B-Scan

B-scan or longitudinal scan is generated by collecting many single axial scans linearly across the tissue and in subsequent transverse positions. The images thus obtained will have both depth axis and lateral or angular axis. Collection of many such parallel B-scans can be used for 3D data acquisition.[3,4]

### T-Scan

T-scan or en-face scan is produced by transversally scanning the beam over the target maintaining the reference mirror fixed to generate a reflectivity profile in angle or lateral position.[4]

### C-Scan

C-scan, also called as transverse slice scans, are made from many T-scans in the transverse plane. Different transversal slices are collected for different depths either by advancing the optical path difference in steps after each complete transverse scan, or continuously at a much slower speed.[4]

## DENTAL APPLICATIONS OF OCT IN CARIES DIAGNOSIS

Presently, diagnoses of carious lesions are mainly through visual and radiographic examination. Unfortunately, the former does not detect the noncavitated lesions, whereas the latter known for its high sensitivity and specificity for diagnosing primary caries are highly invasive and less reliable in the detection of early caries.[5] In such instances, OCT can provide information about the extent of the carious lesion and it can also differentiate between stain, enamel dysplasia and active decay.[1] Moreover, OCT can image through water, saliva and plaque and can record microstructural changes underneath any materials for marginal integrity, bonding interphase, structural fractures, voids and early stages of demineralization beneath occlusal sealants or orthodontic composite brackets.[1]

OCT imaging can play a vital role in evaluation of remineralization of the tooth following fluoride application or in case of arrested caries and thereby can be helpful in determining the progression of decay and the treatment outcome. This is based on the hypotheses that the restoration of mineral volume would result in a measurable decrease in the depth-resolved reflectivity.[8] Jones and Fried in 2006

conducted a study to test the above stated hypotheses by measuring the optical changes in artificially caries induced and remineralized human tooth specimens using PS-OCT. The authors concluded that the mineral volume changes before and after remineralization can be measured accurately on the basis of the optical reflectivity of the lesion.[8]

## ENDODONTICS

In case of root canal therapy, understanding the complexity of the root canals plays a vital role in its outcome. Recently, camera-based endoscopes have been used to image the anatomy of the root canals.[1] Here, the image obtained is macroscopic and it is similar to an intraoral camera image. The drawbacks of the endoscopes are that the imaging is possible in only straight canal systems and requires a dry canal for appropriate imaging. In this regard, the OCT outsmarts endoscopes through its small diameter and increased flexibility of the probe.[1] In addition, OCT imaging does not require dry root canal and they provide a characterized microscopic detailed image through the surrounding root canal circumferential from dentin to cementum. Such measurements are capable of indicating the exact thickness of the dentinal wall and can aid in determination of minimal dentin thickness to prevent root canal over preparation and possible perforation of canal walls.[1] Intraoperatively, OCT imaging of root canals can indicate uncleaned fins, transportation of the canals, hidden accessory canals and measurement of the apex.[8] Shemesh et al in 2007 evaluated OCT's ability to image root canal walls following endodontic preparation and correlated these images to histological sections. The authors concluded that OCT was reliable for imaging root canals and the dentinal wall in a nondestructive manner.[9]

Determining the presence of vertical root fractures pose a challenge to the clinician and a threat to the tooth's prognosis, both during root canal therapy and postoperatively. Diagnosis of such fractures is difficult and mostly subjective, involving direct visualization, bite tests, staining, transillumination, probing and radiographs.[11] Radiographs are limited and can reveal a vertical root fracture only if the X-ray beam is parallel to the line of fracture. A controlled blind OCT endodontic study concluded that OCT is a valuable tool for imaging and identifying vertical root fractures and detecting the fracture's location along the root.[10]

## PERIODONTAL DISEASE

The microanatomy of periodontium and its soft tissue density does not allow routine imaging. Hence, the current periodontal diagnosis is completely based on clinical examination and evaluation of alveolar bony changes which are seen only after the progression of the disease.

Otis et al in 1998 evaluated the accuracy of OCT for taking *in vitro* images of periodontal structures using an animal model. The authors found that the OCT images were comparable with the histopathology.[11] However, the observations were limited because of the poor signal-to-noise ratios associated with the bulk optics used. The images produced were thus merely topographical maps corresponding to characteristic reflections from the interface between tissue and air.[11]

With the promising observations noted in the previous study Otis et al in 1998 performed a study with porcine mandibles using two prototypes dental OCT systems (an 850 nm wavelength, 700 mW system with a relatively low numerical aperture of 0.03 and a 1,310 nm wavelength, 140 mW system with a higher numerical aperture of 0.20).[2] The images obtained through OCT were correlated with histological sections and clinical probing. The authors observed that the images generated using the 1,310 nm wavelength systems were significantly better as compared with those images obtained from 850 nm system. The authors opined that the improvement in the image quality of 1,310 nm wavelength system was primarily due to the two-fold increase in its imaging depth and also due to its larger numerical aperture.[2] The authors concluded that the OCT can provide excellent images of the periodontal soft tissue attachment, contour, thickness and depth of the periodontal pockets *in vitro*.[2] At the outset, the authors hypothesized that another important mechanism that can improve the quality of the OCT image is the composition of tissue that is imaged. Hence, it is likely that *in vivo* OCT images will have improved contrast when compared to the nonvital specimens used in the present study. This is based on the theory proposed by Brezinski et al that the strong contrast between cardiac muscle and adjacent adipose tissue on OCT images found in his study may be attributable to their water content.[2] Similarly, it is conceivable that sulcular fluid will enhance contrast for imaging periodontal tissues *in vivo*. Variations in the tissue fluid resulting from periodontal diseases may provide differences in contrast important for clinical imaging.[2]

To evaluate the efficacy of OCT *in vivo* imaging of periodontium, Otis et al in 2000 performed a study among healthy adults with no clinical evidence of gingivitis or periodontal disease.[5] The dental OCT system consisted of 140 μW, 1,310 nm superluminescent diode light source which can detect up to 70 femtowatts of reflected light. It has an imaging depth of approximately 3 mm; with an image acquisition time of 45 seconds.[5] The authors concluded that the *in vivo* dental OCT images clearly

depicted periodontal tissue contour, sulcular depth and connective tissue attachment. In addition, the authors stated that as OCT reveals microstructural detail of the periodontal soft tissues, it offers the potential for identifying active periodontal disease before significant alveolar bone loss occurs.[5]

## PROSTHODONTICS

The dental prosthesis incorporates various materials, such as acrylics, ceramics, polymers, composites and metals, which are bridged and bonded together. The prostheses are more prone for fractures due to masticatory stress or it can be triggered by defects in the processing of the materials leading to microleakage.[12] Currently, several methods are employed for evaluation of the microleakage, such as bacterial penetration, fluid transport, clarification and penetration of radioisotopes, electrochemical methods and gas chromatography.[12] However, none of them are found be effective and can be considered standard.

Sinuescu et al in 2008 performed a study to evaluate the capability of OCT in detection and analysis of possible fractures in several fixed partial dentures using two single mode directional couplers with a superluminescent diode as the source at 1,300 nm employing enface scanning procedure. Here, the image acquisition was done by obtaining both C-scans as well as B-scan images. The resultant images showed voids of different sizes and shapes between the material interfaces at different depths.[12]

## MALIGNANCY

Oral cancer is predominantly preceded by white or red lesions that are visible to the naked eye, and often present for a considerable period of time prior to transformation.[14] The current approach is completely based on visual examination, vital staining, tissue fluorescence and biopsy. Visual examination provides very poor diagnostic accuracy, biopsies are invasive and unsuitable for regular screening whereas, the other modalities are although promising but have their own demerits. A noninvasive diagnostic approach that would enable detection of these lesions at a very early, relatively harmless stage is the need of the hour. In view of this, OCT is found to be promising as it enables minimal invasive imaging of near-surface abnormalities in complex tissue. Above all, cross-sectional images of tissues can be constructed in real time, at resolution of approximately 10 m with the current technology.[1]

Smith et al in 2005 performed a study using the Golden Syrian hamster cheek pouch model affected with oral premalignant and malignant lesions. The authors found that using OCT, imaging of multiple epithelial and subepithelial layers as well as the presence or absence of basement membrane were possible.[13] In addition, they also observed visualization of epithelial invasion during malignant transformation, blood vessels presence, size, localization relative to tumor tissue. The authors concluded that the diagnostic sensitivity and specificity for differentiating between malignant *vs* nonmalignant lesions as 100 and 96%.[13]

## EVALUATION OF MUCOSAL CHANGES

Oral mucosa is prone to myriad of alterations secondary to developmental, infections, inflammations and neoplasms as stated earlier. Most of the mucosal changes can be assessed by simple visual examination, whereas some requires early evaluation at cellular level. Radiation-induced mucositis is a classical example for the above statement. Studies quote that the mean overall incidence of mucositis as 80%.[14] It will be advantageous to use OCT for assessment of tissue injury during radiation therapy. OCT imaging can offer 3D imaging of tissue microstructure *in situ* and in real time without requiring a transducing medium and contrast enhancing agents while achieving spatial resolution approximately as the same depth of conventional biopsy.

Muanza et al in 2005 performed a study in murine radiation-induced mucositis models. The authors found that OCT can be helpful for both qualitative and quantitative assessment (using MIPAV—the medical image processing analysis and visualization) of acute mucosal damages. The promising aspect of the study was that the significant changes in the mucosa as registered by the OCT images could be discerned before visible macroscopic manifestations, such as ulcers became apparent.[14]

## MOLECULAR IMAGING

Molecular imaging is description and measurement of biologic elements at the cellular and molecular level. They evaluate the molecular abnormalities that are the basis of disease at an early stage in contrast to conventional imaging methods, where imaging is done to assess the end effects of these molecular alterations.[15] To image specific molecules *in vivo*, several key criteria must be met: Availability of high affinity probes with reasonable pharmacodynamics; the ability of these probes to overcome biologic delivery barriers (vascular, interstitial, cell membrane); use of amplification strategies (chemical or biologic) and availability of sensitive, fast, high resolution imaging techniques. In this regard, the properties of OCT and its improved resolution capabilities can be exploited to help evaluation of the diseases at molecular level in the near future.[15]

## CONCLUSION

OCT offers noninvasive, noncontact, *in vivo* and real-time subsurface images with high depth resolution. With the advent of promising results through *in vitro* experiments, we can expect more applications in the near future through development of dedicated processing protocols and novel hardware techniques.

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## ABOUT THE AUTHORS

### MPV Prabhat

Professor, Department of Oral Medicine, St Joseph Dental College Eluru, Andhra Pradesh, India

### S Sudhakar (Corresponding Author)

Reader, Department of Oral Medicine and Radiology, St Joseph Dental College and Hospital, Eluru, Andhra Pradesh, India
e-mail: drsudhakaroralmed@yahoo.co.in

### Karthikeya Patil

Professor and Head, Department of Oral Medicine and Radiology JSS Dental College and Hospital, Mysore, Karnataka, India

### VG Mahima

Professor, Department of Oral Medicine and Radiology, JSS Dental College and Hospital, Mysore, Karnataka, India

### K Srikrishna

Professor and Head, Department of Oral Medicine and Radiology, Hazaribag College of Dental Sciences, Hazaribagh Jharkhand, India