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Research Article

Optical Coherence Tomography - An Update

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ABSTRACT

Optical Coherence Tomography (OCT) is a non invasive, real time imaging technology capable of producing high-resolution cross-sectional images of the internal architecture of materials and tissues (1 – 2 mm in depth). OCT gives quantitative and qualitative information of both hard and soft tissue. The reviewed studies include images of normal and abnormal dental hard tissue structures and also teeth after several treatment methods. These are performed in order to assess the material defects and micro leakage at the tooth filling interface, as well as to evaluate the quality of bracket bonding on dental hard tissue. OCT can also be used for evaluation of prosthetic restorations and micro leakage at prosthetic interfaces, for imaging root canals and root dentin and the presence or absence of apical micro leakage and to detect osteointegration of dental implants. This imaging method has emerged as one of the forefront imaging modality because of the wide variety of information and the three dimensional data it can provide. This review focuses on the basic sciences of OCT with its potential dental applications.

INTRODUCTION

Optical coherence tomography (OCT) is a noninvasive and nondestructive method for imaging the micro-structural details of the tissue. 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. 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 non contact for the patient[1]. 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 femto seconds, hence, OCT uses low-coherence interferometry to see the time difference corresponding to the distances between structures[1]. Initially, OCT was developed to image the transparent tissue, such as eye, recently it has been used to image nontransparent tissues[2]. This added advantage has been utilised 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 fibre-optic OCT device[3].

Application of OCT in dentistry has become very popular. The first in vitro images of dental hard and soft tissues in a porcine model were reported in 1998[4]. Later, the in vivo imaging of human dental tissue was presented[5]. The traditional diagnosis of caries is based on examination using dental exploration and radiographs. The diagnosis of periodontal disease needs the examination of periodontal probes. The poor sensitivity and reliability of periodontal probing make it difficult for dentists to monitor the progression of periodontal destruction and the treatment outcome[6]. Radiography may be the most popular diagnostic tool recently. However, radiography provides only two-dimensional images. The caries or bone structure on the buccal and lingual sides of teeth may be superimposed with tooth structures or normal anatomic structures. The radiation exposure of radiographic techniques is also a great concern. Furthermore, early detection of caries, periodontal disease and oral cancer is quite difficult with clinical examination or radiographs.

OCT may provide a solution to these problems. Dental OCT detects qualitative and quantitative morphological changes of dental hard and soft tissues in vivo. It has the potential to detect and diagnose very early stages of demineralisation, remineralization, recurrent caries, restorative failures, root canals, periodontal disease, soft tissue dysplasias and precancerous lesions in real time.

This review paper discusses the development of dental OCT and also its application in dentistry.

Historical Perspective

The concept of using light and optics to image biological tissues was first proposed by Duguay in 1971[7]. Fujimoto in 1989 imaged the retina of the eye using OCT[1]. Huang et al in 1991 did extensive work on the usage of OCT for imaging retina, optic nerve head structure and coronary arteries. 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[3]. 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.

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Principle of OCT

An OCT system operates on the basic principle of white light Michelson interferometry[1]. OCT utilises 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. 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[7].

Otis et al in 2000 developed a dental OCT system which consists of a computer, compact diode light source, photodetector and hand piece that scans a fibre-optic cable over the oral tissues. The system uses a white light fiberoptic Michelson interferometer connected to a hand piece that moves the sample arm linearly to create a tomographic scan[3]. A fibre-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. 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. 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.

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[3]. 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.

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[2].

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[2].

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[2].

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[2].

Types of OCT

There are two main types of OCT.

- Time Domain OCT (TDOCT)
- Spectral Domain OCT (SDOCT)
- Functional OCT
- Sensitive OCT
- Polarisation Sensitive OCT
- Differential Absorption OCT
- Doppler OCT
- En-Face OCT or Full-Field OCT

Time Domain OCT (TDOCT)

In TDOCT the path length of the reference arm is scanned in time. Interference (i.e. series of dark and bright fringes) is only achieved when the optical path difference (OPD) lies within the coherence length of the light source. The envelope of this modulation changes as the OPD is varied, where the peak of the envelope corresponds to path-length matching[8]. Several reports deal with this type of OCT. TDOCT has been used for evaluation of indirect dental restorations, apical micro leakage after laser – assisted endodontic treatment[9], monitoring the periodontal ligament changes induced by orthodontic forces and orthodontic interfaces[10].

Spectral Domain OCT (SDOCT)

In SDOCT, the spectrum at the output of the low coherence interferometer is measured. Due to the Fourier relation (Wiener-Khintchine theorem between the auto correlation and the spectral power density) the depth scan (A-scan) is calculated by a Fourier-transform from the acquired spectra, without movement of the reference arm[11]. Because all depths are obtained in one measurement, SDOCT improves imaging speed dramatically. SDOCT has also an improved signal to noise ratio in comparison to TDOCT.

SDOCT can be also divided into swept source (SS) OCT and camera based, Fourier domain (FD) OCT.

In SSOCT, a narrow band optical source is used, whose frequency is tuneable in time. Point photodetectors are used. The depth resolution is inverse proportional to the tuning bandwidth while the axial range is limited by the coherence length of the source, the narrower the line width, the longer the axial range.

In FDOCT, a broadband optical source is used and the spectrum is acquired using a dispersive detector. The optical source bandwidth determines the depth resolution while the axial range is limited by the spectrometer resolution.

Functional OCT

Functional OCT provides depth resolved information of reflectivity, phase and polarisation of the backscattered signal. 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.

Polarisation Sensitive OCT

PS-OCT can detect and quantify the polarisation properties of the tissue by analysing changes in the polarisation state of the backscattered probe light beam. The information provided by polarisation 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 polarisation sensitive OCT can sense these changes in the collagen.

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.

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.

En-Face OCT or Full-Field OCT

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.

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 non cavitated 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. 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[7].

Moreover, OCT can image through water, saliva and plaque and can record micro structural changes underneath any materials for marginal integrity, bonding interphase, structural fractures, voids and early stages of demineralisation beneath occlusal sealants or orthodontic composite brackets.

OCT imaging can play a vital role in evaluation of remineralisation 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[12]. 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 demineralisation can be measured accurately on the basis of the optical reflectivity of the lesion.

Because strong birefringence in enamel and anisotropic light Sensors propagation through dentinal tubules was observed, many research projects are focused on the application of PS-OCT in caries detection[13]. Baumgartner et al. presented the first polarisation resolved images of dental caries[14]. Wang et al. measured the birefringence in dentin and enamel and suggested that the enamel rods acted as waveguides[15]. PS-OCT is suitable for the detection of secondary caries, because the scattering properties of restorative materials and dental hard tissue have marked differences.

Nowadays, PS-OCT is often used for very early caries diagnosis, because it can determine the level of demineralisation for early detection of caries. Moreover, recent researches showed that an OCT system with an integrated micro mechanical system (MEMS) scanner could obtain a 3D OCT image[13]). This could lead to rapid detection of both early demineralisation and more severe lesions.

Endodontics

In case of root canal therapy, understanding the complexity of the root canals plays a vital role in its outcome. The OCT outsmarts conventional endoscopes through its small diameter and increased flexibility of the probe. In addition, OCT imaging does not require dry root canal and they provide a characterised 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.

Intraoperatively, OCT imaging of root canals can indicate uncleaned fins, transportation of the canals, hidden accessory canals and measurement of the apex. 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[16].

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 visualisation, bite tests, staining, transillumination, probing and radiographs[17]. 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.

Dental Restorations

OCT appears to be a promising technique for examining the structural quality of restorations. In some studies amalgam, composite resin, and compomer were used to restore teeth[18]. The amalgam (by virtue of its metallic composition) completely obscures the tooth interior beneath it in an OCT image. However, the other two materials, exhibit lower absorption and therefore allows distinguishing internal landmarks such as the DEJ.

Periodontology

OCT is particularly well-suited for periodontal diagnosis, generating ultrahigh resolution cross sectional images of dental tissues. OCT provides rapid, consistent, and reproducible images of the surface topography, pocket morphology, and attachment level that are digitally recorded. These images pinpoint with great accuracy sites of disease progression. OCT also provides quantitative information regarding the thickness and character of the gingiva, root surface irregularities, and the distribution of sub gingival calculus.

The results of Otis L.L et. al. study, convincingly demonstrate the capacity of OCT to determine gingival thickness and the shape and contour of the alveolar crest. Visualizing these anatomical features represents a significant contribution to periodontal surgical treatment planning.

A TDOCT system was implemented with a fiber-based Michelson interferometer to evaluate the periodontal ligament (PDL). With OCT images, it is possible to measure changed ligaments from all directions; radiography could not show the portions overlapped by teeth. This suggests possible applications of optical imaging for predicting tooth movements precisely and preventing side effects in the early stages of orthodontic treatment[19].

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 micro leakage. Currently, several methods are employed for evaluation of the micro leakage, such as bacterial penetration, fluid transport, clarification and penetration of radioisotopes, electrochemical methods and gas chromatography. However, none of them are found be effective and can be considered standard[19].

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 super luminescent 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.

Malignant Lesions of Oral Mucosa

Accounting for 96% of all oral cancers, squamous cell carcinoma (SCC) is usually preceded by dysplasia presenting as white epithelial lesions on the oral mucosa (leucoplakia). Dysplastic lesions in the form of erythroplakias carry a risk of malignant conversion of 90%[19]. Tumour detection is complicated by a tendency toward field cancerization, leading to multi centric lesions. This high-resolution optical technique permits minimally invasive imaging of near-surface abnormalities in complex tissues, having a penetration depth of 1-2 mm. This permits *in vivo* noninvasive imaging of the macroscopic characteristics of epithelial and subepithelial structures, including: depth and thickness, histopatological appearance and peripheral margins. Oral mucosa is very thin, ranging from 0,2 to 1 mm. In a study of Wilder-Smith, 50 patients were evaluated, examined and photographed with white or red intra-oral lesions. The imaging was carried out along the long axis at the center of each lesion using either a fiber optic high-resolution 3D OCT probe with a scan length of up to 10 mm or a commercially available 2D probe with a scan length of 2 mm Niris TM OCT imaging system by Imalux (Cleveland, OH). Contra lateral healthy tissues were scanned in a similar fashion. The acquisition required approximately 5-180 seconds per 3D scanning and 1,5 seconds for 2D scanning, totalling less than 15 minutes for each patient[20].

In the OCT images, epithelium, lamina propria, and basement membrane are clearly visible. The OCT image of a dysplastic lesion parallels histopathological status, showing epithelial thickening, loss of stratification in lower epithelial strata, epithelial down growth, and loss of epithelial stratification as compared to healthy oral mucosa. The epithelium is highly

variable in thickness, with areas of erosion and invasion into the sub epithelial layers. The basement membrane is not visible as a coherent landmark. OCT image is rapid, unproblematic and well received by all patients.

Implantology

OCT images provide quantitative information regarding micro-structural architecture, including the character of the gingiva as well as that of the implant and the soft tissue relationships. More importantly, OCT identifies the earliest signs of inflammation that are so minimal that clinical examination is unlikely to detect. OCT imaging offers the exciting potential to detect periimplantitis before significant osseous destruction occurs. Several histological animal studies have shown that gingival connective tissue forms a scar-like fibrous connective tissue adjacent to titanium implant surfaces, while periimplantitis is characterised by a disorganised connective tissue containing more vascular elements. The preliminary data demonstrate that in OCT images of healthy implant sites, collagen appears well organised and its birefringent nature produces a characteristic high OCT signal intensity. OCT images of soft tissue surrounding failing implants are characterised by linear signal deficits, low-intensity collagen signals, and pronounced increases in vascular elements. OCT will improve clinical evaluation of periimplant soft tissues and will provide significant advantages over existing diagnostic procedures.

OCT can produce two- or three-dimensional images depicting the topography of the implant sulcus and the relationship of implants soft tissue interfaces. A fiberoptic clinical OCT system was used to obtain large size, 12 mm occlusal-apical OCT images.

DISCUSSION

In vivo and in vitro imaging of hard and soft tissue of the human oral cavity has been demonstrated using different OCT techniques. Several types of oral mucosa and healthy and damaged tooth structures, can be imaged and differentiated. Also, OCT can diagnose periodontal diseases. In addition, it has been demonstrated that OCT is an efficient diagnostic tool in dental restorative procedures. eFOCT imaging proved that laser-assisted endodontic treatment improved the prognosis of root canal filling and led to a reduction in the apical micro leakage. In measurement of demineralisation inhibition, results obtained suggest that PS-OCT is well suited for the nondestructive assessment of caries inhibition by anti-caries agents.

The studies about periodontal ligament under orthodontic tooth movement show the possible evaluation and prediction of precise tooth responses under orthodontic forces by using real-time OCT. Considering the possibility of investigating the periodontal ligament around the tooth in real time, the OCT imaging relevance is superior to the radiographic one.

All studies, regarding prosthetics, directed towards assessing the quality of dental prosthesis, as mentioned in this review, show the importance of adopting non-invasive methods of investigation, like OCT. It was demonstrated that OCT represents a viable solution for investigating all sorts of dental prosthesis before their insertion into the oral cavity. OCT could act as a valuable tool in analysing the integrity of prostheses, saving time and resources.

In comparison with all other invasive and noninvasive imaging technologies, OCT exhibits the highest resolution in depth a safe method.

CONCLUSION

OCT represents a valuable method for investigation and assessment of the health status of soft oral tissues and of hard dental structures. OCT can be used for evaluation of dental treatments reducing their failure rate and saving time and resources, by eliminating incorrect restorations before their insertion in the oral cavity.

The unique capabilities of OCT recommend this technology for fundamental research and clinical practice. The review was based on reports on OCT directed towards both in the practice of dental medicine practice as well as to its associated research. As a general conclusion, OCT extends the resolution capabilities of current X-ray techniques while being completely noninvasive method. We envisage continuous progress in advancing OCT into a widely used investigative tool in dentistry.

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