Review Article

Optical Coherence Tomography-A Boon for Dental Diagnostics

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A B S T R A C T

Objective: Presently oral examination of a patient is carried out by three methods –clinical or visual examination, periodontal examination and radiography. However each of these has their own limitations. Optical coherence tomography (OCT) is a3dimensional,non-invasive imaging modality that produces high resolution images in cross section through in homogeneous samples such as biological tissue. Colston *et al* in 1998 first used OCT in dentistry.

Method: OCT is of 3 main types- Time domain OCT (TD-OCT), Fourier domain OCT (FD-OCT) and Parallel OCT. There are various scanning procedures depending on the engine performing the imaging and its application, A scan, B scan, C scan and T scan. It has various uses in non-medical fields, medical field and dentistry. The dental optical coherence tomography (OCT) system aims to produce images of dental microstructure *In vivo,* that help in assessing the qualitative and quantitative status of oral tissue health. This review has taken into consideration all these imaging modalities.

Conclusion: Through these images, the clinically anatomical structures can be correlated such as location of the soft tissue attachment, morphological changes in gingival tissue, tooth decay, and structural integrity of dental restorations.

Introduction

Oral examination of a patient is carried out through three main avenues: visual/tactile examination, periodontal examination and radiographic imaging. However each of these has their own limitations. Visual examination depends on the clinical acumen and tactile sensitivity of the operator. Periodontal examination by probing is often painful, uncomfortable and highly operator dependent and hence diagnostically unreliable. Due to a difference in probing force, inflammation of underlying tissue and probe design, probing is diagnostically not precise. Radiographs are also subject to variation due to a difference in angulations and radiographic techniques. They are helpful in determining advanced bone loss. Hence conventional methods of periodontal disease diagnosis are inaccurate and fail to warn against early signs and symptoms of periodontal disease by correctly evaluating hard and soft tissue changes.[1] Optical coherence tomography (OCT) is an emerging non-destructive 3-dimensional imaging technique that is capable of producing high resolution cross sectional images through in homogeneous samples such as biological tissue.[2] Optical coherence tomography is a well known technique for creating non-invasive, high resolution (< 20 μm) images of biological microstructure[3]. Clinically, OCT systems have been developed for ophthalmic[4], dermatological[5], and endoscopic[6] applications. It is non-invasive and can help in diagnosing hard and soft tissue changes, several periodontal structures including sulcus, epithelium, connective tissue layers well as alveolar bone. OCT is a promising, futuristic tool in dentistry which can evaluate, diagnose and assess the advancement of periodontal disease. (Figure 1 and 2).

Optical interferometry was first used by Simonsohn *et al* in 1969[7] for assessing refractive index of animal eye lenses. It was used in humans by Rossow *et al* in 1978 for retinal measurements. Optical coherence tomography (OCT) was first developed by Fujimoto's group at MIT in 1991.[8] Huang et and co-workers combined transverse scanning with a fibre optic optical coherence domain reflectometry (OCDR) system to produce the first OCT cross sectional images of biological microstructure in 1991. In 1993, the first *In vivo* OCT images were created by groups in Vienna and Boston.[9] Colston *et al* in 1998 were the first to perform a dental OCT.[10] They developed a prototype OCT and acquired images of porcine periodontal tissues.

Types of OCT

OCT is of three main types - Time domain OCT (TD-OCT), Fourier domain OCT (FD-OCT) and Parallel OCT. (See figure 3.)

OCT works on the principle of Michelson or Mach-Zehnder interferometer. Depending on the type of OCT used, the signal is captured by a photodiode (PD) or charge-coupled device (CCD). The signal may undergo two types of interference-Non constructive and constructive. Non constructive occurs when the optical path length (OPL) of light reflected by the reference and sample is same. Constructive interference occurs when OPL between the light reflected by the reference and sample is in multiples of wavelength.

In time domain OCT (TD-OCT), the path length of the reference arm is scanned in time. It was the first OCT used in dentistry. In spectral domain OCT (SD-OCT), the spectrum at the output of the low coherence interferometer is measured. It can be divided into Swept source (SS-OCT)[11] and camera based, Fourier domain (FD-

OCT).[12] Other types of OCT are en-face optical coherence tomography (eFOCT)[13] and Polarization sensitive (PS) OCT.[14]

Principles of operation

OCT is comparable to ultrasound imaging but here light is used instead of sound. Cross-sectional images are generated by measuring the echo time delay and intensity of light that is reflected or backscattered from internal structures in tissue.[8] Because the velocity of light is extremely high, the echo time delay cannot be measured directly. Instead, it is necessary to use correlation or interferometry techniques. One method for measuring the echo time delay of light is to use low-coherence interferometry. Low-coherence interferometry was first developed for measuring reflections in fiber optics and optoelectronic devices.[15] (Figure 4)

The first application of low-coherence interferometry in biomedicine was in ophthalmology to perform precision measurements of axial eye length and corneal thickness.[16]

Low-coherence interferometry measures the echo time delay and intensity of backscattered light by interfering it with light that has traveled a known reference path length and time delay. Measurements are performed using a Michelson-type interferometer. Light from a source is directed onto a beam splitter, and one of the beams is incident onto the sample to be imaged, while the second beam travels a reference path with a variable path length. The backscattered light from the sample is interfered with reflected light from the reference arm and detected with a photodetector at the interferometer output. If the light source is coherent, then interference fringes will be observed as the relative path lengths are varied.

However, if low-coherence light or short pulses are used, then interference occurs only when the two path lengths match to within the coherence length of the light. The echo time delay and intensity of backscattered light from sites within the sample can be measured by detecting and demodulating the interference output of the interferometer while scanning the reference path length. This method is analogous to heterodyne optical detection in optical communications.

OCT can perform cross-sectional imaging. The optical beam is focused into the sample being imaged, and the echo time delay and intensity of the backscattered light are measured to yield an axial backscattering profile. The incident beam is then scanned in the transverse direction, and the axial backscattering profile is measured at several transverse positions to yield a two dimensional data set. This data set represents the optical backscattering through a cross section of the tissue. The data is displayed as a logarithmic gray scale or false color image.

In contrast to conventional microscopy, the mechanisms that govern the axial and transverse image resolution in OCT are independent. The axial resolution in OCT is determined by the coherence length of the light source. Thus high resolution can be achieved independent of the beam focusing conditions.

Different scanning procedures

There are three main scanning procedures depending on the engine performing the imaging and its application.

A-scan or Axial scan

It measures the depth of the object being scanned. The data obtained is one dimensional.

B-Scan

It is similar to ultrasound B scan. It is actually a collection of different A-Scans,

taken linearly across the object and following this in a transverse direction. Thus both depth and lateral aspect of the object can be assessed.

T-Scan or en-face scan

It is produced by a beam which scans the object transversally while maintaining a fixed reference point. This reference point could either be angulated or in a lateral direction. It is the most popular modality to record the occlusion. It accurately records the force exerted, time taken and amount of occlusal surface in contact. This scan helps in determining the length of bite and the time and force with which the teeth occlude.

C-Scan or Coronal scan

It scans in a transverse direction and is actually a collection of many T scans transversally. It is particularly useful in imaging the retina.

Dental applications of OCT

Initially OCT was developed to image the transparent tissue like the eye, recently it has been used to image no transparent tissues.[18] The oral cavity is ideal for OCT imaging as it has both non transparent and transparent tissues .Also it is easily accessible for interrogation by the fibre optic OCT device.[19]

1. Caries diagnosis

OCT provides the capability for early detection of caries.[20] The enamel displays powerful birefringence and there is anisotropic propagation of light via dentinal tubules. Secondary caries can be detected using PS-OCT. OCT can predict the boundaries of the carious lesion and can also distinguish between active lesion, enamel dysplasia and stain. 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 demineralization beneath occlusal sealants or orthodontic composite brackets.[21] OCT can be very helpful in evaluation of tooth remineralisation after application of fluoride or arrested caries and thus can be help in assessing the decay progression and hence predict the outcome of treatment. Figure 5 (a and b).

2. Endodontics

Recently, camera-based endoscopes have been used to image the anatomy of the root canals.[23] 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 out smarts endoscopes through its small diameter and increased flexibility of the probe.[23] OCT imaging can be done in wet canal and gives detailed microscopic images from cementum to dentin. 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.[23] Intra-operatively, OCT imaging of root canals can indicate unclean fins, transportation of the canals, hidden accessory canals and measurement of the apex.[24]

3. Periodontal disease

The diagnosis of periodontal diseases is based on clinical examination, radiolographic findings and periodontal examination/probing. The hard and soft tissue structure of periodontium makes it difficult to assess through routine imaging modalities. The accuracy of OCT for taking *in vitro* images of periodontal structures was evaluated using an animal model.[25] The images produced were thus merely topographical maps corresponding to

characteristic reflections from the interface between tissue and air.[25] With the promising observations noted in the previous study further studies were performed 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.[26]

The system with wavelength 1,310 nm produced better images than the 850 nm system. 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*.[27] 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.[18]

Another study was carried out to evaluate the efficacy of OCT *In vivo* imaging of periodontium among healthy adults with no clinical evidence of gingivitis or periodontal disease.[18] The authors of this study 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 micro structural detail of the periodontal soft tissues, it offers the potential for identifying active periodontal disease before significant alveolar bone loss occurs.[27] (See figure 6 and 7.)

4. Prosthodontics

The dental prosthesis are composed of various materials which are bridged or bonded together. They are liable to fracture due to a variation in their physical and mechanical properties and masticatory load.[26] 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.[26] However, no method could be regarded as totally reliable. The ability of OCT to detect and analyze probable fractures in fixed partial dentures has been evaluated by different studies. 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. [26] (See figure 8.)

5. Malignancy

The hallmark of intraoral cancer is the presence of visible white or red lesions. The diagnosis is based on visual examination, tissue fluorescence, vital staining and biopsy. Visual examination is not conclusive; biopsy is invasive and unsuitable for screening. Other modalities too have their own merits and demerits. Hence there is no single fool proof diagnostic aid for detecting oral cancer. OCT is found to be promising as it is minimally invasive, all cross-sectional imaging of tissues can be constructed in real time.[31] The authors found that using OCT, imaging of multiple epithelial and sub epithelial layers as well as the presence or absence of basement membrane were possible[32] In addition, they also observed visualization of epithelial invasion during malignant transformation, blood vessels presence, size, localization relative to tumour tissue. The authors concluded that the diagnostic sensitivity and specificity for differentiating between malignant versus non-malignant lesions as 100% and 96%.[33] The movement of gold nanoparticles in administering anticancer treatment has been studied extensively using OCT.[34]

6. In evaluation of mucosal changes

Various infections, inflammations and neoplasm can earliest be perceived as alterations in the oral mucosa. Though most of these can be detected by visual examination some of these conditions such as Radiation-induced mucositis, requires early detection at a cellular level. OCT can assess tissue damage at the time of radiation therapy, in real time. According to a study performed 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.[33] 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.[35]

7. Temporo-mandibular joint disc

Marcauteanu and Colab investigated the micro structure of temporomandibular disc by using OCT.[36] Two different OCT systems were used: an Enface (TDOCT) system working at 1300nm (C-scan and B scan mode) and a spectral OCT system (a FDOCT) system, working at 840nm (B scan mode). The OCT investigation of the temporomandibular joint discs revealed a homogeneous microstructure. The longer wavelength of the FDOCT offers a higher penetration depth (2.5mm in air), which is important for the analysis of temporomandibular joint.

8. Implantology

OCT images provide an assessment of gingiva, implant as well as their relationship. It also identifies the earliest signs of inflammation, even before clinical changes become evident. OCT imaging may detect peri-implantitis before significant osseous destruction. [37] In several histological studies on animals it has been found that scar like fibrous gingival connective tissue forms adjacent to titanium implant surfaces, while in peri-implantitis the connective tissue is disorganized with more vascular elements.[37] The preliminary data demonstrate that in OCT images of healthy implant sites, collagen appears well organized and its birefringent nature produces a characteristic high OCT signal intensity.[38] The soft tissues around failing implants produce OCT images with linear signal defects, collagen signals of low intensity and a significant increase in vascular elements.[38] OCT can provide a realistic evaluation of soft tissues around the implant and is certainly advantageous over other diagnostic modalities. It helps in visualizing the implant sulcus in two and three dimensions and also provides valuable information about the implant soft tissue inter relationship.

Discussion

OCT can produce tissue imaging in micron scale both in real time and in situ which can be analogus to an optical biopsy. Imaging in real time saves the need of invasive procedures like incision, excision and processing of histological specimen. A comprehensive OCT system with an optical handpiece has helped in producing *In vivo* images in cross-section of dental microstructure. The future of OCT lies in conducting more clinical studies emphasizing its various facets in dentistry. However, the unique capabilities of OCT imaging suggest that it has the potential to have a significant impact on the diagnosis and clinical management of many oral and systemic diseases. Hand held OCT systems can be placed alongside the dentist chair just like other dental gadgets.

The advantage of OCT compared to non-optical imaging modalities are its

- High depth and transversal solution

- Contact-free and non-invasive operation, and the possibility to create
- Function dependent image contrast
- OCT uses light for imaging of tissues hence patient is not exposed to ionizing radition[39]
- OCT helps in early diagnosis of oral diseases
- OCT helps in real time monitoring of both hard and soft tissues.
- It has excellent resolution and penetration depth and hence can image the normal and abnormal changes in the oral mucosa.
- T scan can be for occlusal mapping and help in recording the pattern of occlusion.[39,40]

The disadvantage of OCT are,

- OCT has limited penetration depth in scattering media.
- The scanning range of OCT is usually several millimeters; hence many pictures would be needed to scan an entire lesion.[41]
- OCT takes a longer time to acquire the image.
- Artifacts are produced due to tissue birefringence.

Conclusion

OCT can be used for evaluating dental treatments hence reducing failure rates. This will help in economising resources and time. The sensitivity and specificity of OCT as a diagnostic tool needs to be established. The unique features of OCT make it ideal for research and clinical practice. Hence OCT provides a diagnostic approach which is both comprehensive and quantitative.

Source of funding
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Figure 1. Dental OCT system
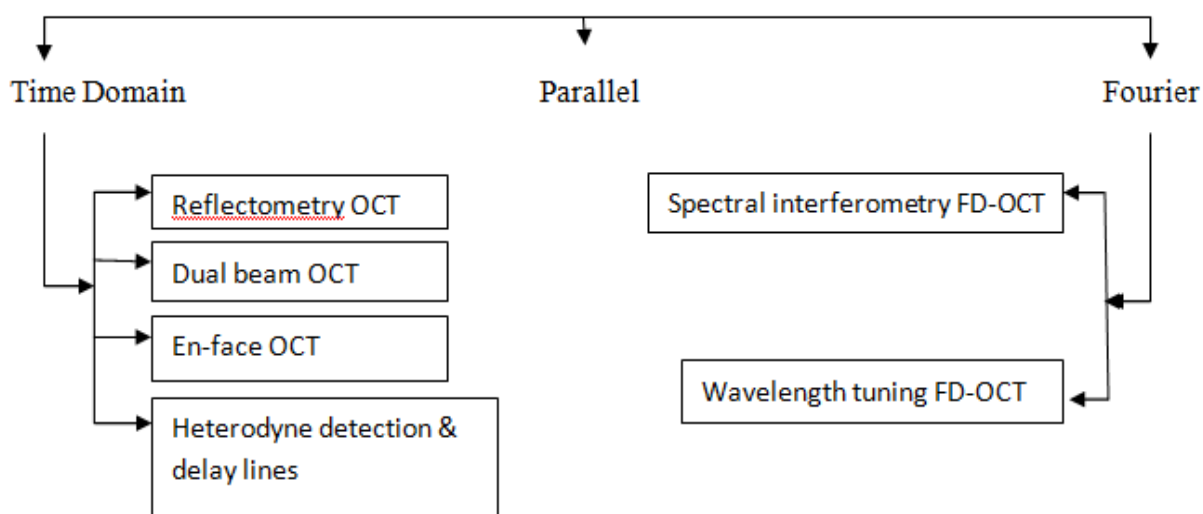
Figure 2. Handheld probe for oral OCT

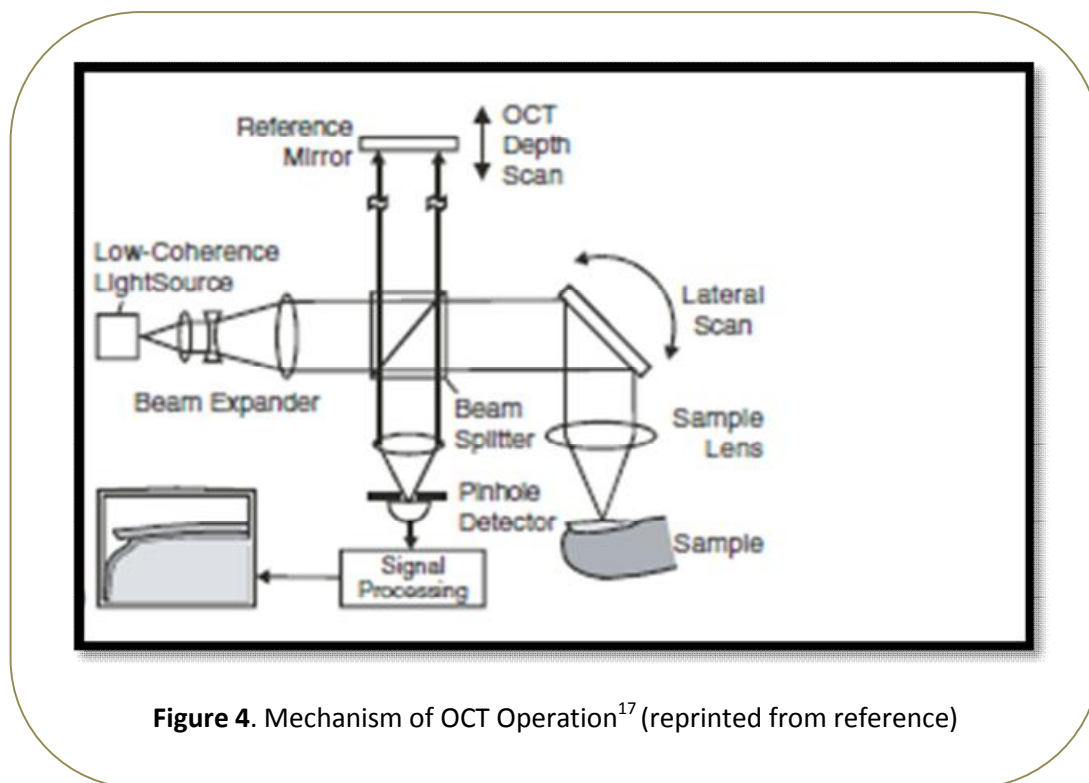**Figure 3**. Schematic diagram of types of OCT

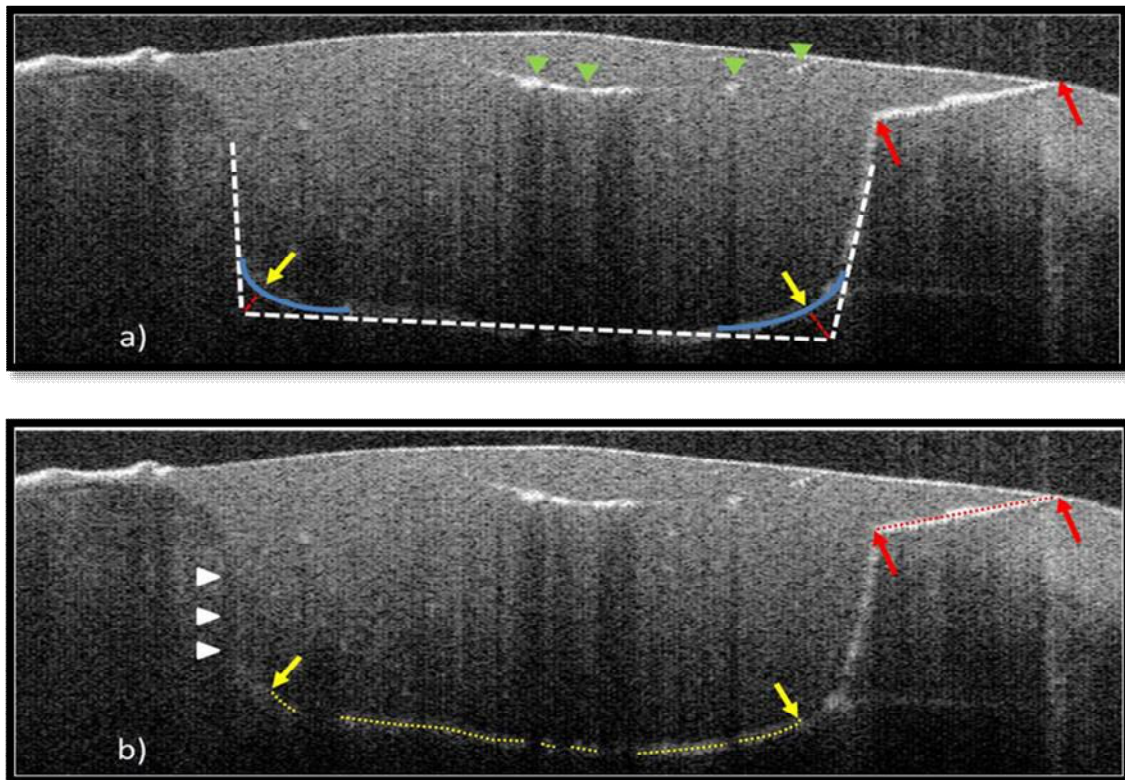**Figure 4**. Mechanism of OCT Operation[17] (reprinted from reference)

Figure 5. (a and b) The area between the two Red arrows indicates the bevelled enamel

- The area between the two yellow arrows indicates the cavity floor.
- The walls of the cavity are indicated by white triangles.
- The gap induced OCT signals are denoted at the enamel margins by red and at the cavity floor by yellow.
- Air entrapments can be seen between composite layers[22] (denoted by asterisk) E: enamel, D: dentin and C: composite inlay) (reprinted from reference).
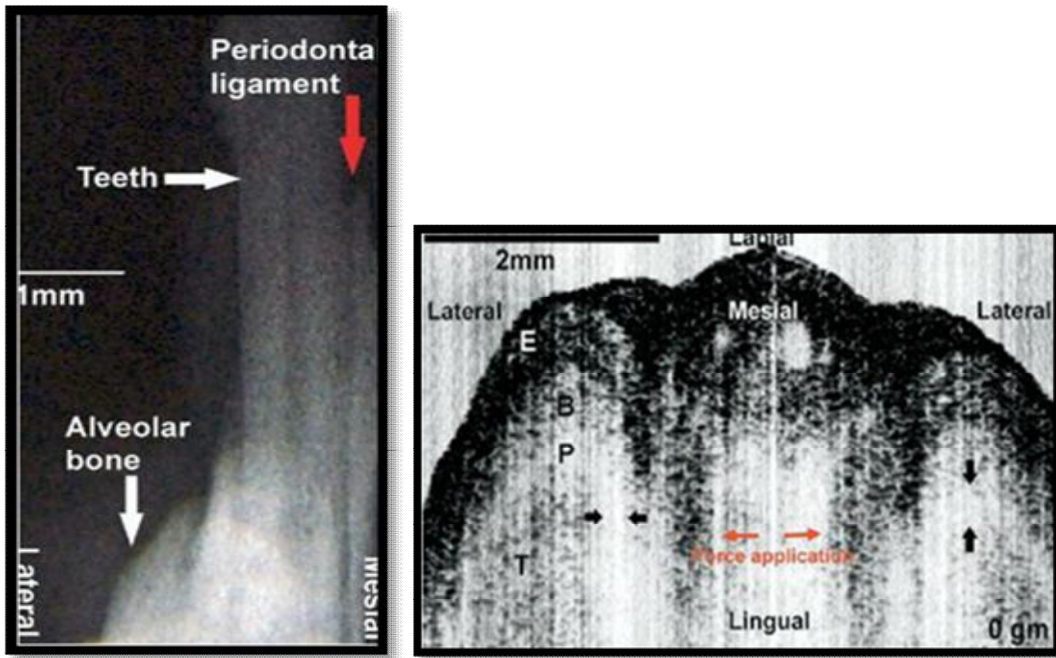
Figure 6. Images of a periodontal ligament. (A) Radiograph. (B) OCT [28] (reprinted from reference)

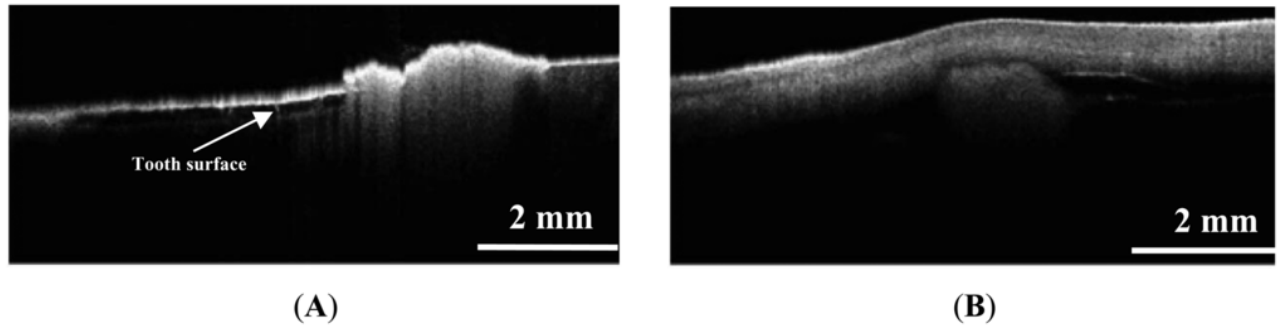**Figure 7.** OCT image of subgingival calculus. (A) Subgingival calculus without coverage of gingiva. (B) Subgingival calculus covered with gingiva[29] (reprinted from reference)
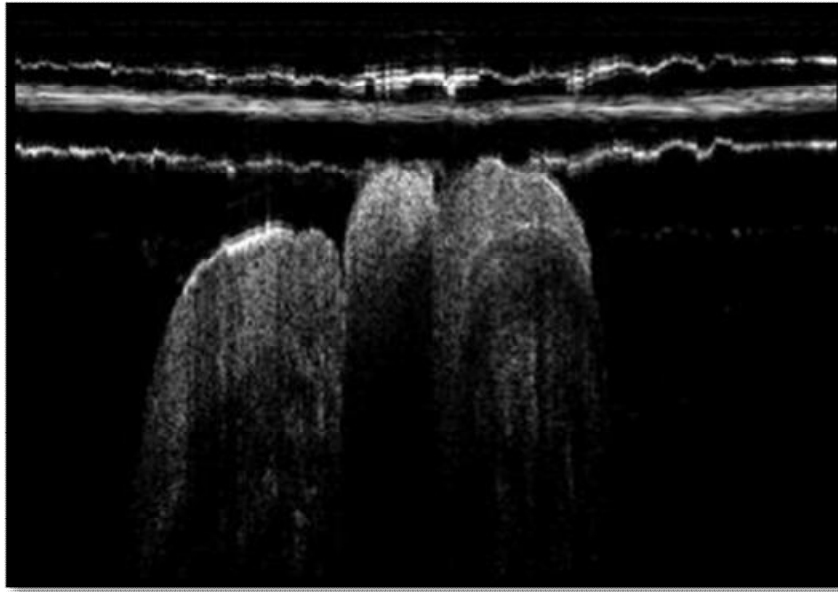
Figure 8. *In vivo* OCT image of microleakage detected by a custom-made dental optical probe[30] (reprinted from reference)