Optical Coherence Tomography (OCT) – Present and Future Applications in Dentistry

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Abstract

Background: Optical coherence tomography(OCT) is an evolving optical technology thatis capable of delivering real time and high resolution imaging of soft and hard tissuestructures. OCT is analogous to ultrasound imaging except that it uses light instead ofsound. OCT can function as a type of optical biopsy and is a powerful imagingtechnology in medical and dental diagnosis.

Objectives: The reviews aims to identify the various potential applications and challenges inthe use of the optical coherence tomography (OCT) in the field of dentistry.

Results: A thorough literature review reveals the presence of an effective role ofOCT in the diagnosis of dental caries, secondary caries, defective restorations, oralprecancerous and cancerous lesions, gingival ailments and periodontal diseases. Witha number of advantages supported by literature OCT has the potential to become amainstay of futuristic diagnosis.

Conclusions:OCT is a new and emerging diagnostic tool in the medical field. Its expanseinto the dental field would result in non-invasive and quick diagnosis of oral diseases.Earlier and quicker the diagnosis, the better the treatment optionsincluding a greater chance of prevention rather than cure. With the evolution ofmedicine and dentistry into a more modern and digital one, OCT has the potential tobecome the norm of dental diagnosis.

***Keywords**:* Optical Coherence Tomography, Diagnostic aid, Non-invasive, Dental imaging, Visible light diagnosis

1. Introduction

Optical coherence tomography (OCT) is an emerging noninvasive, noncontacttechnology capable of high resolution imaging using very low wattage of light.1 OCT hasbeen applied in several areas, from analytical technology where conservators use it to identify the quality and age of paintings, ceramics or glass to many areas of medicineand dentistry. OCT uses visible light of wavelength of 850nm-1310nm. OCT was firstintroduced in 1991 where in the internal cross-sectional microstructure of tissues waselicited using measurements of the optical backscattering or back reflection (reflectionof waves, particles or a signal in the direction from where they originate). It was initiallyapplied for imaging of the eye.2 OCT provides two dimensional images with a resolutionof 1-15 µm and has a tissue penetration depth of 1-2 mm.1 The unique feature of this technology enables a broad range of clinical applications.The use of optical coherence tomography in dentistry was first made in 1998 byresearchers from the laboratory of medical technology of Livermore, California incollaboration with the researchers from the University of Connecticut.3 The prototype ofthe dental OCT designed by them scanned both hard tissues to a depth of 3mm andsoft tissues to a depth of 1.5mm. They demonstrated the possibility of imaging thegingival margin and periodontal pockets and attachments. Fig: 1, 2 shows the OCTsystem setup.

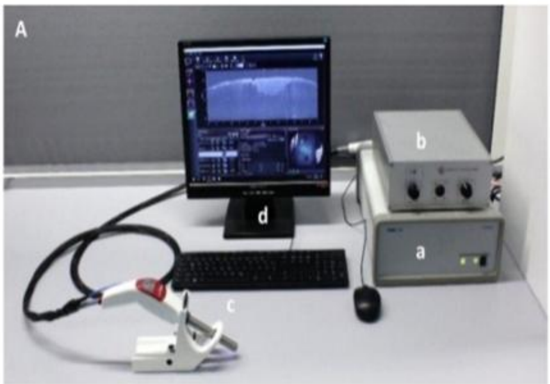

Figure 1: Photograph of a OCT system setup (a) Scanner controller (b) balance detector (c) OCT probe (d) computer

Figure 2: Examination of the oral cavity with OCT

Review Results

Operating principles of Optical Coherence Tomography

OCT is a modular device which consists of coupled software and hardware components.3 It consists of five basic modules which includes a partially coherent light source, an imaging apparatus, a measurement head, a module for data processing and image generation along with a computer controlled system. The axial resolution and depth of penetration of light beam depends on the light source used in the device. The OCT imaging apparatus is capable of measuring the reflected or back scattered light with high sensitivity and resolution.

The light source used in an OCT has a broad spectral bandwidth which has a low coherence.4, 5 An interferometer is used to split this light source into two, using a beam splitter (BS). In an OCT the type of interferometer used is a Michelson's interferometer. This light, passing through the beam splitter is split into the reference beam and the probe beam .The reference beam along with a movable mirror (M1) constitutes the reference arm from where the light is reflected back to the screen D (Detector).The second beam which is the probe beam along with the fixed mirror (M2) constitutes the sample arm, from where the light is reflected back in a perpendicular direction and falls on the detector. The OCT scanner, scans each sample point with the reference arm ,thus providing a complete profile depth of the sample reflectivity which is given as an amplitude scan (A scan).1, 3 The cross sectional images are created by using the sagittal scan (B scan) and the lateral scan (C scan). Thus by combination of measurements of the probe beam, a two dimensional image of the subject is formed. A Micro- Electro- Mechanical System (MEMS) scanner was used to provide a lateral scanning range and a field of view (FOV) of 3.3mm.4 The simultaneous visualization of the sample is enabled by a charge coupled device (CCD) camera in order to guide the OCT beam during imaging. The objective lens which is present within the handheld probe has a focal length of 50mm. The probe could work either in contact or noncontact mode by adjusting the lens tube. In addition, a mirror mounted at 45 - degrees is used to visualize the lingual sides of teeth and buccal sides of posterior tooth. The adjustable lens tube has a diameter of half an inch. Fig. 3, 4, 5 portrays the OCT system

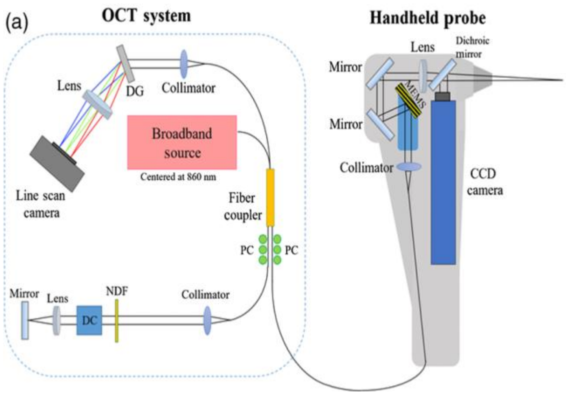

Figure 3: Schematic diagram of OCT system. Abbreviations: DG, diffraction grating; PC, polarization controller; NDF, neutral density filter; DC, dispersion compensation unit; MEMS, micro electro mechanical system; CCD, charged coupled device.

Figure 4: Photograph of portable OCT handheld scanner

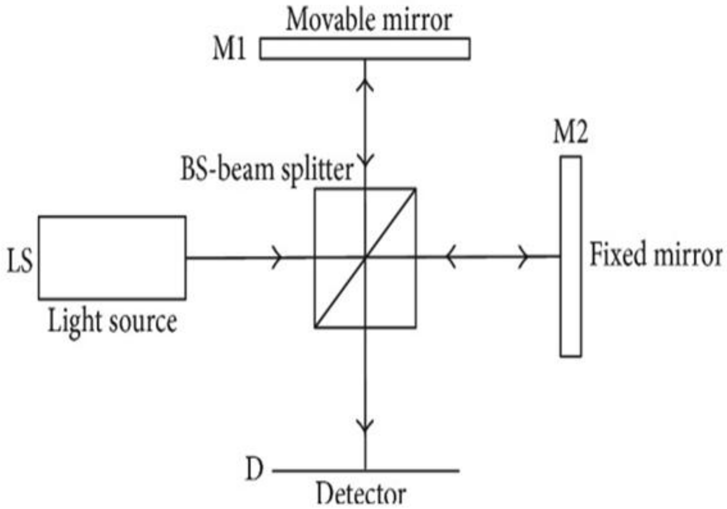

Figure 5: Schematic diagram of OCT system

Types of optical coherence tomography

OCT uses a beam of partially coherent light to create tomographic images.3 There are two basic types of OCT; time domain optical coherence tomography (Td-OCT) and Fourier domain (frequency domain) optical coherence tomography (Fd-OCT). The Td-OCT technique was developed in 1991 by Massachusetts Institute of Technology in the United States for use in ophthalmic diagnosis. When compared to the Td-OCT, optical tomography with detection in the frequency domain (Fourier domain optical coherence tomography) reduces the capture time by more than hundred times. Additionally, Fd-OCT creates superior images which are three-dimensional images when compared to the two dimensional images produced by Td-OCT.

In Td-OCT the reflected lights are measured by step movement of the reference mirror whereas in Fd-OCT the reflected lights come in from all axial depth at the same time and are detected as modulations in the source spectrum, with all the spectral components captured simultaneously.3, 5 Fd-OCT detection system are capable of higher data acquisition speeds compared to the Td-OCT systems. Fd-OCT further comprises of two primary methods, spectral domain optical coherence tomography (SD-OCT) and swept source optical coherence tomography (SS-OCT). The SD-OCT also works with the Michelson - type interferometer with a stationary reference mirror. The spectrum in case of SD-OCT is spread out or dispersed and is detected by a CCD line camera.

Unlike SD-OCT where inference pattern is dispersed immediately before detection, in case of SS-OCT there is narrowing of band laser which is detected by a one point detector. The SS-OCT uses a wavelength of 1050nm, which has an improved image penetration with an axial resolution of 5.3µm and an axial scan rate of 10,000scans per second. It also provides possibility of a wide field scan of up to 12x 12 mm. Point detection is the advantage of SS-OCT over the SD-OCT. Therefore, a scanning laser with a narrow line width enables a deeper probing depth whereas a wide spectrum enables high resolution OCT images. Fig. 6 shows the optical set up of SD-OCT and SS-OCT.

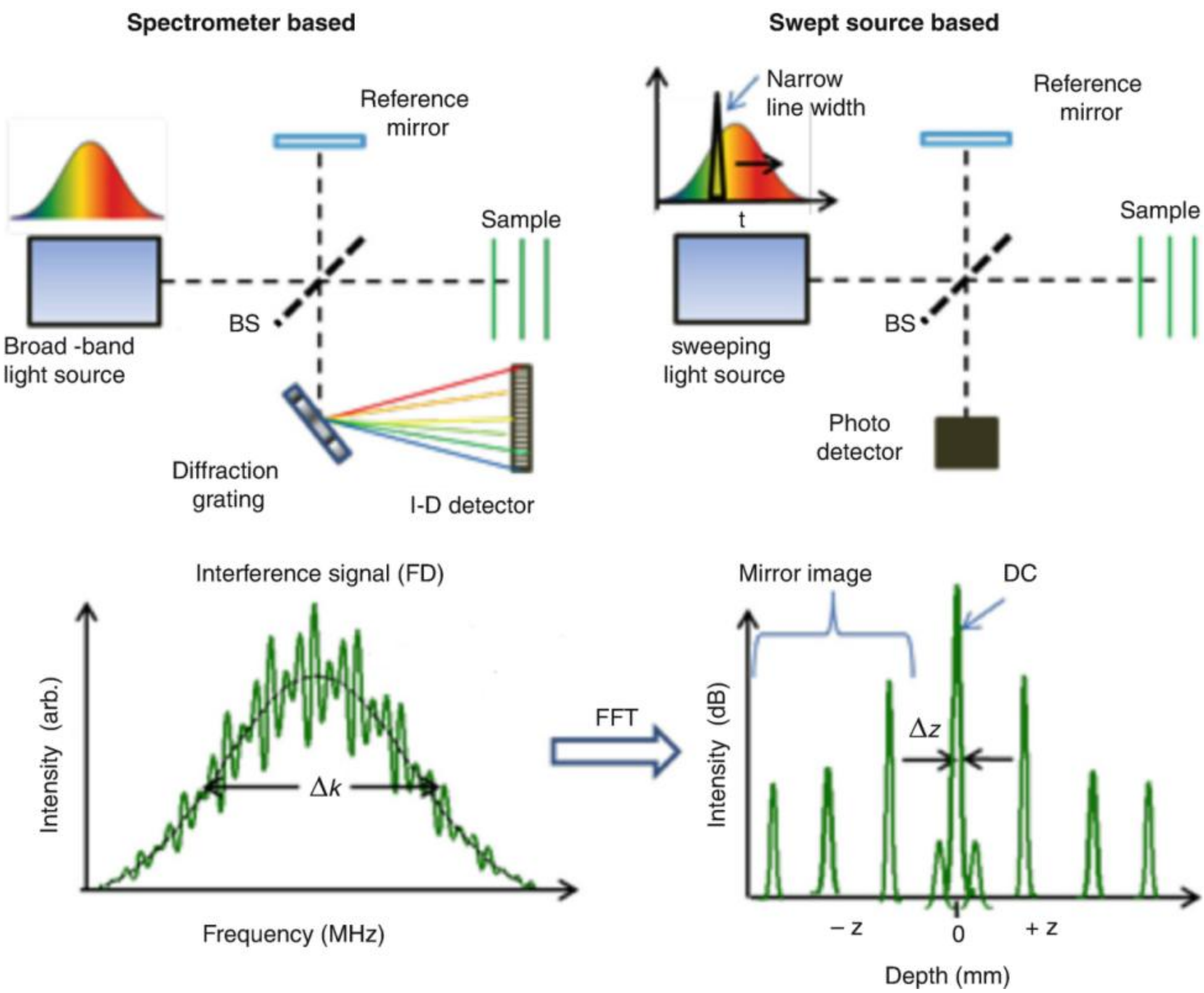

Figure 6: Optical setup of SD-OCT (Spectral domain OCT) in the upper left inset and SS-OCT (Swept source OCT) in the upper right inset. While SD-OCT uses a spectrometer for wavelength separation, SS-OCT features a light source which sweeps the wavelength in time. Both implementations record an interference spectrum which carries the depth in formation of the sample. FFT is used to transform the interference signal into the A – scan.

2. Discussion

Applications in medicine

OCT was first used in medical field as early as 1991 and since then it has been widely used in diagnosing and monitoring retinal diseases.2 Kim et al proposed an approach to allow compatibility between Td-OCT and Fd-OCT where he presented a 3D (three dimensional) dataset to scan a circular location of 3.4mm. The Fd-OCT along with the Td-OCT aids in planning and evaluation of eye surgeries.1, 2 In case of 3D imaging, longer wavelength are required for surgical preparation and evaluation of surgical outcome.

Brezinski ME et al in 1996 reported, in vitro studies of arterial lesions performed to investigate correlations of OCT and histology.5 The OCT imaging was done at a wavelength of 1300nm using super luminescent diode light source with an axial resolution of 20μm. The high contrast among tissues, high resolution and ability to penetrate heavily calcified tissue of the OCT, has made it a better modality for diagnosis of intracoronary diseases. Kume et al. concluded more than 90% sensitivity and specificity for detecting lipid plaque.6 The capability of OCT in imaging the arterial wall before and after percutaneous coronary intervention (PCI) makes it a superior imaging modality compared to angiography and intravascular ultrasound (IVUS).

Tearney GJ et al in 1997, conducted an in vivo study where OCT allowed a high speed visualization of tissues in living animal with an endoscope/catheter of diameter 1mm.7 Various studies conducted with OCT endoscope reveals that they can be used in the screening of Barrett's oesophagus, inflammatory bowel disease, intestinal polyps and for visualization of the pancreatico-biliary tract and gastric lesions.8 OCT has been used in dermatology for the diagnosis of melanoma, benign pigmented tumour, nonmelanoma skin cancer such as basal cell carcinoma (BCC) of skin and actinic keratosis.9 Other than tumours, OCT also detects inflammatory diseases such as psoriasis, Darier disease, bullous autoimmune disease and parasite infections such as scabies mites, larva migrans and hookworm infestation. As OCT enables fast detection and assessment of the infiltration depth of the tumour they are primarily indicated for the nonmelanoma skin cancers,especially BCC of skin.

Applications in dentistry

Dental caries and secondary caries

Dental caries occurs due to the demineralization of enamel and dentin by bacteria.10, 11 OCT aids in detection of dental caries by imaging the demineralization of the enamel. Demineralization causes an irregular arrangement of porosities in the enamel with an increase in size and number of defects that are filled with water and organic material. Demineralization causes a higher degree of backscattering and depolarization than healthy tissue. The cross polarization images provide excellent contrast between demineralized and healthy tooth structure. Fried D et al in 2002 conducted a study with sound and carious permanent teeth for imaging the interproximal caries, early root caries and secondary caries beneath composite restorations.12 In addition, to contrasting demineralization with healthy sound enamel, cross polarization OCT imaging has the benefit of identifying secondary caries formation beneath a restoration.10 The high refractive index of enamel (n=~1.63) and the dental materials such as resin composite (n=~1.5) causes a significant surface reflection which can confound the imaging. This imaging technique can also be used in pediatric dentistry for detection of the early dental caries in the primary teeth.

Defective restoration

Composite restorations are most popularly used these days due to the esthetic concern and improved strength.13 One of the major steps involved in the use of this restoration is acid etching, which enables resin penetration into the carious tooth. Improper acid etching causes irregular and nonhomogeneous resin penetration. Schneider H et al in 2017, on preselected extracted teeth such as premolars and molars found that during acid etching there is formation of carbon dioxide from the hydrochloric acid thus leading to bubble formation which hinders the resin penetration into the caries affected areas.14 In OCT images the carious lesion appears as a bright area. During resin penetration there is reduced brightness due to difference in the refractive indices. This phenomenon has aided in identifying improper resin penetration into the carious lesion. The study shows that increase in active application of etchant gel can improve the resin penetration into the carious region. This helps in avoiding failure in the composite restorations.

Other restorative materials were also examined using the OCT technique which aided in determining the marginal leakage which leads to secondary caries formation.13, 14 OCT imaging clearly identified the defective area where there was improper contact between the tooth and the restorative material. Since the images were digital, alteration of the contrast and magnification of these images to visualize minute details, were possible.

Oral precancer

OCT has been used in differentiating cancerous lesions from normal tissues.15-17 Jerjes W et al. conducted an in vitro study for examination of oral lesions by comparing the histological features with the OCT images. They acquired a results of 97% validation in assessing the basement membrane, 93.5% in identifying the epithelial layer and its changes and 94% in assessing the keratin layer. OCT was used in conditions where incisional or excisional biopsy could cause complications, thereby playing the role of optical biopsy in such situations.

An ex vivo study was conducted in 2013, Hamdoon Z et al. to assess the oral lesions by analyzing the epithelial thickness of different pathologies.10, 15 In normal keratinized mucosa, the keratin layer appears as a bright line on the upper most layer of the epithelium. The study was conducted in benign conditions such as frictional keratosis, mucocele, papillomas and in premalignant lesions such as leukoplakia, erythroplakia and erythroleukoplakia. In benign conditions there is keratosis leading to thickening of epithelium which results in high backscattering of light compared to the normal keratinized epithelium.16, 18, 19 In dysplasia and carcinoma in-situ there is hypo reflective keratin layer due to the disorganized tissue differentiation. OCT images showed the changes occurring and clear differentiation of the keratin layer, epithelial layer, basement membrane and lamina propria was possible.20 OCT has a specificity of 78% and sensitivity of 85% in the diagnosis of oral malignant disorders. Lee CK et al. conducted an in vivo study for diagnosis of oral submucous fibrosis using OCT.18 In case of oral submucous fibrosis OCT imaging shows decrease in the thickness of the epithelial layer.21 Additionally, homogenous contrast of the image is seen indicating the collagen rich layer which are effective indicators for the diagnosis of oral submucous fibrosis. The sensitivity and specificity is 100% in oral submucous fibrosis.

Gambino A et al. conducted an in vivo study on oral lichen planus .OCT images showed a hyper-reflective, nonhomogenous area indicating the lesion occurring within the epithelial layer.22

Oral cancer

Various diagnostic aids used in cancer detection such as the brush biopsy, raman spectroscopy are usually time consuming with poor resolution and difficulty in visualization of high grade carcinomas. Whereas, OCT has shown to have sensitivity of 82% and specificity of 93%.23-26 Usually SD-OCT has been used in imaging the premalignant and malignant lesions.27, 28 OCT images the changes occurring in the thickness of epithelial layer at the tumour resected margin. SS-OCT works on combination of the texture features and the machine algorithms.29 The accuracy of disease diagnosis depends on the algorithm processing time and their images provide rich information about the tumour. OCT also aids in the detection of boundaries of the tumour which would help the surgeon during the resection of the tumour. The drawback with OCT imaging is that they cannot detect the cellular aggregations and disorganization of cells. Studies are being conducted to improve their efficiency. Surgical management of oral cancer is often followed by radiotherapy, which can result in radiation induced ulceration of oral mucosa.30 They usually become clinically visible at radiotherapy doses of

30Gy whereas the epithelial damage begins at doses of 15 Gy. Muanza TM et al. in 2005 proved that these changes can be detected at the earliest stage with the help of OCT thus aiding in prompt treatment. Tsai MT et al in 2009 conducted studies to differentiate early stage SCC and well developed stage of SCC.31 SS-OCT images were used to analyze the staging of the cancer. Since the study sample was minimal the evaluation of sensitivity and specificity in detection is difficult.

Gingival and periodontal diseases

Gingival and periodontal disease are diagnosed usually by means of periodontal probing and through x-ray investigations.4, 32 Research on porcine jaws by Mota CC et al. in 2015 utilized Fd-OCT at a wavelength of 930 and 1315nm. OCT imaged the free gingival margin, attached gingiva and calculus deposits on the tooth surface without any contact or probing of gingival tissues. Higher resolution and depth of images were obtained at a wavelength of 1315nm compared to 930nm wavelength. In vivo study was conducted by Kakizaki S et al in 2018 at a wavelength of 1330nm making a comparison between the porcine gingiva and human gingiva.33 The epithelial and connective tissue thickness of the gingiva, biological width of the gingiva, gingival thickness and the alveolar bone were imaged using OCT. The healthy gingiva and the diseased conditions such as periodontal pockets and bone loss were detected by analyzing the changes in the refractive index.

Dental plaque and calculus

Acid producing bacteria from a dental biofilm (dental plaque) can demineralize enamel leading to incipient caries.34, 35 In 2012, Lenton P et al. studied the growth of bacterial colonies on hydroxyapatite discs. The hydroxyapatite disc had similar chemical composition as dental tooth enamel. Oral biofilms were grown on the hydroxyapatite disc following which they were imaged .The CP-OCT (Cross-polarization OCT) images showed uniform growth and height of the biofilm. The current diagnostic aids used in the detection of dental plaque and gingivitis are visual examination, plaque disclosing agents and by periodontal probing.4 These methods are usually confined to the tissue surface and can cause discomfort to the patient. Therefore several noninvasive techniques such as x-rays, magnetic resonance imaging, ultrasound imaging have been used in investigations. In vivo study conducted by Won J et al. showed OCT imaged soft and hard tissues. This included the dental plaque, in between the gingiva, the enamel of the facial and lingual/palatal sides of all teeth and the subgingival and root surface calculus deposits. Thus the study reveals the versatility and feasibility of the handheld OCT in assessing the dental plaque and gingiva.

3. Clinical Significance

Advantage of OCT

OCT has wide applications in medicine and dentistry as a diagnostic aid.1 Since they use visible light source for the detection, there is no side effects, which makes it a desirable noninvasive diagnostic modality. Diagnosis in real time makes it less time consuming. Site specificity makes it possible to image the exact diseased area.3 As OCT images are digital, it allows the clinician to improve the quality of the image and zoom in for proper visibility. They act as optical biopsy tool eliminating the concern of resection or excision of tissues.15, 24 The advantage with the design is that the hand held probe can access any site of the oral cavity.4 The availability of various types of OCT such as SD-OCT, SS-OCT, Fd-OCT for higher resolution and increased depth of the images are an added advantage.3 The working mechanism of OCT is simple, enabling the clinician to directly work with it without the necessity of specialized operators.4

Disadvantage of OCT

The drawbacks with OCT is that it analyses the tissue changes but cannot identify the causative organism responsible for an infection.25, 27 In detection of malignant and premalignant conditions, the OCT images usually provide information about the thickness of the layer which supports the diagnosis, whereas the increase in cellular aggregations, disorganization, irregular collagen or elastic fibers and disorganization of the basement membrane which are the indicative factors of the cancerous process are not detected. Therefore OCT acts as a supportive diagnostic tool rather in the diagnosis of cancerous conditions.32 Cancer staging cannot be done with OCT images. Nevertheless there are ongoing studies to improve OCT signals to analyze blood perfusions and tissue organization.24 Although the OCT technique is highly effective and user friendly, they are not commonly used due to high cost.

4. Conclusion

Optical coherence tomography, a noninvasive diagnostic tool is commonly used in the medical field and is gaining popularity in the dental field. The real time, digital and site specific images obtained makes it a less time consuming diagnostic procedure. Higher resolution of images and penetration depth into the tissues has improved its application widely in the dental field.

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