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OPTICAL COHERENCE TOMOGRAPHY FOR DENTAL AND ORAL SOFT TISSUES

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Abstract
Optical coherence tomography (OCT) is a non-invasive imaging technology that can provide high-resolution microscopic images for diagnostic purposes. The device measures the time delay and intensity of light that is backscattered and reflected from tissues, enabling tomographic imaging of their internal structures. OCT provides real-time imaging of tissues in situ circumventing the need for invasive techniques such as biopsy followed by histology or the need for X-rays. Its properties are used in many branches of medicine. Recently, the OCT visualization technique has been tested in different areas of dentistry. This research will provide the principles of diverse OCT methods and applications of this innovative modality in dentistry.

Keywords: Optical Coherence tomography; Dentistry; Caries diagnosis; Oral soft tissues

1. Introduction

Tomographic imaging is among the different tools that have been increasingly used over the past two decades to improve clinical examination of soft and hard oral tissues. Optical coherence tomography (OCT) is a highly innovative tool that is among the very rapidly evolving optical imaging methods. In OCT, the light waves that are reflected back from the tissue are analyzed along with their delay, which provides data on the depth at which the reflection occurred. The technique produces high-resolution cross-sectional images of internal microstructures of both biological samples and other materials.[1] In general, light in the near-infrared (NIR) spectral range, which has the ability to penetrate several hundred micrometers into the tissue, is used for OCT.

Since its introduction the early 1990s, various OCT systems operating on different principles have evolved from an experimental imaging method, into a valuable tool that is used in various areas of health sciences including diagnostic medicine, notably in ophthalmology, cardiology, dermatology, dentistry and industrial non-destructive testing.[2-5]

OCT has a much higher resolution (around 20–5 μm) compared to other medical imaging modalities such as ultrasound (US) or magnetic resonance imaging (MRI).[6] Since its introduction as an imaging modality nearly 30 years ago, OCT has evolved into ultrahigh-resolution system that uses broad-bandwidth laser technology to obtain an axial resolution of 1 μm and transverse resolution of 3 μm, making sub-surface imaging feasible.[7] The maximum imaging depth in most tissues is around 2–3 mm. This limitation is primarily due to optical attenuation and scattering. The non-invasive nature of OCT, its penetration depth of 1 to 1.5 mm, high resolution, real-time image viewing, and the ability to generate cross-sectional and 3D tomographic images provide excellent conditions for *in vivo* screening and diagnosis of oral tissues.[8] This research discusses the principles and basics of OCT, including a description of OCT systems, the use of OCT for dental and oral soft tissues, and its advantages and limitations.

2. Principles of OCT

The working principles of OCT are similar to those of US B-mode imaging. Both technologies use energy waves that are backscattered after reflection from different layers of tissue. However, OCT uses light instead of acoustic waves.[9] US determines the echo of the imaged tissue while OCT measures the reflected light waves.

The image generated with OCT is a two-dimensional (2D) representation of light that is reflected from the tissue sample. Superimposition of the images generated in real-time from tissue sections can be superimposed to create a 3D image of the target tissue. This allows *in vivo* non-invasive visualization of structures including the margins of any lesions, their depth and thickness, along with histopathological appearance.

2.1 OCT Applications

OCT imaging may be carried out using handheld probes, endoscopes, catheters, laparoscopes and needles for the *in vivo* examination of specific body parts. Furthermore, Doppler OCT,[10] polarization-sensitive OCT,[11] and spectroscopic OCT[12] enable functional imaging.

2.2 OCT Basics

When light passes through different structures, it generally travels faster in materials with a low refractive index and slows down when the material has a high refractive index. Moreover, a sharp change of refraction of the light wave may lead to a reflection of the wave towards the outside or inside. The extent of reflection is proportional to the extent of refraction, the angle at which the light travels, and its polarization. If the change in refraction between the different materials is slow, the reflection will be minimal.[13] Some of the parameters that can define the performance of OCT systems include: axial resolution & penetration depth, lateral resolution & field of view (FOV), as well as A-Scan rate & sensitivity. OCT is an interferometric measurement method; therefore, the axial resolution is defined by the light source.[6] The penetration depth of OCT has been identified to be <3 mm and is therefore highly limited for some applications. Dental structures and restorations can be imaged up to a depth of 2–2.5 mm. This is attributed to the translucency and specific refractive indices of dental hard tissues and restoration materials when NIR radiation is provided at 1325 nm.[14]

Axial resolution & Penetration depth

The OCT technology can be classified into three major types:

1. A-scan type uses a single light beam that can be reflected and enables the determination of the depth of the structure (single depth profile).[15] The OCT light probe is used to scan the surface of the structure and the reflected A scans are collected and used to generate 2D and 3D images computationally.
2. The B-scan type provides a 2D view of the observed structure in its cross-section by laterally scanning the OCT beam. The 2D image can be obtained by collecting sequential A-scans and combining multiple A-scan data on the x and z axes. This type of image is also called a "longitudinal" image.[15] The speed with which a B-scan is collected depends on the speed of the A-Scan or the Line rate.
3. The C-scan type provides an “en face” image with a 2D cross-sectional view on the x- and y-axes. 3D reconstruction of the structure is feasible from a series of B-scan and C-scan images.[1,16]

The success of the OCT imaging modalities depends on its resolution, imaging depth, sensitivity and speed. The numerical aperture of an optical system is a dimensionless number that characterizes the range of angles at which the system can accept or emit light. Resolution of the image relies on the central wavelength of the light source, $\lambda 0$, and the numerical aperture of the objective lens**.** The axial

resolution and range of the OCT depends on the source of light and characteristics of the detector.[6] Thus, the axial resolution (Δz) is determined by the coherence length of the broadband light source, while transverse resolution (Δx) relies on the size of the focal spot.[17] The central wavelength is inversely related to the axial resolution. Therefore, an increase in the spectral bandwidth or decrease in the central wavelength can improve the axial resolution of OCT.
The depth of imaging is a key factor for many applications that use OCT. A close relationship exists between axial resolution and imaging depth, whereby one improves at the cost of the other. Other factors associated with axial resolution include the central wavelength, the bandwidth of the optical source and the refractive index of the sample. In biological tissues exposed to NIR radiation, the central wavelength determines the maximum depth of penetration due to the scattering and absorption properties of the tissues.[1,5,6] Optical scattering occurs due to the varying refractive indices in the different tissue components. Therefore, materials with comparable refractive index will have similar OCT images.[1,5]

Lateral (transverse) resolution and field of view (FOV)
The lateral resolution for OCT imaging is dependent on the scanning lens on the imaging probe and is also determined by the size of the spot that the probe focuses on. The length and width of the FOV depends on the characteristics of the scan lens. Lateral resolution and FOV are coupled parameters and are inversely related to each other.

A-Scan rate and sensitivity are optical performance parameters that are dependent on each other; therefore, a higher A-Scan rate is associated with lower sensitivity and vice versa. The depth of imaging and axial resolution are also performance parameters that are dependent on each other. The maximum depth of imaging in OCT is highly dependent on the design of the base unit of the OCT. The optical absorption and scattering properties of the sample often limit the depth to which the light probe can penetrate.

2.3 OCT Systems
Over the past decade, many OCT systems designed for novel biomedical research applications have been reported. Although OCT is based on a Michelson interferometer, the method can be classified into time-domain OCT (TD-OCT) and Fourier-domain OCT (FD-OCT) according to the detection method of the interference signal. Conventional TD-OCT is a 2D imaging method based on low-coherence interferometry that works with a low-coherence-length broadband light source. In TD-OCT imaging, light from a diode source with low-coherence-length is conveyed to the interferometer via an optical probe. The beam is split into two arms by a fiber optic beam splitter. One part of the light (one interferometer arm) is directed to the test substance and the other part is sent to a reference arm of known length. The light that is reflected back from each arm is combined; these waves can interfere only if the optical path lengths (OPL) match. In this way, the interfering beam is collected with the help of a detector, the waves that are reflected back are analyzed and any delay in their reflectance is measured to reveal the depth at which the reflection occurred. Echo time delays of light are collected as a function of time by moving the reference mirror. The interferometric signal is recorded by using a photo detector.[6,] Time-domain OCT (TD-OCT) is the first and simplest OCT device, which slowly measures the time taken for light to reflect, allowing for approximately 400 vertical scans to be recorded per second.
The use of FD techniques can improve image resolution, imaging speed and image quality.[18] The system offers real-time imaging and 3D volume rendering without any artifacts resulting from the movement of the samples. This is particularly relevant when *in vivo* imaging for living biological samples is being carried out. Unlike TD-OCT in which the reflectance of light is detected sequentially by the stepwise movement of a reference mirror, in FD-OCT the reflected light arrives at the same time from all axial depths. Thus, FD-OCT uses spectral information to generate A-scans without any need for the physical scanning of the OPL.[4] Images taken in the time domain carries out six radial scans at 30-degree intervals to acquire approximately 400 A-type scans per second. With this method,

there is a risk of missing any pathology that may affect the areas between scans. On the other hand, Fourier/Spectral domain technology continuously performs approximately 20,000-40,000 scans per second, increasing the accuracy, improving image resolution and speed. This technology also reduces the risk of artifacts that can occur when certain parts of the tissue remain un-scanned and consequently mitigates the possibility of missing a pathology.

The FD-OCT system can vary depending on the system that is used as a light source: Spectral domain optical coherence tomography (SD-OCT) and Swept-source optical OCT (SS-OCT). The common items that are used in both methods are fixed (stationary) reference mirrors, as opposed to TD-OCT in which the reference mirror moves. SD-OCT includes a spectrometer similar to TD-OCT; however, the algorithms used with SD-OCT differ from those of TD-OCT.[19] The delay patterns relative to each other are analyzed using Fourier formulae.[1] The broadband light source used in the SD-OCT system is identical to the TD-OCT. Unlike TD-OCT, however, the OPL in SD-OCT is based on different wavelengths (usually 840 nm). The spectrometer measures the interference pattern as a function of wavelength. The depth of the image that can be obtained with SD-OCT relies on the central wavelength of the light source and the resolution of the spectrometer.

SS-OCT utilizes a narrowband tunable laser light (wavelength-swept laser) and a photodetector instead of a spectrometer.[1,5,20] SS-OCT is known to have longer wavelength compared to SD-OCT, allowing a deeper penetration.[21] SS-OCT uses a laser source that sequentially emits laser light at different wavelengths at ultra-high speed. It provides improved image resolution and 3-3D image rendering with real-time imaging.[1,17]

Additionally, full-field OCT (FF-OCT) with a tunable laser source, uses an incoherent light source and field array camera. It is a rapid volumetric imaging technology that effectively avoids motion artifacts during imaging as it uses a fast camera. Submicrometer spatial resolution enables imaging of small structures in milliseconds and over a large field of view. FF-OCT has potential applications in non-invasive medical diagnosis and imaging of dynamic biological tissues such as cancer cells *in vivo* and can also perform non-destructive testing and high-precision measurements of materials (e.g. pearls).[17] (Figure 1)

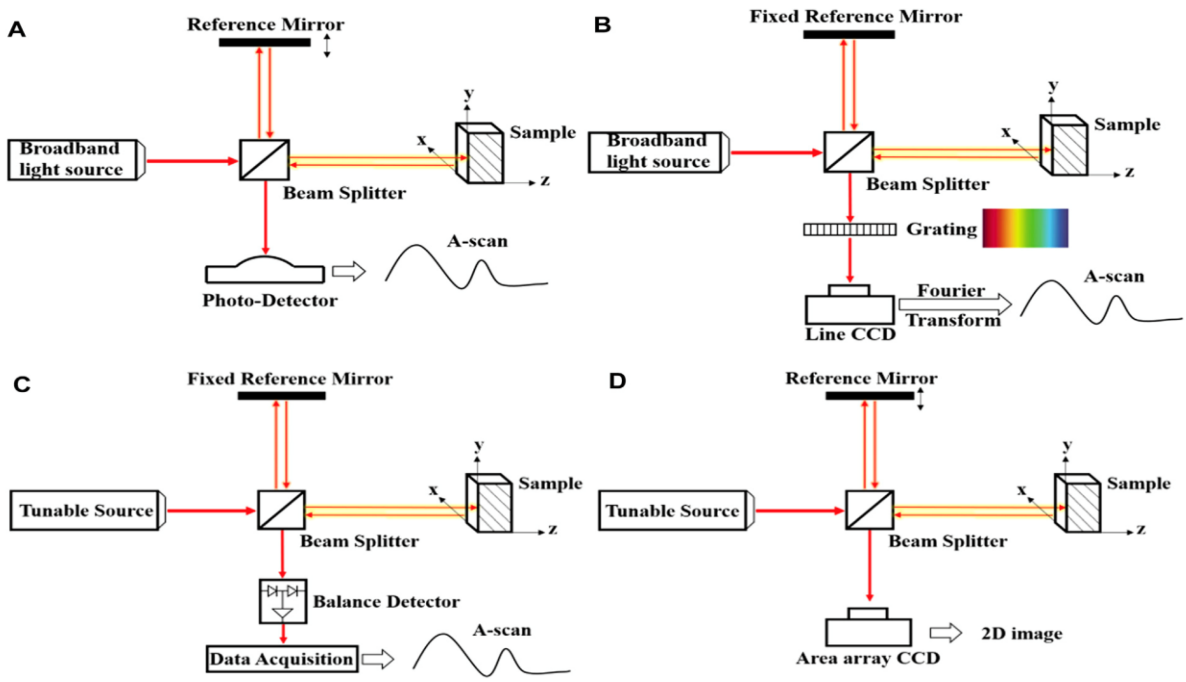

Figure 1. *Schematic diagrams showing a- Time-domain OCT (TD-OCT), b- Spectral domain optical coherence tomography (SD-OCT), d- Swept-source optical OCT (SS-OCT), and d- Full-field OCT (FF-OCT) (reprinted from Reference[17])*

Attempts to use OCT in dentistry were first made in 1998 in a collaboration between researchers at the Medical Technology Laboratory in Livermore, California, and researchers at the University of Connecticut. Regarding the use of OCT in dentistry, there are challenges related to the wide availability of the equipment and the limited penetration depth of OCT rays. In dentistry, lesions often reach deeper into the tooth tissue, which may require numerous scans to fully illustrate the extent of the problem. However, recent studies have made progress in overcoming this limitation by using intraoral probes.

Wavelengths below 1000 nm are preferred for dental imaging because they provide efficient imaging, as the scattering properties of light are similar in size to tissue particles. Additionally, the choice of wavelength can be adjusted based on the type of tissue being tested, as hydrated tissues behave differently from hard tissues with lower water content. Dental OCT is a promising technology for dental diagnosis but faces several technical and methodological challenges. One major problem is that the published studies lack a "gold standard" methodology, making it difficult to compare their results. Another challenge is the variability in the structure of individual teeth and the existence of dental fillings or prosthetic materials with different light absorption and reflection properties.

3. Applications of Dental OCT

In 1998 Colston et al. published pioneering work on the use of OCT in dentistry.[13] OCT, as a non-invasive imaging technique, has since shown significant potential as a valuable tool for studying dental microstructures and intraoral soft tissues (Figure 2).

OCT utilizes NIR light in the range of 700–1500 nm. These longer wavelengths of light have the advantage of penetrating dental tissues more deeply because they scatter less compared to visible light. One of the key advantages of OCT is its superior spatial resolution. This means that OCT images can reveal dental issues at better resolution and therefore allow the detection of damage or subtle morphological changes at an earlier stage than conventional radiographs.[22]

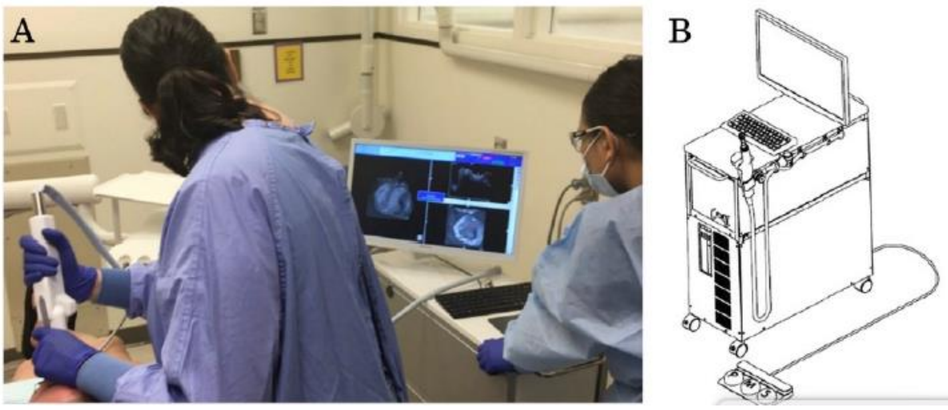

Figure 2. *Clinical imaging using a prototype OCT system. An attached intraoral imaging probe is used to generate images that are available in real-time on a computer screen (A). A schematic overview of the OCT system (B). (reprinted from Reference[23])*

Dental OCT detects structural changes of hard and soft dental tissues *in vivo* at both qualitative and quantitative levels and thus has a wide range of applications in dentistry. Some of these applications are as follows:

a) Dental pathologies: OCT can be used to diagnose demineralized lesions in teeth. It provides detailed data on the structure and integrity of dental hard tissues.[5,18]
b) Treatments and Endodontic Obturations: OCT can help evaluate treatment outcomes and the quality of root canal fillings.[22]
c) Diagnosis of Oral Cancer and lesions in the oral mucosa: OCT is valuable for the early detection and monitoring of oral cancer and mucosal lesions. It can provide high-resolution images that can help evaluate changes at the tissue level.[3,5,24]

d) Diagnosis of Periodontal Diseases: OCT can be used to evaluate the state of the periodontal tissues, and aid in the diagnosis and monitoring of periodontal diseases.[5,25]
e) Non-Destructive Testing of Dental Materials: OCT can be used for non-destructive testing of dental materials, such as evaluating the quality of dental restorations and prosthetic devices.[26]

The design of OCT systems is not flexible enough to easily perform intraoral, full-mouth examinations, so the scan area is generally limited to the buccal surface of the anterior teeth. There is still a need for handheld or endoscopic OCT probes that can be used in the oral cavity in the clinics. Several groups have reported the development of specialized OCT systems and intraoral probes.[25-28]

3.1 OCT for Dental Hard Tissues

The mineral content of the enamel defines its optical properties in the visible and NIR range.[29] OCT has increasingly been reported to be used in dentistry for the diagnosis of caries, assessment of erosion and cracks and detection of defects of dental restorations using different OCT systems.[27,30,31] Sound enamel appears to be nearly transparent (high translucency) in the OCT wavelength range, while dentin allows some transmission of light. The dentin and enamel can be easily distinguished from each other since the dentin-enamel junction (DEJ) appears as a dark border. Enamel with a low mineral content and dentin are displayed as bright regions due to the formation of micropores that can increase the backscattering of the OCT signal. In cavitated caries in the interproximal or occlusal occult region, the upper border of the cavity reflects the signal showing a distinct bright border on the SS-OCT image.[18] (Figure 3)

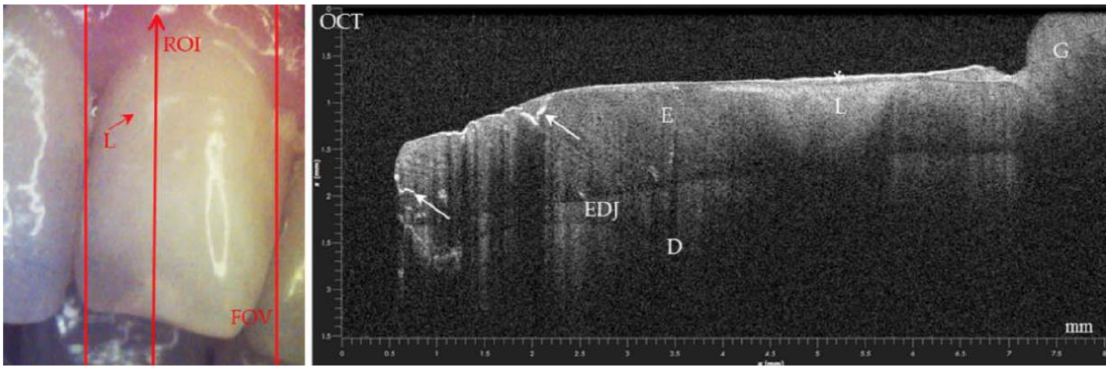

Figure 3. *In vivo image of a human incisor. A caries lesion (L) can be visualized on an air-dried enamel surface (shown with a red arrow). In the SD-OCT B-scan, this lesion has the appearance of a brightly shaded area without any cavitation. In comparison with visual assessment, the OCT signal shows an enlarged lesion with the involvement of dentin (D) and the presence of a mineral-rich and porous surface layer (*). Shadowing is seen (white arrows) because of defects, or cracks in the enamel (E). G: gingiva, EDJ: enamel-dentin junction. SD-OCT: spectral domain OCT. (reprinted from Reference [42])*

It has been proven that cross-sectional images on OCT can detect carious lesions, cracks, and dental restoration defects with a higher sensitivity and specificity compared to the visual inspection method.[32] Detection of occlusal caries by considering the three-dimensional spread of caries is a highly desirable feature for potential clinical applications. For this purpose, Luong et al.[33] investigated the use of dynamic slicing of 3D OCT data as a chairside method for caries diagnosis in an in vitro study. The authors concluded that OCT may allow the clinician to estimate the DEJ-related depth of the lesion to decide on the need for further intervention.

Previous studies have reported that OCT has the potential to detect early carious lesions, and the maximum extent of a lesion can be determined.[34] Various researchers have attempted to develop a smaller intraoral probe that could facilitate access to each intraoral region.

Schneider et al.[27] modified a commercial SD-OCT to investigate proximal carious lesions, indicating the suitability of OCT as a complementary diagnostic method. However, SD-OCT is limited by its low signal-to-noise ratio at distances deeper than 1 mm, reducing imaging quality in deeper layers such as dentin. This problem is often relevant to oral tissues, where the surface topology of the scan tissue is uneven.[35]

3.2 OCT for Oral Soft Tissues

The majority of studies on the application of OCT in the oral cavity have focused on changes in the mineral content of the tooth. However, recent studies have demonstrated the potential of OCT in the detection of oral mucosal changes associated with cancer therapy-induced mucositis and inflammatory or immune diseases, including lichen planus, pemphigus, pemphigoid, lupus erythematosus, or vascular lesions.[1,28,36] Gentile et al.[16] reported OCT findings of healthy oral mucosa and different types of oral lesions, including benign, premalignant, and malignant lesions in a systematic review. Several studies have attempted to determine reference values for the mean epithelial thickness using OCT.[37]

Oral applications of optical systems have been adapted from other medical branches. The challenge is the need for a handheld, small and lightweight probe for clinical oral screening. Li et al.[38] proposed to use a MEMS-based scanner to achieve maxillofacial tissue imaging. However, the imaging probe was also limited to a small FOV and thus had low applicability in clinical settings.

Recently, Walther J. et al.[28] developed a smallest known probe for use in the oral cavity which is integrated with a Fourier domain OCT system based on a swept-source (SS) laser. The feasibility of use of the probe was shown in patients diagnosed with oral lichen planus.[39] (Figure 4)

Recent advances have made swept source OCT (SS-OCT) technology a more suitable tool for imaging. The main benefits of these improvements are better signal-to-noise ratio over longer depth range, negligible sensitivity loss and faster imaging speed. However, four main challenges have been identified in the adaptation of SS-OC as a diagnostic tool in dental practice: validity for soft tissues only, real time guidance, the field of view and accessibility.[20]

Tsai et al.[36] demonstrated the potential of intraoral OCTA (functional angiography) to image the vascular system of the oral mucosa. However, the implementation of the OCTA intraoral probe is still a challenging issue. (Figure 5)

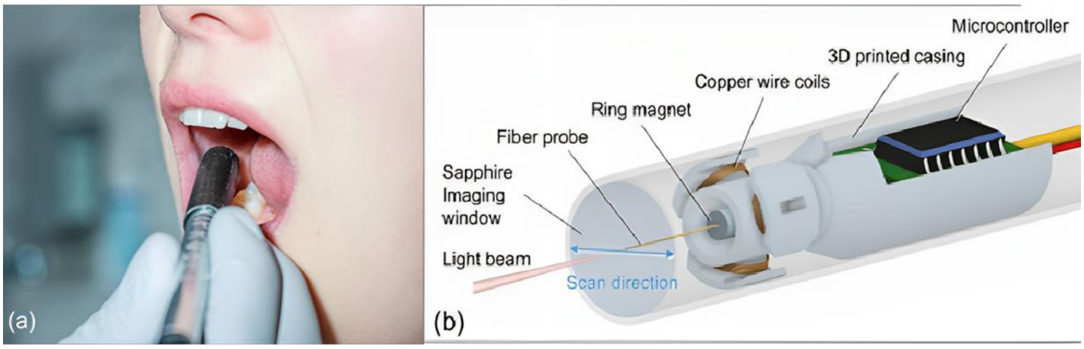

Figure 4. *(a) In vivo application of a handheld miniprobe in the human oral cavity. (b) Internal design of the miniprobe. (reprinted from Reference [28])*

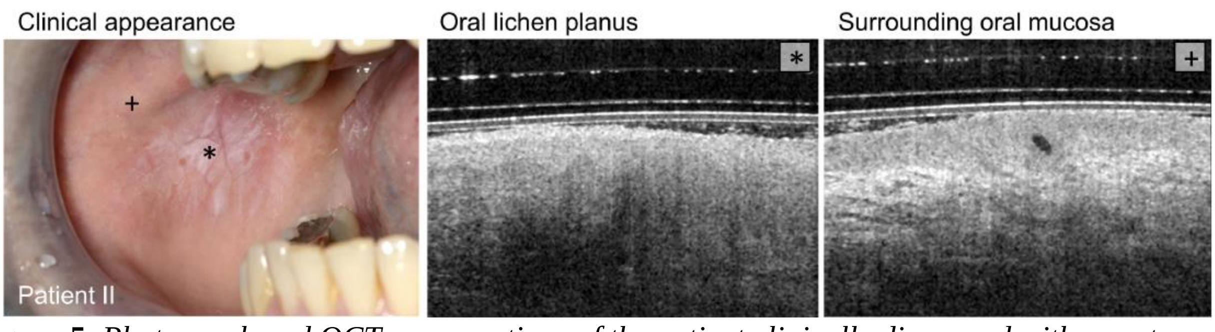

Figure 5. *Photograph and OCT cross sections of the patient clinically diagnosed with symptomatic oral lichen planus in the buccal mucosa (reprinted from [28]).*

3.3 OCT for Periodontal Diseases

Won and colleagues[40] developed a handheld spectral domain OCT (SD-OCT) that allows 2D imaging of molars and surrounding gingivae. These authors demonstrated specific optical properties associated with gingivitis, such as lower signal strength, compared to healthy gingival tissue. Putra et al.[41] reviewed several different studies that were designed to visualize and quantify the morphology of periodontal tissue using OCT. According to these studies, plaque and calculus deposition can be detected using OCT.[16] However, a well-designed case-control clinical trial designed to investigate the clinical feasibility of OCT for imaging the subgingival space has not yet been reported. Improvements in the depth of imaging and development of an intraoral sensor may establish OCT as a technique suitable for periodontal applications.[34]

3.4 OCT for Non-Destructive Testing of Dental Materials

OCT can be used for the study of dental materials and for monitoring the quality of sintering processes of ceramic crowns.[26] Unlike conventional biopsy and histopathology, OCT can also provide "optical biopsy" without requiring any excision or processing of specimens.[3,5,24]

Certain factors that affect the performance of OCT in dental applications include axial resolution, imaging speed, dental optical probe design, penetration depth, wavelength choice, time required for data acquisition, and scanning range. Insufficient scanning range may prevent the clinician from scanning the entire lesion and direct attention rapidly to the problematic area.[5,17] The design of a optical scanning probe that can be used to scan different regions of the oral cavity for the visualization of different types of oral mucosa is therefore necessary.

The weight of the probe is one major issue and has the potential to cause movement artifacts during OCT measurements. For example, scanning the tongue can be a challenge due to involuntary movement. An OCT system that can scan a larger number of frames at higher speed is required to reduce motion artifacts.

The oral cavity is a saliva-filled environment; moreover, the mucosal tissue has a curved structure, making the scanning the oral cavity difficult. For this reason, it is appropriate to use a replaceable protective cover on the output end of the probe before application. The time required to acquire the appropriate amount of data is another key factor in the application of OCT. Although the OCT can acquire images in seconds, the image will be of a lower quality due to insufficient processing time. Users should therefore try to find a balance between image quality and acquisition time. The efficiency of OCT for dental diagnostics can be maximized if the wavelengths of light that is used to generate the image is tailored to the type of tissue tested. Thus, imaging of the periodontal and tooth tissue should be carried out at different wavelengths.[1]

4. Conclusion

Due to considerable advancement in both optical specifications and equipment capabilities, OCT has shown great potential in both research and in the clinics. It can be easily applied to patients who have developmental disabilities as it entails minimal levels of pain and discomfort, and also does not use any ionizing radiation. Despite these advantages, OCT has a very limited depth of penetration (<3 mm), because of which it cannot fully replace radiography. To circumvent the low penetration, light at a different wavelength may need to be tested to image the targeted oral tissue. The other primary disadvantage is the design of current OCT systems which limits their utility in intraoral examinations. However, further advances in dentistry may elevate OCT from a tool that is used for experimental purposes to an imaging modality that can be used in routine dental practice.

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