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Review article

Early caries detection using optical coherence tomography: a review of the literature

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ABSTRACT

Early detection of carious lesions increases the possibility of treatment without the need for surgical intervention. Optical coherence tomography (OCT) is an emerging three-dimensional imaging technique that has been successfully used in other medical fields, such as ophthalmology for optical biopsy, and is a prospective candidate for early caries detection. The technique is based on low coherence interferometry and is advantageous in that it is non-invasive, does not use ionizing radiation, and can render three-dimensional images. A brief history of the development of this technique and its principles are discussed in this paper. There have been numerous studies on caries detection, which were mostly *in vitro* or *ex vivo* experiments. Through these studies, the feasibility of OCT for caries detection was confirmed. However, further research should be performed, including *in vivo* studies of OCT applications, in order to prove the clinical usefulness of this technique. In addition, some technological problems must be resolved in the near future to allow for the use of OCT in everyday practice. (J Kor Acad Cons Dent 2011;36(5):367-376.)

Key words: Dental caries; Diagnosis; Optical coherence tomography (OCT)

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INTRODUCTION

Dental caries is a chronic infectious disease that is one of the most common problems encountered in clinical dentistry that results in the localized dissolution and destruction of dental calcified tissue.[1,2] An understanding of the dental caries process and strategies to manage this disease have advanced through numerous studies.[3] Modern evidence reveals that there is a continuum of disease states ranging from subclinical, subsurface changes to more advanced, clinically detectable subsurface caries, to stages of more advanced lesions with microscopic and later macroscopic cavitations of the enamel and significant dentin involvement.[4,5]

If carious lesions are detected early enough, they can be arrested or reversed through nonsurgical therapies.[6] The effectiveness of this nonsurgical therapy is contingent on detecting the lesion in the outer enamel and requires imaging modalities that can safely and accurately monitor the success of such treatment.[7] Visual examination and probing with a sharp explorer is a rather subjective method depending on the examiner's experience and training.[8]

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Clinical radiology is another widely used method that has poor sensitivity for detecting early carious lesions since the lesions are too shallow and do not provide enough contrast.[9] Furthermore, clinicians need a diagnostic tool that employs nonionizing radiation to aid in caries management and diagnosis and reliably tracks the course of caries lesions over an extended time period in order to determine whether the lesion is active and expanding and requires intervention or if the lesion has been arrested.[10]

Efforts have been made to develop an imaging modality for the accurate detection of early caries. Quantitative laser fluorescence (QLF) and DIAGNOdent (KaVo, Biberach, Germany) are examples, and these tools have been reviewed in recent papers.[10,11] New fields of research have resulted from studies like these in conjunction with the rapid technological growth that has occurred over the past two decades. In addition to ensuring accuracy, every attempt is made to eliminate and substitute invasive, hazardous, and contact methods in favor of other techniques that provide similar results without having a negative impact on the examined object.[12] Optical coherence tomography (OCT) is another candidate for early caries detection in addition to the advancement of medical optics.

OCT is an emerging nondestructive three-dimensional imaging technique that is capable of producing high-resolution cross-sectional images through inhomogeneous samples such as biological tissue.[13] Basically, OCT is analogous to ultrasound B mode imaging except that it uses light instead of sound.[14] It was originally used in ophthalmology, and as a result, more than 50% of the estimated 4,000 OCT publications dated up to 2008 have been published in ophthalmic followed by endoscopic applications.[14]

The optical configuration of OCT is that of a low coherence (white light) interferometer (LCI), similar to those used in industrial metrology for measuring the thickness of thin films and the refractive index.[15-17] The potential use of LCI for three-dimensional imaging in biological tissue was first realized in 1991.[18] Since that original work, a large number of papers have been published regarding every aspect of OCT.[13] These are available in a variety of publications covering general physics, optics, materials science, and a wide array of specific medical areas. Therefore, it is becoming increasingly difficult to keep abreast of the current developments and applications of OCT. It is even more difficult to form a comprehensive review of the subject.

To limit the study of OCT to the field of dentistry, the investigation of porcine dental tissue by Colston *et al*. in 1998 was the first *in vitro* imaging of OCT.[19] Until now, several studies have been completed to investigate the diagnostic utility of *in vivo* OCT in detecting and diagnosing oral pre-malignancies and actual malignancies.[20-26] Two studies have used OCT in determining tooth movement.[27,28] Many trials in dentistry have been mainly restricted to detecting dental caries.

In this article, a brief history of the development of and a basic introduction to OCT theory will be reviewed according to the scheme. The applications of OCT in caries detection will also be discussed in detail according to the research groups.

BRIEF HISTORY OF OCT DEVELOPMENT

The early use of optical interferometry in the biomedical field, which was related to the measurement of the refractive index of animal eye lenses, was described by Simonsohn *et al*. in 1969.[29] Human *in vivo* retinal resolving power measurements were reported by Rassow *et al*. in 1978.[30] In the early 1980s, Fercher *et al*. reported on an ophthalmologic length measurement experiment.[31] This study was the first to reveal that laser interferometry could be used for *in vivo* distance measurements of the human eye. Hence, several studies have reported the use of low-time coherence light for interferometric eye length measurements.[32-35] Low coherence interferometry enables ocular biometry without making contact with the eye, has significantly higher resolution compared to ultrasound methods, and has high repeatability.[36-39]

After some success in biometry, recording structural data in a similar fashion to the ultrasound B-scan technique was the next investigative step. A 2D *in vivo* depiction of a human eye fundus contour along a horizontal meridian was presented by Fercher in 1990.[40] Huang *et al*. combined transverse scanning

with a fiber optic optical coherence domain reflectometry (OCDR) system to produce the first OCT cross-sectional images of biological microstructure in 1991.[18] In 1993, the first *in vivo* OCT images were created by groups in Vienna and Boston.[41,42]

The first commercial OCT instruments, developed by Humphrey Instruments, were based on the work of the group in Boston. Further developments including endoscopic OCT paved the way for new fields such as cardiovascular OCT and gastrointestinal OCT.[43-45] The introduction of ultrahigh-resolution OCT and spectral domain OCT has dramatically increased the diagnostic potential of OCT.[46,47] In the meantime, approximately 17 OCT equipment manufacturers share a current market of about $200 million with a growth rate of 34% p.a. This trend is expected to continue for the next several years, with revenues topping $800 million by 2012.[48]

PRINCIPLES OF OCT

The principles discussed in this section will be limited to the types of OCT used in caries research.

a. Time-domain OCT (TdOCT)

OCT is an interferometric technique that relies on interference between a split and a later re-combined broadband optical field. The general scheme of an interferometric OCT setup is presented in Figure 1. Here, the amplitude of electromagnetic radiation in the Michelson interferometer is divided into two parts by a beam splitter. The split field travels in a reference path, reflecting from a reference mirror, and also in a sample path where it is reflected from multiple layers within a sample. The light wave returning from the object is a superposition of waves arriving with different delays, $\tau = \Delta z/c$. Due to the broadband nature of the light, interference between the optical fields is only observed when the reference and sample arm optical path lengths are matched to within the coherence length of the light. Therefore, the depth (axial) resolution of an OCT system is determined by the temporal coherence of the light source. Sharp refractive index variations between layers in the sample medium manifest themselves as corresponding intensity peaks in the interference pattern. A time domain interference pattern can be

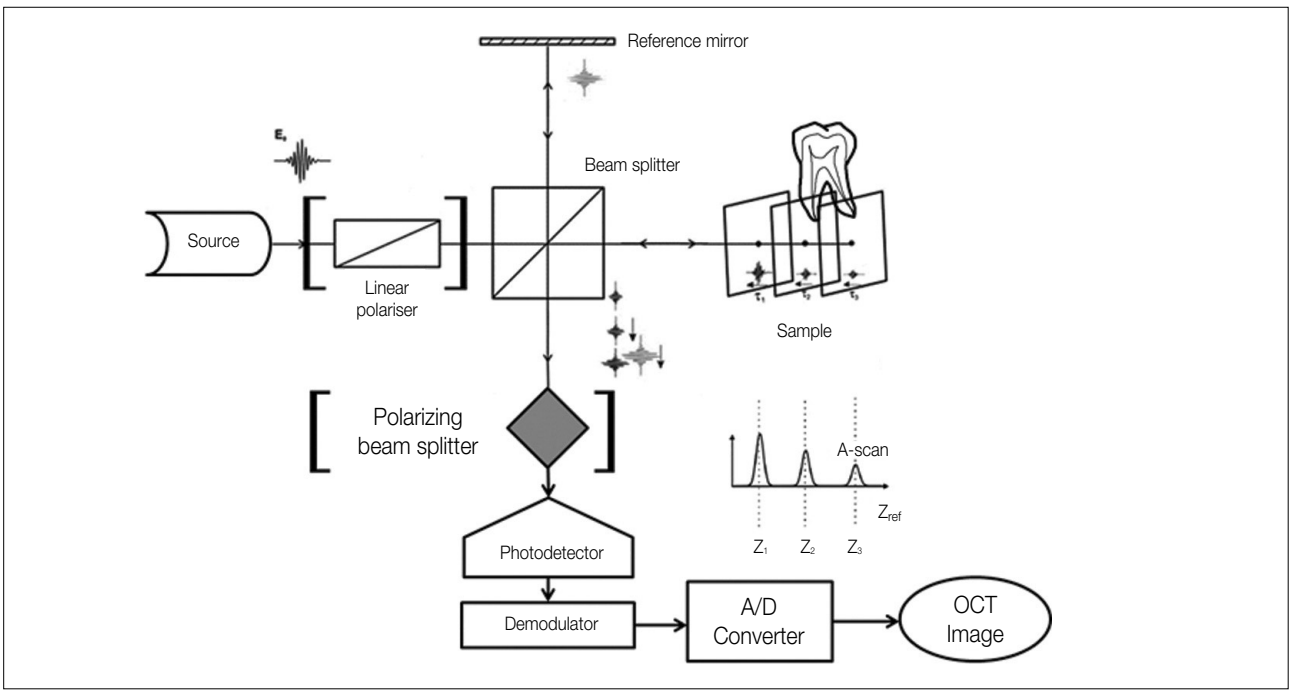

Figure 1. The general scheme of an interferometric OCT setup. The linear polarizer and the polarizing beam splitter in parenthesis are equipped in PS-OCT. OCT, optical coherence tomography; PS-OCT, polarization-sensitive OCT. This illustration was partly modified with permission from the original one of Wojkowski[12] by courtesy of Optical Society.

obtained by translating the reference mirror to change the reference path length and match multiple optical paths due to layer reflections within the sample.

b. Fourier-domain OCT (FdOCT)

In the original study from 1991, TdOCT enabled researchers to obtain cross-sectional images of relatively low quality.[49] This was mainly due to physical limitations influencing the measurement time, sensitivity, and resolution of the TdOCT method. An alternative solution to time-domain detection is FdOCT.[50] Here, information on the location of reflective points along the sampling beam is coded in the frequency of the oscillatory signal modulating an original spectrum of the light source. In such an arrangement, the reference optical path length remains fixed and component frequencies of the OCT output are detected using a spectrometer. Subsequent scientific studies have shown that the change from time-domain to Fourier-domain detection enables one to increase the acquisition rate over 100 times. An additional advantage of this method is that it is possible to separate dependence on axial resolution (defined as the resolving power of the imaging system in the direction parallel to the probing light beam) from imaging speed.[51,52] For the same reasons, it has been very difficult to create an *in vivo* image of the entire three-dimensional structure of the examined object by TdOCT. Thanks to these features, it is now possible to reconstruct a 3D structure with axial resolution on a micrometer scale from *in vivo* measurements.[53,54]

c. Polarization-sensitive OCT (PS-OCT)

The basic structures of PS-OCT are similar to those of the aforementioned TdOCT. However, dental hard tissue has a special characteristic called "birefringence." Birefringence, or double refraction, is the decomposition of a ray of light into two rays when it passes through certain anisotropic materials. In contrast to sound enamel that is highly transparent, sound dentin and carious enamel strongly scatter light in the near-IR and are also highly birefringent, which can interfere with polarization resolved imaging.[55] The optical properties of tooth enamel and dentin change markedly as a result of demineralization during the caries process. Therefore, caries detection schemes that exploit such changes hold considerable promise for the early detection and characterization of caries lesions.[56,57]

Prior to 1992, the emphasis in OCT was the reconstruction of 2D maps of tissue reflectivity while neglecting the polarization state of light. Thus, the original TdOCT and FdOCT configurations do not account for birefringence within a sample, treating the electromagnetic wave as a scalar quantity. However, light waves are transverse and have extra degrees of freedom described by the polarization state. Hee *et al*. first demonstrated a low-coherence reflectometer capable of polarization sensitive measurements of birefringence.[57] This technique was later extended by de Boer *et al*. to enable two-dimensional imaging of the birefringence within a biological sample.[58] The polarization sensitive OCT (PS-OCT) measurement apparatus is similar to that of TdOCT or FdOCT, with the addition of a linear polarizer after the source, and a polarizing beam-splitter (PBS) with an extra detector in the output arm. Propagation of light through a sample may alter the optical polarization state of the reflected light. This can occur due to optical scattering and birefringence within the sample. Since birefringence describes a change in the polarization state of light due to the refractive index difference for light polarized in two orthogonal planes, polarization sensitive measurements of the output interferogram can resolve depth correlated information about the birefringence of the sample material.

Mathematically, the two orthogonal polarization states can be treated separately as two electromagnetic waves propagating in separate interferometers. The two states are coupled by the Jones matrix of the sample that specifies its birefringence. Currently, Mueller-Stokes formalism has replaced the Jones matrix since the latter is unable to describe partially polarized light and the processes that lead to depolarization.[59]

d. Swept-source OCT (SS-OCT)

FdOCT can also be performed using a single detector by sweeping the source spectrum and detecting the intensity due to component frequencies.[60] FdOCT

of this type has been called swept source OCT (SS-OCT), and uses a tunable laser that sweeps the wavelength over a certain range. SS-OCT time-encodes the wavenumber by rapidly turning the narrowband and source through a broad optical bandwidth. Fringe response versus frequency is detected with a balanced detector and the signal is Fourier transformed to obtain a depth-reflectivity profile from which a cross-sectional image is reconstructed.[60] It should also be possible to use a monochromator and broadband light source. However, the spectral intensity of the monochromatic light may be too low for imaging in highly scattering media if only a single conventional superluminescent diode (SLD) is used.

APPLICATIONS IN CARIES DETECTION

A PubMed search from 1965 to February 2011 was conducted for articles published in dental literature, using the search terms "optical coherence tomography" and "dental caries." Manual searches of the bibliographies of all of the full text articles and related reviews selected from the electronic search were also performed and the review articles were excluded.

As mentioned above, the first OCT in the field of dentistry was performed by Colston *et al*. in 1998.[19] They developed a prototype OCT and acquired images of porcine periodontal tissues. In these images, enamel and cementum were clearly visible, representing the first application of OCT for imaging biologic hard tissue. In that same year, they presented *in vivo* OCT images of human dental tissues.[61] For this purpose, they developed a novel dental OCT system that incorporated a sample arm and scanning optics into a handpiece instrument. Their system had a lateral resolution of 50 ㎛ and an average total lateral scan distance of 12 mm. The system used a 15 mW fiber amplified source that had a central wavelength of 1,310 nm.

After that initial study, several groups showed interest in imaging dental hard tissue using OCT. Amaechi *et al*. from the University of Texas have published three articles since 2001. The first article was a short communications dealing with the methodology of OCT.[62] The second investigation in 2003 involved the quantitative comparison of OCT with QLF in an artificial caries model.[63] The third study in 2004 elaborated on the comparison of OCT with transverse microradiography (TMR) in the quantification of mineral loss in root caries.[64] Both the second and third reports demonstrated the possibility of using OCT to image dental hard tissues by comparing the results of OCT with QLF and TMR. The authors used a system developed initially for retina imaging, which had 250 ㎼ power, a wavelength of 850 nm, and an optical source line width of 16 ㎛. In particular, they collected c-scans, which are also known as en-face transverse images.

It is impossible to discuss the use of OCT in caries detection without mentioning the group from the University of California San Francisco (UCSF). Until now, the number of papers published by this group comprised almost half of the total publications reviewed. The experiments sequentially performed were systematic. In 2002, Fried *et al*. demonstrated that PS-OCT was well-suited for monitoring changes in enamel demineralization over a time period of 1 to 14 days.[65] After that, a series of studies using an artificial caries model and PS-OCT was performed to evaluate caries under composite sealants and restorations, the severity of interproximal caries lesions, occlusal surface caries, remineralization of the lesion, inhibition of demineralization by anti-caries tools such as fluoride or lasers, demineralization of enamel by CO_2 lasers, demineralization of exposed root surfaces, and de-/re-mineralization of dentin.[7,66-75] In addition, this group compared the near-infrared (NIR) transillumination to PS-OCT and combined these methods with other optical techniques into image-guided laser ablation systems.[76-78] Recently, the study of automated analysis algorithms to assess enamel demineralization and the use of novel cross-polarization OCT were reported.[79,80] Except for one recent study, this group used a conventional PS-OCT as their tool.[80] This system has a polarized SLD operating at a central wavelength of 1,310 nm. The authors usually compared the *in vitro* study results with TMR and polarized light microscopy.

Although, the devotion and achievements of the UCSF group are noteworthy, the first use of PS-OCT for early caries detection was not the work of this

group. Baumgartner *et al*. presented the first polarization resolved images of dental caries, however the penetration depth was limited and the image quality was poor due to the limited source intensity.[81] Feldchtein *et al*. presented *in vivo* high resolution dual wavelength (830 and 1,280 nm) images of dental hard tissues, enamel and dentin caries, and restorations.[82] Wang *et al*. measured the birefringence in dentin and enamel and suggested that the enamel rods act as waveguides.[83] In the following year, Everett *et al*. presented polarization resolved images using a high power 1,310 nm broadband source and a bulk optic PS-OCT system.[84] In those images, changes in the mineral density of tooth enamel were resolvable to depths of 2 - 3 mm. Otis *et al*. demonstrated improved imaging characteristics of a system operating at 1,310 nm vs. 850 nm.[85]

Canadian groups have also devoted their studies to caries research using OCT.[8,86-88] They also used PS-OCT systems; however, they creatively combined polarized Raman spectroscopy (PRS) with OCT in detecting early carious lesions. Raman spectroscopy uses laser excitation and the resulting scattering effect is observed in the target tissues. Inelastic scattering results in a frequency shift in the reflected Raman spectra, which are functions of the type of molecules in the sample. PRS can provide information not only about bacterial porphyrins leached into carious regions, but also about the primary mineral matrix and, thus, the state of demineralization or remineralization of the tooth. They suggested that PRS can be used to confirm suspect lesions identified by OCT and rule out false-positive signals. Recently, a rotating kernel transformation filter for OCT image analysis was introduced by this group.[89]

In addition to the research conducted by the aforementioned groups, several other studies of OCT in the context of caries detection have been performed.[2,90-93] Most of these investigations stressed the possibility of using OCT in the diagnosis of early carious lesions and provided some useful information. Overall, PS-OCT was the most frequently used system for caries detection. Shimada *et al*. first introduced SS-OCT for this purpose.[2] This system acquired images more rapidly than previous systems, and speed is particularly important for clinical applications. PS-OCT and SS-OCT are not incompatible and as a result, several reports have mentioned combining them to create PS-SS-OCT.[94]

CONCLUSIONS

Caries remains prevalent throughout modern society and is the primary disease in the field of dentistry. The early detection of lesions and application of the appropriate treatment before cavitation is of utmost importance. OCT is an emerging non-invasive three-dimensional imaging technique that produces high-resolution cross-sectional images of biological tissue to create an "optical biopsy." In this article, the brief history and the general principles of OCT and its usage in caries detection were extensively reviewed. As OCT is a nondestructive optical diagnostic tool that does not use ionizing radiation, it has substantial promise for clinical use. However, most studies performed to date have been *in vitro* or *ex vivo*. Several problems that limit the clinical application of OCT such as short penetration depth, patient motion, and other disturbing intraoral environments during image acquisition and optimal image processing must be resolved. In addition, it needs more customization for dental usage and is not easily available for now as a commercial product. Although, it could be made for relatively lower costs in comparison with computed tomography, the price of the instruments will be crucial for popular use as well as the superiority to the conventional tools. Nonetheless, this technology has the advantage of rendering a 3D image of the lesion. Combining this technology with other optical devices or automations in the near future seems possible. For this to be possible, however, additional studies must be performed.

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국문초록

광간섭단층촬영술을 이용한 치아우식증의 발견

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치아우식증의 조기 발견은 외과적 삭제를 피하면서, 적절한 치료를 할 수 있는 좋은 기회를 제공한다. 광간섭단층촬영술은 최근 각광받기 시작한 3차원 이미지 기술로서, 안과에서 광학적 생검의 목적으로 빈번히 이용되는 것을 필두로 다양한 의학 분야에 적용되어 왔고, 최근 초기 우식증의 발견에 전도유망하여 다양한 연구가 진행 중이다. 이 기술은 저 상관도 간섭계의 원리에 근거하고 있으며, 장점으로는 비침습적이고, 방사선을 사용하지 않으며, 3차원 이미지 구축이 가능하다는 점이다. 본 연구에서는 광간섭단층촬영술의 원리와 개략적인 개발 과정에 대한 기술과 함께 치아우식증에 관한 연구들에 대하여 고찰해 보았고, 이를 통해 이 기술의 응용 가능성을 확인하였다. 그럼에도 불구하고, 임상적인 유용성을 입증하기 위해서는 몇 가지 기술적 문제를 해결해야 하고, 보다 많은 생체 내 실험이 뒷받침되어야 할 것이다.

주요단어: 광간섭단층촬영, 진단, 치아우식증, Optical coherence tomography (OCT)