OPTICAL COHERENCE TOMOGRAPHY APPLICATIONS IN DENTISTRY

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INTRODUCTION

During the last 20 years, optical coherence tomography (OCT) has evolved into a powerful technique for imaging of transparent and translucent structures.⁴,⁵ OCT is an attractive noninvasive, non-touch imaging technique for obtaining high-resolution images. OCT is based on low-coherence interferometry (LCI) and achieves micron-scale cross-sectional image.⁴,⁵ LCI has evolved as an absolute measurement technique which allows high resolution ranging⁶ and characterization of optoelectronic components.⁶,⁷ The first application in the biomedical optics field was for the measurement of the eye length.⁷ A reflectivity profile in depth is obtained, called A-scan, as shown in Figure 1. An LCI system is generally based on a

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two-beam interferometer. A-scan technique was facilitated by a technical advantage: when moving the mirror in the reference path of the interferometer, not only is the depth scanned, but a carrier is also generated. The carrier frequency shift frequency is the Doppler shift produced by the longitudinal scanner itself (moving along the axis of the system, $Z$, to explore the tissue in depth). Adding lateral or angular scanning of the optical beam across the target.

Due to the high potential of the low coherence interferometer to provide thin section slices from the tissue, the technology was termed as optical coherence tomography.8

Figure 1. Relative orientation of the axial scan (A-scan), longitudinal slice (B-scan), $x$-$y$ (transverse) scan (T-scan) and en-face or transverse slice (C-scan).

Figure 2. Different modes of operation of the three scanners in an OCT system.

B-scan images, analogous to ultrasound B-scan are generated by collecting many A-scans for different and adjacent transverse positions. The lines in the raster generated correspond to A-scans, the lines are oriented along the depth coordinate. In the OCT T-scan based B-scan, the transverse scanner (operating along $X$ or $Y$, or along the polar angle $\theta$ in polar coordinates in Figure 1, with $X$ shown in Figure 2 top) advances at a slower pace to build a B-scan image. The transversal scanner produces the fast lines in the image.9,10,11 We call each such image line as a T-scan. This can be produced by controlling either the transverse scanner along the $X$-coordinate, or along the $Y$-coordinate or along the polar angle $\theta$, with the other two scanners fixed. The example in the middle of Figure 2 illustrates the generation of a T-scan based B-scan, where the $X$-scanner produces the T-scans and the axial scanner advances slower in depth, along the $Z$-coordinate. As shown below, this procedure has a net advantage in comparison with the A-scan based B-scan procedure as it allows production of OCT transverse (or en-face) images for a fixed reference path, images called C-scans.

There are two main types of OCT. In time domain OCT (TDOCT) the pathlength of the reference arm is scanned in time. Interference (i.e. series of dark and bright fringes) is only achieved when the optical path difference (OPD) lies within the coherence length of the light source. The envelope of this modulation changes as the OPD is varied, where the peak of the envelope corresponds to path-length matching.12-14 Several reports deal with this type of OCT. TDOCT has been used for evaluation of indirect dental restorations15-20, apical microleakage after laser – assisted endodontic treatment 21, monitoring the periodontal ligament changes induced by orthodontic forces22,23 and orthodontic interfaces.24-27

In spectral domain OCT (SDOCT), the spectrum at the output of the low coherence interferometer is measured. Due to the Fourier relation (Wiener-Khintchine theorem between the auto correlation and the spectral power density) the depth scan (A-scan) is calculated by a Fourier-transform from the acquired spectra, without movement of the reference arm 28-31. Because all depths are obtained in one measurement, SDOCT improves imaging speed dramatically. SDOCT has also an improved signal to noise ratio in comparison to TDOCT, the higher the number of separate spectral windows used in the spectrometer, the larger the signal to noise ratio. The width of the spectral windows limits the axial scanning range, while the full spectral bandwidth sets the axial resolution.

SDOCT can be also divided into swept source (SS) OCT28,29,32-37 and camera based, Fourier domain (FD) OCT.35,38

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

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

Compared with TDOCT, SDOCT has the advantage of increased phase stability for functional imaging.29

However, the SDOCT has three main disadvantages: decay of sensitivity with OPD, impossibility to move the focus to the depth investigated while scanning and symmetric (ghost) images if the OPD = 0 position crosses the object volume. The impossibility of focusing at selected depths renders the technology unsuitable for high transversal resolution microscopy, where TDOCT is favored. If minute details of defects are to be identified in dental constructs, then TDOCT is better. In case large size images are to be generated from soft moving tissue, then SDOCT methods should be used.

High speed, three-dimensional OCT imaging can provide comprehensive data which combines the advantages of optical coherence tomography and microscopy in a single system.31,39-41

Both TDOCT and SDOCT performing 3D imaging have been reported.

Polarization sensitive (PS) OCT is a functional extension of OCT. PS-OCT takes advantage of the additional polarization information carried by the reflected light, and can therefore add new image contrast compared to intensity based OCT.34,42,43 PS-OCT can reveal important information about biological tissue, such as quantitative distribution of birefringence, which is unavailable in conventional OCT.13,15,17,34,35,39 The recent development of PS-OCT belongs to spectral domain principle due to its superior speed and sensitivity that are critical for in vivo three dimensional applications.34,44

There are studies that provide theoretical and experimental results which demonstrate the superior sensitivity of SS OCT and FDOCT over the conventional TDOCT.13

Due to superiority of TDOCT for minute investigations, several groups have reported evaluation of dental treatments. Longitudinal TDOCT produces B-scans composed from A-scans. Feldchtein and collaborators38 used a compact, dual wavelength, fiber-based OCT scanner to perform OCT imaging of oral mucosa. The in-depth resolution of the OCT scanner was 13 μm (830 nm) and 17 μm (1280 nm).38 To receive a signal from the tissue in the orthogonal polarization in a polarization maintaining (PM) fiber interferometer, they mounted a Faraday rotator in front of the optical scanner at the output of the probe arm.

Another version of TDOCT reported was that of en-face optical coherence tomography (eF OCT) treatments.39,41,43,44,46-49,50-52 eFOCT is preferred for microscopy as it can provide real time images with similar orientation as that of microscopy images. Such systems used similar pigtailed superluminescent diodes (SLD) emitting at various wavelengths and having spectral bandwidths of 75 nm, which determined an OCT longitudinal resolution of around 17.3 μm in tissue. A first OCT system performs OCT only, equipped with a low numerical aperture _NA_ interface optics, which allows 1-cm lateral image size. A second system uses a higher NA interface optics with a maximum 1-mm image size. In addition, the second system is equipped with a confocal channel at 970 nm.17

In dentistry, OCT is successfully used for acquiring images of incipient carious lesions33,45 as well as advanced carious lesions21,17,45, for evaluating their severity16,17, or their remineralization,7,53 for determining the efficiency of chemical agents in the inhibition of the demineralization,23,34 It can also be used for testing the inhibition of demineralization in an in vitro simulated caries model by different fluoride agents on smooth enamel surfaces peripheral to orthodontic brackets33, for evaluating the demineralized white lesions surrounding orthodontic brackets33, for determining tooth movement under light orthodontic forces.23 Additionally, it is possible to evaluate the oral mucosa45, the microlakage of dental restorations and endodontic fillings23, the dental implant status52, the integrity of dental prostheses11,17,18, their quality and their marginal fitting.13,17,19,20,24,26,30-32

Some of the OCT applications in dentistry will be presented, depending on the type of the investigated structures and the OCT method used.

Oral Mucosa

To perform OCT imaging of oral mucosa, a compact, dual wavelength, fiber-based superluminescent diodes operating at 830 nm (Dl = 25 nm) and 1280 nm (Dl = 50 nm) served as the short coherent length light source, producing 1.5 mW and 0.5 mW powers to the object respectively. The in-depth resolution of the OCT scanner was 13 microns (830 nm) and 17 microns (1280 nm).45

1. Masticatory Mucosa (gingival and hard palate mucosa)

A characteristic feature of keratinized regions in the oral cavity is the presence of relatively high connective tissue papillae projecting into the overlying epithelium. The 200 μm thick region beneath the squamous epithelium is the lamina propria (L.P).
papillae of the LP within the epithelium contain strong bundles of collagen fibers which are tightly interlaced and woven into the periosteum45 (bone covering tissue). In the OCT scan, a distinct boundary between the LP and the periosteum is visible. The total depth of OCT imaging in the gingival mucosa is 600-650μm.45

2. Lining Mucosa (alveolar, soft palate, labial, and buccal mucosa, as well as the mucosa of the mouth floor and the ventral surface of the tongue)

In OCT image of vestibular alveolar mucosa, the epithelium (EP) is seen as a straight, transparent layer ~150 μm in thickness. The LP, seen as the brightly backscattering (500 μm thick) strip in the OCT scan, is a fibrous connective tissue structure and is separated from the EP by a basement membrane. It also contains muscle fibers and blood vessels which weakly backscatter and appear as dark structures in the scan above the darker, bony attachment.45

3. Specialized Mucosa (lips, dorsum of the tongue)

OCT images of those parts where the epithelium evidences high keratinization (marginal gingiva, vermillion border of the lip, buccal zona intermedia, dorsal surface of the tongue, hard palate) substantially differ from images of those parts where EP evidences low or no keratinization in its normal state (alveolar mucosa, labial mucosa, floor of the mouth, and soft palate). Keratinization may reduce the contrast and makes it difficult to distinguish the lamina propria and submucosa from EP. OCT imaging also reveals blood vessels and glands in LP and submucosa because their optical properties differ significantly from their environment (fibrous connective tissue).45

Malignant lesions of oral mucosa

Accounting for 96% of all oral cancers, squamous cell carcinoma (SCC) is usually preceded by dysplasia presenting as white epithelial lesions on the oral mucosa (leukoplakia). Dysplastic lesions in the form of erythroplakias carry a risk of malignant conversion of 90%,31 Tumor detection is complicated by a tendency toward field cancerization, leading to multicentric lesions.

This high-resolution optical technique permits minimally invasive imaging of near-surface abnormalities in complex tissues, having a penetration depth of 1-2 mm.1,2,15,35 This permits in vivo non-invasive imaging of the macroscopic characteristics of epithelial and subepithelial structures, including depth and thickness, histopathological appearance and peripheral margins. Oral mucosa is very thin, ranging from 0.2 to 1 mm. In a study of Wilder-Smith45, 50 patients were evaluated, examined and photographed with white or red intra-oral lesions. The imaging was carried out along the long axis at the center of each lesion using either a fiber optic high-resolution 3D OCT probe with a scan length of up to 10 mm or a commercially available 2D probe with a scan length of 2 mm Niris™ OCT imaging system by Imalux (Cleveland, OH). Contra lateral healthy tissues were scanned in a similar fashion. The acquisition required approximately 5-180 seconds per 3D scanning and 1.5 seconds for 2D scanning, totaling less than 15 minutes for each patient.55

In the OCT images, epithelium, lamina propria, and basement membrane are clearly visible. The OCT image of a dysplastic lesion parallels histopathological status, showing epithelial thickening, loss of stratification in lower epithelial strata, epithelial down growth, and loss of epithelial stratification as compared to healthy oral mucosa.51 The epithelium is highly variable in thickness, with areas of erosion and invasion into the subepithelial layers. The basement membrane is not visible as a coherent landmark.55 OCT image is rapid, unproblematic and well received by all patients.

Hard dental tissues

1. Polarization Imaging of Normal Dental Hard Tissue

In a study by Feldchtein45 for hard tissue images it was used single-wavelength OCT device operating at 1280 nm with about 2 mW superluminescent source. A 52 year old male tooth (1.1) was analyzed, showing a considerable enamel wear on the incisal edge of the tooth and further sclerotic (heavily mineralized) dentin beneath the worn incisal edge. Normal dentin is evidences below the sclerotic dentin. The horizontal dental enamel junction (DEJ) can be seen at approximately 1 mm below the facial surface and the left to right downward sloping lingual surface DEJ 1.5 - 2 mm below the facial surface. The high reflectivity ‘echoes’ present in the normal OCT image are suppressed in the orthogonal polarization image. In addition, the overall amount of coherent backscattered light is reduced in the orthogonal polarization image.45

2. Caries Lesions

The OCT image is represented by a strongly backscattering region on the tooth surface in the fissure area. The defect occupies a region 250-270 microns thick, at this point in time still confined to the enamel. Depth penetration is especially important when a caries lesion is completely hidden under the visually observable tooth surface. This is often the case with a secondary caries lesion.45 Another study evaluated
the potential of eFOCT as a possible non-invasive high resolution imaging method in supplying information on the quality of dental hard tissues. Teeth after several treatment methods were imaged in order to assess the quality of dental hard tissue. C-scan and B-scan OCT images as well as confocal images were acquired from a large range of samples.56

3. Noncarious Lesions
Feldchtein has also investigated the abfraction lesions, where the enamel structure in the defect is characterized by increased mineralization and narrowing of the space between enamel prisms. Images showed such a cervical lesion in enamel supported by an intact, healthy dentin structure. OCT imaging allows clear differentiation of this abfraction lesion from a caries lesion.45

Occlusal overload is an issue of major concern to dentists because of its unwanted consequences: tooth wear (pathological attrition, abfractions) of fracture, failure of dental restorations, temporo-mandibular disorders, etc. An early diagnosis is essential in such cases.

Our research team proposed for the first time the microstructural characterization of occlusal overloaded dental hard tissues by means of eFOCT in vitro.57 Using eFOCT images, we identified a characteristic microstructural pattern for teeth with various degrees of pathological attrition large cracks in the enamel and dentin layers, which reached the tooth surface. Reliable results were obtained further in an OCT examination restricted to maxillary anterior teeth, which are most frequently exposed to occlusal overload in patients with eccentric bruxism.58 The microstructural signs of enamel and dentin damage can be successfully monitored by a combination of confocal microscopy (CM) and eFOCT.59 eFOCT/CM is a combined technique that offers a low resolution guiding image (FM) for the higher resolution image (eFOCT).

The high occlusal forces can produce, besides pathological attrition, loss of cervical hard tooth substance called abfraction. The OCT C-scan and B-scan images obtained from occlusal overloaded bicuspids visualized a wedge-shape loss of cervical enamel and large cracks in the underlying dentin that are reaching the tooth surface (fig. 3).60

Figure 3. C-scan images an occlusal overloaded bicuspid: the cracks (K) penetrate the cervical dentine, reaching the surface of the abfraction (image size 2 mm x 2 mm, at a depth of 780 µm from the top measured in air).

eFOCT was further used in vitro to investigate anterior teeth with a normal crown morphology (without pathological wear), derived from young patients with first degree active bruxism (diagnosed by means of BiteStrip devices).61 Despite their normal morphology, the eFOCT images showed signs of enamel damage. The occlusal overload produced a characteristic pattern of enamel cracks restricted to the enamel layer thickness (fig. 4). They did not reach the tooth surface.

Figure 4. Fracture lines (FL) in enamel, zoom (occlusal overloaded anterior tooth, with a normal crown morphology): 18 degree in air if 18 degrees, this is not zoom, for the review you should give the size in mm.
In conclusion, eFOCT is a promising noninvasive alternative technique for the early detection and monitoring of occlusal overload, before it becomes clinically evident. The OCT system we used in the above studies operates at 1300 nm (B-scan mode at 1 Hz and C-scan mode at 2 Hz). It has a lateral resolution better than 5 µm and a depth resolution of 9 µm in tissue.

**Dental fillings**

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

**Endodontic treatments**

In the Todea C. et al. study the quality of endodontic treatments and root canal fillings were investigated with eFOCT/CM technology. Areas of apical microleakage were detected between the gutta-percha cones and the root canal walls and the filling material of the root canal space. Pairs of confocal eFOCT images were used to achieve, with dedicated computer software, a 3-D reconstruction of the investigated area.

The quality of the endodontic treatment and root canal filling, represented schematically in Figure 7. L was assessed using both systems. Apical microleakage areas were detected between the gutta-percha cones, root canal walls, and the sealing material (Fig. 3.R). For better assessment of the quality of the endodontic treatment, the second system was used, which provides dual imaging, OCT/CM, and magnified view. The confocal image aids guidance and allows focus adjustment to the OCT investigation. Figure 8 R shows the sample in front of the microscope objective. Pairs of eFOCT/CM images are shown in Figure 8 L a and b.
In order to obtain the images, sections up to a depth of 2 mm were scanned. The depths where defects appeared within the filling material or between the filling material and the gutta-percha point, with respect to the dentinal wall, was quantified. During examination, it has been evidenced that in some samples, defects were present in all sections to a full depth of 2 mm, while in others, defects were observed in fewer layers.\(^{45}\) This observation permitted a quantitative statistical analysis based on quantification of the number of sections in which defects were present. In those groups where biomechanical treatment of the root canals was associated with laser irradiation, according to the results of the one-way ANOVA, the number of defects was significantly lower (P<0.005) than in the control group. Moreover, no statistical differences were noted between the laser groups (P=0.049).\(^{21}\)

**Temporo-mandibular joint disc**

The study of Marcauteanu and colab revealed the microstructural characterization of the temporo-mandibular disc by using OCT investigation.\(^{65}\) 8 human temporo-mandibular joint discs were harvested from dead subjects, under 40 year of age, and conserved in formalin. They had a normal morphology, with a thicker pars posterior (2.6 mm on the average) and a thinner pars intermedia (1 mm on the average). Two different OCT systems were used: an eF(TDOCT) system, working at 1300 nm (C-scan and B-scan mode) and a spectral OCT system (a FDOCT) system, working at 840 nm (B-scan mode). The OCT investigation of the temporo-mandibular joint discs revealed a homogeneous microstructure. The longer wavelength of the FDOCT offers a higher penetration depth (2.5 mm in air), which is important for the analysis of the pars posterior, while the FDOCT is much faster.

**Periodontology**

OCT is particularly well-suited for periodontal diagnosis, generating ultrahigh resolution cross-sectional images of dental tissues. OCT provides rapid, consistent, and reproducible images of the surface results show microleakage in all the investigated root canal fillings.\(^{62}\) In a different study, 21 extracted single-root canal human teeth were selected. All roots were instrumented using NiTi rotary instruments. All canals were enlarged with a 6% taper size 30 GT instrument, 0.5 mm from the anatomical apex. The root canals were irrigated with 5% sodium hypochlorite, followed by 17% ethylenediaminetetraacetic acid (EDTA). After the instrumentation was completed, the root canals were obturated using a thermoplasticizable polymer of polyesters. In order to assess the defects inside the filling material and the marginal fit to the root canal walls, cone beam micro-computed tomography (CBµCT) was used first. After the CBµCT investigation, time domain optical coherence tomography working in en face mode (eOCT) was employed to evaluate the previous samples. The eOCT system operated at 1300 nm and was doubled by a confocal channel at 970 nm. The results obtained by CBµCT revealed no visible defects inside the root-canal fillings and at the interfaces with the root-canal walls. The eOCT investigations permit visualization of more complex stratified structures at the interface filling material/dental hard tissue and in the apical region.\(^{63}\) Also, OCT was employed to investigate the adaptation and gaps width between fiber posts, adhesive luting cement and root canal wall. The results prove the importance of assessing the quality of the interface after each process of fiber post luting.\(^{64}\)
topography, pocket morphology, and attachment level that are digitally recorded. These images pinpoint with great accuracy sites of disease progression. OCT also provides quantitative information regarding the thickness and character of the gingiva, root surface irregularities, and the distribution of subgingival calculus. The results of Otis L.L et. al. study convincingly demonstrate the capacity of OCT to determine gingival thickness and the shape and contour of the alveolar crest. Visualizing these anatomical features represents a significant contribution to periodontal surgical treatment planning. A prototype OCT system (1,310 nm wavelength light source, 14 μW, 95 dB dynamic range, 0.46 numerical aperture).

The preliminary study of Jae Ho Baek et al. for successive human studies tried to evaluate whether OCT can be helpful in determining tooth movement under light orthodontic forces. A TDOCT system was implemented with a fiber-based Michelson interferometer to evaluate the periodontal ligament (PDL). The system used a broadband light source having an output power of 4 mW. The center wavelength was 1310 nm, and the bandwidth 58 nm. The changed periodontal ligaments were imaged with OCT and digital 2D intraoral radiography. Both tensile and compressive ligaments were measured and compared. With OCT images, it is possible to measure changed ligaments from all directions; radiography could not show the portions overlapped by teeth. The averages of measured ligament width in OCT were larger than those from radiography in all groups. The results suggest possible applications of optical imaging for predicting tooth movements precisely and preventing side effects in the early stages of orthodontic treatment.

The study of Jihoon Na et al. used two specially designed orthodontic appliances installed on the maxillary anterior teeth of white rats for applying different magnitudes of orthodontic forces. Constant distraction force magnitudes of 0, 5, 10, and 30 gf were applied over a period of 5 days. At the end of the treatment period, the rats were sacrificed and the maxillaries were extracted for X-ray and OCT imaging. A fiber-based OCT system was utilized, employing broadband light source with an output power of 4 mW, a center wavelength of 1310 nm, and a bandwidth of 38 nm. The PDL variations, proportional to the force magnitude, were clearly identified by OCT. The OCT images further showed that the ligament was torn for a constant orthodontic force of 30 gf. These results support the clinical dental application of OCT for monitoring the ligament changes during orthodontic procedures.

Orthodontics

Studies conducted by Sinescu C. et al. used an eF OCT system to evaluate the connection between the bracket and the tooth structure. Orthodontic attachments bonding strength cannot be measured with OCT; however, by identifying and visualizing the voids in the composite, the quality of the restoration can be established. OCT investigation provides information on the microleakage of the bracket's bonding - several gaps are seen along the bracket base (Fig. 9 L). Also, a lack of adhesive material on the side of the bracket (Fig. 9 R) was identified. Although this work refers to an in-vitro investigation, it suggested that tooth-bracket interfaces could also be imaged in vivo.

![Figure 9.](image-url)

Regarding the tests for inhibition of demineralization, PSOCT was effective at measuring significant differences in the integrated reflectivity in depth between the control and fluoride groups (P<0.001). The fluoride sealant demonstrated a greater protective effect than the fluoride in solution and the glass ionomer cement.

In the study that compared demineralization surrounding orthodontic brackets, the positive and negative predictive values were better from the polarized images (0.97 and 0.84, respectively) than from the nonpolarized images (0.90 and 0.74, respectively). The limits of agreement and intraclass correlation coefficients between measurements of repeated images were lower for lesion area from cross-polarized images, suggesting better reproducibility, but not for lesion areas and degree of whiteness.
The real-time imaging capability of OCT, together with its high resolution, has the potential to help dentists with in vivo orthodontic treatments.

**Implantology**

OCT images provide quantitative information regarding microstructural architecture, including the character of the gingiva as well as that of the implant and the soft tissue relationships. More importantly, OCT identifies the earliest signs of inflammation that are so minimal that clinical examination is unlikely to detect. OCT imaging offers the exciting potential to detect periimplantitis before significant osseous destruction occurs. Several histological animal studies have shown that gingival connective tissue forms a scar-like fibrous connective tissue adjacent to titanium implant surfaces, while periimplantitis is characterized by a disorganized connective tissue containing more vascular elements. OCT images of soft tissue surrounding failing implants are characterized by linear signal deficits, low-intensity collagen signals, and pronounced increases in vascular elements. OCT will improve clinical evaluation of periimplant soft tissues and will provide significant advantages over existing diagnostic procedures. OCT can produce two- or three-dimensional images depicting the topography of the implant sulcus and the relationship of implants soft tissue interfaces. A fiberoptic clinical OCT system was used to obtain large size, 12 mm occlusal-apical OCT images. This system employed a 6 mW, 1,310 nm light source and produced images that had an axial resolution of 21 μm.

The quality of the implant insertion could be investigated by implant bone interface analysis. In the study of Sinescu and colabs, it was demonstrated that eFOCT can be used to evaluate these interfaces. Both C-scan OCT images (en-face) as well as B-scan OCT images (cross section) were collected. 3D analysis was possible by acquiring 30-100 C-scans, which were used post-acquisition to explore the volume of the tissue around the interface. The results from this study were evaluated by numerical simulation and tensitional stamps in the report by Antonie and colabs.

Ionita and colab used OCT as a competitive non-invasive method of osseointegration investigation. FD-OCT with Swept Source was used to obtain 3-D image of the peri-implant tissue (soft and hard) in the case of mandible fixed screw. A central wavelength of 1350 nm, gives better penetration depth than 850 nm in hard tissue.

**Prosthodontics**

This paragraph refers to studies using two different OCT systems assembled by the Applied Optics Group of the University of Kent. Unlike conventional A-scan based time-domain OCT, eFOCT systems were used which can deliver B-scans and C-scans from en-face (or T-scan) reflectivity profiles. Sequential and rapid switching between the en-face regime and the cross-section regime, specific for the eFOCT, represents a significant advantage in the non-invasive examination of prostheses.

These studies focused on investigating fixed partial dentures. One in vitro report presented two study groups. Group 1 included several types of prostheses, such as: metal-ceramic fixed partial prostheses, metal-ceramic crowns, metal-polymer fixed partial prostheses, metal-polymer crowns, polymer and all-ceramic fixed partial prostheses, and complete dentures. The main goal in imaging this group was to detect the presence or absence of material defects and microleakage at the prosthetic interfaces.

Another study analyzed the potential of the noninvasive method of eF in identifying problems related to the integral ceramic veneers immediately after the bonding process in order to assess the prognostic of prosthetic treatment. 32 Empress Veneers (Ivoclar Vivadent, Liechtenstein) were investigated. The scanning procedure was performed vestibular, oral, mesial and distal for each sample.

In several of the investigated prostheses, defects which may cause their fracture were found. The areas depicted present several small canals in the base that can be colonized in time with bacteria. This will represent the esthetic and functional failure of the prosthetic treatment.

The investigations upon fixed partial prosthesis presented many defects that can lead to their deterioration. These defects are usually located inside the material and cannot be depicted visually or by other conventional imagistic method. A series of these defects are illustrated in figures 10-14.

**Figure 10.** L-Metal-polymer fixed partial prosthesis in front of the scanning head. R1-C-scan OCT image. Part a shows an aeric inclusion at approx 0.5 mm depth in air from the top of the polymer; part b shows an aeric inclusion at the metal-polymer junction. R2-B-scan OCT image that displays the cross section through the defect, with a depth of 1.8 mm measured in air along the vertical axis, 4.4 mm lateral size in both b and c.
Figure 11. L-Metal-ceramic fixed partial prosthesis. R-C-scan OCT image matching the depth of the defect at b approx 0.2 mm measured in air from the top, lateral size 9.5 mm. The image shows the interface between pillar crown part a and pontic part c in a metalceramic fixed partial prosthesis. The defect inside the ceramic layers is in the center of the circle at b.

Figure 12. C-scan images from a metal-polymer veneer crown at two magnifications, showing an incorrect marginal fit. Lateral size: a 9.5 mm; b 4.4 mm. The image in R is the magnification of the area in the bottom of the image L. Part a shows the metal-polymer crown; part b the empty space between the crown and the pillar tooth; part c the luting cement; and part d the pillar tooth.

Figure 13. C-scan OCT images from esthetic fixed partial prostheses. L and C refer to the same polymer prosthesis; images are acquired from different depths and with different lateral size. L: 140 µm from the top measured in air, with a void well defined inside the material; C: Zoom image 4.4 mm lateral size and deeper than in L by 100 µm. R: All ceramic crown pressed ceramic technology. Part a: crown and part b: defect inside the ceramic layers at approximately 600 µm depth measured in air.

In the ceramic veneers study, the eFOCT scanning revealed poor marginal adaptation for 18 out of 32 samples tested. The marginal adaptation problems were identified especially in proximal and oral areas.51

DISCUSSION

In vivo and in vitro imaging of hard and soft tissue of the human oral cavity has been demonstrated using different OCT techniques. Several types of oral mucosa and healthy and damaged tooth structures, can be imaged and differentiated. Also, OCTcan diagnose periodontal diseases.72,73 In addition, it has been demonstrated that OCT is an efficient diagnostic tool in dental restorative procedures.17,45
eFOCT imaging proved that laser-assisted endodontic treatment improved the prognosis of root canal filling and led to a reduction in the apical microleakage.17,74

Figure 14. Poor Marginal adaptation on proximal area of an Empress Veneer: L: C scan, slice put the depth here, put lateral size from JBO here; R: B scan OCT image showing problems of marginal adaptation.

In measurement of demineralization inhibition, results obtained suggest that PS-OCT is well suited for the nondestructive assessment of caries inhibition by
The unique capabilities of OCT recommend this technology for fundamental research and clinical practice.

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

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