Ability of Optical Coherence Tomography to Detect Caries Beneath Commonly Used Dental Sealants

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Background and Objective: The onset and progression of early tooth decay is often preventable with dental sealants. However, occasionally decay progresses underneath the sealant. Current technology does not permit monitoring of potential lesion progression or arrest. Dental sealants themselves mask the visual cues that identify early tooth decay, and radiographs are not sufficiently sensitive. Therefore, clinicians can be reluctant to use dental sealant. The objective of this ex vivo study was to evaluate the ability of dentists to detect decay beneath commonly used dental sealants using optical coherence tomography (OCT) imaging.

Study Designs/Materials/Methods: Forty extracted teeth were divided into equal groups of carious and non-carious teeth, as determined by visual inspection. After radiographs and OCT imaging, teeth were randomly assigned for sealant placement with one of four commonly purchased dental sealants: Clinpro™, Fuji Triage™, Embrace Wet Bond™, and Delton™.

Following sealant placement, teeth were radiographed, imaged with OCT, sectioned, examined histologically, and scored as healthy/not healthy. The gold standard was histopathological diagnosis from the serial sections. Cohen’s kappa, sensitivity, negative predictive value, and positive predictive value were computed for all measures.

Results: After 90 minutes training, pre-standardized dentists were able to detect tooth decay more accurately using OCT than with visual or radiographic examination. Detection using OCT was somewhat better prior to sealant placement than afterwards. This effect varied in size depending on the type of sealant used. Radiographic diagnosis was also less accurate after sealant placement. Of the four dental sealants, Delton provided excellent positive predictive value and the best post-sealant negative predictive values.

Conclusion: In this ex vivo study, dentists were able to detect tooth decay beneath four commonly used dental sealants based on OCT images. Clinical investigations are now underway to determine the usefulness of this approach in vivo. Lasers Surg. Med. 42:752–759, 2010. © 2010 Wiley-Liss, Inc.

Key words: enamel demineralization; dental decay; dental diagnosis; radiographs; tooth decay

INTRODUCTION

The onset and progression of tooth decay is preventable with dental sealants. The caries process begins when oral bacteria attach to the tooth’s enamel surface—most often in the deep pits and fissures of its occlusal surface. Bacteria metabolize dietary carbohydrates and produce acids which diffuse through the plaque and acquired pellicle, penetrate the intercrystalline and interprismatic spaces between the enamel crystals, and demineralize the enamel. If left untreated, over time, the acid progresses through the enamel into the underlying dentin. Dental sealant prevents bacteria from attaching to the enamel surface. In addition to preventing physical bacterial adhesion to enamel by the physical presence of the sealant, the presence of an intact bond between the enamel and the sealant may reduce demineralization under dental sealants by preventing bacteria and carbohydrates from leaking along the enamel sealant margin, thus arresting the development of demineralization and caries [1].

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Regrettably, dental sealants are not 100% effective [2–4]. This is particularly problematic because clinicians are currently unable to monitor caries progression under the dental sealant. Once a dental sealant is placed, the visual cues that clinicians would use to detect demineralization and caries are masked by the sealant material. Moreover, radiography shows poor sensitivity for detecting/monitoring early carious lesions since these lesions are too shallow to show on radiographs and do not provide enough contrast when compared with the surrounding tissue to be clearly discerned. Therefore, since clinicians may not be willing to accept possibility of caries developing undetected under a dental sealant, they may prefer to place a restoration rather than place a dental sealant [2,3,5–9]—a progressively costly and invasive course. It may well be possible to increase dental sealant utilization if dentists were able to visualize and document cariogenic activity under dental sealants [8], which would lead to reductions in restorative care as well as better utilization of manpower, time, and healthcare dollars.

The use of optical coherence tomography (OCT) imaging techniques may provide the much needed capability for visualization of tooth decay under dental sealants [10]. OCT, an emerging non-invasive, high-resolution optical imaging modality has demonstrated a consistent ability to identify decayed tooth structure [11–18]. OCT uses near-infrared light to provide sub-surface tissue (1.5–2.5 mm) images without ionizing radiation [13,14,19,20]. It compares the scattered light reflected from an object with a control beam. Because sound enamel has very high mineral content; 87% hydroxyapatite-like crystals, 2% organic material, and 11% water, and decayed enamel contains decreased mineral content and more water, characteristic refractive index changes, detectable by OCT, should be commensurate with areas of decay [21]. These optical signals can then be interpreted to create 2D and 3D images of the hard tissues. To date, only one clinical study has used OCT for in vivo dental hard tissue diagnosis [22], although in vitro and ex vivo studies clearly indicate its potential [11,12,23–30]. Using time-domain OCT, Otis et al. [31] demonstrated that sealants could be differentiated from sound enamel. Jones et al. [10] showed that polarization-sensitive OCT can be used to quantify the severity of artificially induced demineralization under sealants and they also showed that the optical penetration varied markedly with the composition of the sealants since some sealants had an added optical opacifier. Several different types of OCT are currently under development and investigation in dental hard tissues, including time-domain OCT (TD-OCT), polarization-sensitive OCT (PS-OCT), and spectral-domain OCT (SD-OCT). Each of these OCT variants uses somewhat different properties and analytical approaches on the light returned from the tooth sample to the detector on the OCT probe. Spectral-domain OCT (SD-OCT), which was used in these studies, measures the magnitude and delay of backscattered or backreflected by spectral analysis of the interference pattern. Advantages of SD-OCT include much faster imaging time, reduced number of scans, 3D imaging, and significantly higher sensitivity [32–38].

It was the aim of this study to evaluate the diagnostic usefulness of SD-OCT for detecting decay under the four dental sealants that are most commonly sold by dental supply distributors. Because our goal was to determine the clinical feasibility and utility of the proposed approach, fast and simple visual examination of OCT images by clinicians such as would be convenient at the chairside was used for the imaging-based diagnosis. Gold standard was also based on clinical usage—consisting of visual and radiographic examination of the tooth.

MATERIALS AND METHODS

Tooth Samples

Forty extracted teeth were divided into two groups consisting of 20 carious and 20 healthy teeth, respectively, as determined by visual inspection by an experienced clinical dental practitioner (JH) using loupes (2.5 magnification). Teeth were considered carious if there were white or brown spot lesions on the tooth not consistent with the clinical appearance of sound enamel [39]. Teeth were photographed, roots embedded into 9 mm × 11 mm vinyl polysiloxane blocks (Rite-Vinyl, Rite Dent Corp., Hialeah, FL) and stored in demineralized water with thymol to maintain tooth hydration and prevent bacterial growth. The blocks were used for ease of handling and to permit reproducibly positioned OCT and radiographic imaging of coronal tooth structure. The area of interest was then imaged with OCT. Next, radiographs were taken of each tooth with the X-ray unit aiming towards the buccal tooth surface and the horizontal aspect positioned as it would be in vivo. The tooth orientation for radiographs and scan line for OCT imaging were clearly marked on a photograph of the tooth with marker immediately at the time of imaging/ X-rays.

After OCT imaging and radiographs, teeth from each group were randomly assigned for sealant placement with one of four commonly used dental sealants: Clinpro™ (3M, St. Paul, MN), Fuji Triage™ (GC, Alsip, IL), Embrace Wet Bond™ (Pulpdent Corporation, Watertown, MA), and Delton™ (DENTSPLY International World Headquarters, York, PA).

Following sealant placement according to manufacturers’ instructions, the teeth were imaged with OCT and radiographed at the same locations as before. Teeth were then sectioned into 0.025 inch sections with a Buehler Isomet precision low-speed saw and wet sections were viewed under a stereomicroscope. Serial photomicrographs (10×) were taken of the region of interest of each section.

OCT Imaging

Five hundred twelve sequential 2D-OCT images of each tooth at a wavelength of 1,350 nm were taken with SD-OCT. The SD-OCT system had a stationary reference arm with the tooth sample set on a stage for imaging.
AMIRA® (Mercury Computer Systems, Visage Imaging, Inc., Andover, MA) software program was then used to reconstruct a 3D-OCT image from the 512 sequential 2D-OCT images.

The schematic diagram of the fiber-based swept source OCT system is shown in Figure 1. The output light from a swept light source (Santec Corporation, Komaki, Aichi, Japan) at 1,310 nm with a FWHM bandwidth of 100 nm and output power of 5 mW was split into reference and sample arms by a 1×2 coupler. The light source was operated at a sweeping rate of 20,000 Hz. Eighty percent of the incident power was coupled into the sample arm while 20% was fed into the reference arm. The reference power was attenuated by an adjustable neutral density attenuator for maximum sensitivity. A 2D galvanometer-based scanner was connected to the sample arm. Two circulators were used in both reference and sample arms to redirect the back-reflected light to a 2×2 fiber coupler (50/50 split ratio) for balanced detection. In the detection arm, the fringe signal collected by the photodetectors was digitized by a 14-bit data acquisition board (National Instrument high speed digitizer 5122) sampling at 33 M samples/second, and the number of data points for each A-line data acquisition was 1,024. The swept source generated an A-line trigger signal that was used to initiate the data acquisition process for each A-line. The complex analytical depth encoded signal was converted from the collected time fringe signal by fast Fourier transform. The structure image was reconstructed from the amplitude term of the complex depth encoded signal. The measured axial resolution of 8 μm was close to the theoretical axial resolution of 7.5 μm since the spectrum of the swept light source is nearly Gaussian shaped. The lateral resolution, which is determined by the sampling optics, was measured to be 12 μm. The measured sensitivity of the OCT system with an ideal partial reflector as the sample was 106 dB.

Data Evaluation

Two blinded, pre-standardized scorers separate from the initial selection of the tooth samples (dentists, each with >10 years clinical experience) diagnosed each sample independently. Diagnostic scorers had no previous OCT experience. They were pre-standardized to 95% accuracy after one 90-minute training session.

OCT and radiographic images were scored separately as healthy/not healthy. During diagnostic OCT scoring of the teeth, reviewers first looked at the 3D images, selected regions of interest, then made final diagnoses based on the 2D pullout images (Fig. 2). When scoring, the images were viewed on the computer screen at an approximate size of 10 cm×8 cm, based on the scorers’ preferences. False scattering of approximately up to 8 mm at an image size of 10 cm×8 cm was considered acceptable. All serial sections were examined for each tooth by two blinded examiners who were not aware of the previous diagnostic test results. Serial wet sections of samples were viewed under a stereomicroscope at 50× magnification and evaluated for the presence or absence of pathology (demineralization [very early stages in the caries process which may be reversible]/caries [more progressed non-reversible lesions]) extending into enamel or dentin [40]. The gold standard was histopathological diagnosis for each tooth as determined by the two-blinded scorers from the serial sections.

Statistical Analysis

Statistical analysis was performed to identify diagnostic agreement (kappa values) between the two scorers. Data were analyzed using combined results from both scorers.
with “healthy” being scored if both observers scored healthy, and “not-healthy” scored if 1 or both observers scored “not-healthy.” Sensitivities as well as positive and negative predictive values were computed for the different diagnostic modalities, and histopathology was used as the gold standard.

RESULTS

OCT imaging was rapid and simple, with an average imaging time of <1 minute per tooth. Using rudimentary visual, qualitative evaluation of OCT images, tooth structures were easily identifiable. The learning curve for
“reading” OCT data was quick, due to similarity with radiographs. Caries/demineralization was easily recognized in the OCT image by its differing optical intensity from the adjacent tooth substance and sealant (Fig. 2b). Using rudimentary visual, qualitative evaluation of OCT images, tooth structures were easily identifiable. OCT images of sound tooth showed an area of intense light backscattering at the tooth surface (Fig. 2a). For the sound surface, beyond the initial first few microns, the light backscattering rapidly reduced with no further changes in intensity deeper into the tooth. Underneath sealants, the transition between sealant and underlying healthy tooth substance was clearly demarcated with one clear optical interface (Fig. 2a), as well as an overlay of scatter of several hundred micrometers. In contrast, demineralization or caries was easily recognized in the OCT image by its differing optical intensity from the adjacent tooth substance and sealant (Fig. 2b). Demineralized or cavious sites appeared as areas of diffuse non-homogenous strong scattering intensity and reduced macrostructure definition. Underneath sealants, areas of demineralization/decay were visible as very bright zones demarcated clearly by their brightness from the overlying sealant, and merging gradually into the underlying tooth substance. An overlay of scatter of several hundred micrometers is visible below the bright core of the lesion.

Diagnostic data are summarized in Table 1. Visual exam falsely identified six decayed teeth as being healthy. Pre-sealant, early lesions in 20 specimens were missed using radiographs, whereas 2 healthy specimens were misdiagnosed as being decayed using OCT. Post-sealant, early lesions in 15 specimens were missed using radiographs, and three lesions remained undetected using OCT.

Statistical analysis data are presented in Table 2. Agreement with histology (Cohen’s kappa) was best for OCT pre-sealant ($k = 0.886$), followed by clinical exam ($k = 0.700$) and OCT post-sealant ($k = 0.634$). Radiographs agreed very poorly with histology: $k$ (pre-sealant) = 0.091; $k$ (post-sealant) = 0.251. As evaluated using positive predictive values (PPV) and negative predictive values (NPV), detection of demineralization or caries was more accurate using OCT than with visual or radiographic examination. OCT was somewhat better in detecting lesions prior to sealant placement (PPV = 0.929, NPV = 1.000) than once

<table>
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<th>TABLE 1. Summary of Diagnostic Data</th>
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<td>Healthy</td>
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<td>No. of teeth diagnosed as healthy/not/healthy pre-sealant</td>
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<td>Clinical</td>
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<td>Radiograph</td>
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<td>No. of teeth diagnosed as healthy/not/healthy post-sealant</td>
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<td>OCT</td>
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<td>Histology</td>
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sealants were in place (PPV = 0.913, NPV = 0.708). This effect varied in size depending on the type of sealant used, with OCT-diagnostics most accurate when Delton was used. The accuracy of radiographic diagnosis versus histology as determined by PPV and NPV was overall not very good, and interestingly, it appeared to be somewhat more accurate after sealant placement (PPV = 0.909, NPV = 0.448) than before (PPV = 0.833, NPV = 0.382).

**DISCUSSION**

Compact, mobile, user-friendly clinical OCT systems are now becoming available to clinicians, offering small, flexible fiberoptic OCT probes that can easily access the oral cavity to provide chair side in vivo clinical imaging, and immediate, real-time OCT images, with total imaging times of less than a minute. Digital data files provide quick and easy data storage, retrieval, and printouts as needed. Furthermore, using OCT imaging, there is no harmful ionization radiation, and no patient discomfort from radiographic sensors or film as seen in conventional radiography. Disadvantages include the limited availability to dentists of oral OCT imaging systems, with existing systems predominantly restricted to TD-OCT.

This study demonstrated the excellent potential of non-invasive OCT imaging for detecting and monitoring demineralization beneath dental sealant. Extracted teeth were used to obtain well-defined specimen groups quickly and predictably. In order to provide clinically useful information, four of the most commonly purchased dental sealants were identified by contacting two large distributors of dental supplies (J.S. Holtzman, personal communications). Of the four dental sealants, Delton™ provided excellent PPVs and the best post-sealant NPVs.

Visual-tactile assessment of demineralization (early reversible caries) or frank (non-reversible) caries relies on the clinical detection of changes in enamel opacity or discoloration (differentiated from extrinsic of intrinsic stain), or of subtle changes in enamel texture. Once these areas are covered with dental sealant, they are no longer accessible for examination by these methods. Therefore, clinical detection of demineralization under sealants is not very accurate. Radiographic detection of demineralization is challenging because minimally demineralized areas may lie below the threshold of resolution and visual detection; detection may be further impeded by superimposition of adjacent structures on the 2D renderings of 3D structures. After sealant application, caries on radiographs may be even more difficult to detect because the radiographic appearance of sealant can be indistinguishable from that of tooth structure and sealant may mask small lesions.

In the OCT images, demineralized tooth structure appeared as areas of diffuse, strong scattering intensity underneath the sealants. This is attributed to the occurrence of multiple scattering and indicative of an area of higher porosity in zones of demineralization. Pilot studies investigating the capability of TD-OCT [13,27] and PS-OCT [16,41] to detect caries reported similar optical changes. In these studies, statistical analysis of data showed OCT to be
OCT provided excellent PPV, correctly identifying more demineralized (early caries) teeth than clinical exam or radiographs pre- and post-sealant placement. Interestingly, OCT falsely diagnosed two teeth as demineralized prior to sealant placement, whereas it missed demineralization in two teeth after sealant placement. The two false-positive diagnoses are attributed to variations in enamel thickness in the area of the occlusal pits and fissures in those specific teeth, resulting in the semblance of a lesion in the OCT images. Both of these teeth were diagnosed correctly as being healthy using clinical and radiographic evaluations.

Lesions in the two teeth in which OCT failed to detect demineralization post-sealant placement were very superficial and were difficult to detect in the OCT images due to the area of intense light backscattering directly at the tooth surface. Neither of these lesions was detected clinically, but one of them was detected in the radiographic image of the sample.

Although OCT-based diagnostics did register some false positives, this relatively low rate of false positives may be acceptable, especially within the context of high risk and underserved populations whose limited access to dental care adds to the challenge of detecting sealant failure in a timely manner. False positives are certainly better than false negatives for patients with limited access to dental services, where a false negative can readily result in the progression of demineralization into frank caries, potentially resulting in a dental abscess and systemic infection.

Clearly, clinicians’ concerns regarding their current inability to detect demineralization are justified. The decision to restore teeth rather than let demineralization potentially progress unmonitored underneath sealants is understandable, yet it is not optimal. The development and validation of an improved tool for monitoring demineralization status under dental sealants may well increase dental sealant utilization, especially in high-risk and underserved populations [8,42–44]. Moreover, providing clinicians with a tool capable of reliably confirming the presence of sound enamel would reduce the number of unnecessary restorations or sealant replacements. Thus, the potential use of OCT for demineralization detection under sealants may result in better utilization of manpower and time, as well as reduced healthcare dollars.

This study has advanced this concept one stage closer to the clinical situation by identifying the diagnostic usefulness of OCT images within a simulated clinical setting—that is, the ease with which clinicians can detect demineralization (early lesion) on the tooth surface underneath resin or GIC sealants from a rapid examination of an image—thus corresponding to current usage with radiographs. Clinical usefulness is critically defined by the ease with which a clinician can learn to use and correctly read

### TABLE 2. Statistical Analysis of Data

<table>
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<tr>
<th></th>
<th>Cohen’s kappa</th>
<th>Sensitivity</th>
<th>Positive predictive value</th>
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<tr>
<td>Comparisons of histology to</td>
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<tr>
<td>OCT (pre-sealant)</td>
<td>0.886</td>
<td>1.000</td>
<td>0.929</td>
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<td>OCT (post-sealant)</td>
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<td>0.808</td>
<td>0.913</td>
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<td>0.769</td>
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<td>OCT (post-sealant) vs. histology</td>
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data from a new diagnostic modality. This study demonstrated that monitoring for potential lesion development or progress in the clinical situation using OCT is feasible. A clinical trial is currently underway to evaluate the in vivo applications of this modality.

CONCLUSION

Using OCT, dentists are able to diagnose sound and demineralized teeth with lower rates of false positives and false negatives than clinical or radiographic examination. Though OCT was able to detect demineralization beneath each of the four most commonly purchased dental sealants from dental distributors, Delton™ was most amenable. Though OCT was able to detect demineralization beneath demineralized teeth with lower rates of false positives and false negatives than clinical or radiographic examination. Through OCT-based detection of demineralization beneath dental sealant. Clinical investigations are now underway to determine the usefulness of this approach in patients.

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