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Ex vivo imaging of early dental caries within the interproximal space

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ABSTRACT

Optical coherence tomography (OCT) is emerging as a technology that can potentially be used for the detection and monitoring of early dental enamel caries since it can provide high-resolution depth imaging of early lesions. To date, most caries detection optical technologies are well suited for examining caries at facial, lingual, incisal and occlusal surfaces. The approximal surfaces between adjacent teeth are difficult to examine due to lack of visual access and limited space for these new caries detection tools. Using a catheter-style probe developed at the NRC-Industrial Materials Institute, the probe was inserted into the interproximal space to examine the approximal surfaces with OCT imaging at 1310 nm. The probe was rotated continuously and translated axially to generate depth images in a spiral fashion. The probe was used in a mock tooth arch model consisting of extracted human teeth mounted with dental rope wax in their anatomically correct positions. With this *ex vivo* model, the probe provided images of the approximal surfaces revealing morphological structural details, regions of calculus, and especially regions of early dental caries (white spot lesions). Results were compared with those obtained from OCT imaging of individual samples where the approximal surfaces of extracted teeth are accessible on a lab-bench. Issues regarding access, regions of interest, and factors to be considered in an *in vivo* setting will be discussed. Future studies are aimed at using the probe *in vivo* with patient volunteers.

Keywords: early dental caries, optical coherence tomography, interproximal space, approximal surface, rotary catheter probe

1. INTRODUCTION

Dental caries (i.e. dental decay) is an infectious disease that arises from destruction of the mineralized tooth matrix due to acid produced by bacteria found in dental plaque biofilm. The acid leaches minerals from the tooth to produce a porous structure that eventually weakens to form a cavitation. At this stage, the only available treatment option is surgical intervention. The dental profession, however, is undergoing a paradigm shift towards preventive measures.[1] Caries that are detected at early non-cavitated stages can be monitored and treated with preventive agents such as fluoride, sealants and antimicrobials to promote remineralization of tooth structure and to arrest progression of caries. For these non-surgical treatment strategies to be effective, detection and diagnosis of caries at early stages is critical. The conventional tools and methods available to dental clinicians, namely probing with a dental explorer, visual and radiographic examination, unfortunately are not well suited for detecting early or incipient dental caries. These methods rely on subjective criteria such as colour and softness on probing, and generally find lesions that are more advanced than those detected by emerging caries detection tools. One of the limitations of conventional dental radiographs is that ~30-40% mineral loss is required before a lesion is visible radiographically.[2] Therefore, these methods lack sufficiently high sensitivity and/or specificity for early caries detection and better clinical tools are needed to assist with preventive measures.[3]

Optical coherence tomography (OCT) is emerging as a technology that can potentially be used for the detection and monitoring of early dental enamel caries. Studies by our group and numerous others have shown that OCT imaging provides morphological high-resolution depth images of hard and soft tissues of the oral cavity such as the outer dental enamel, transition into the dentin at the dentinoenamel junction, gingival tissues, oral mucosa, and dental caries.[4-9] Since the early caries lesion of interest begins at the outer enamel layer of the tooth and progresses inward toward the dentin, OCT is therefore well suited for imaging these near-surface tissue lesions. With OCT imaging, incipient caries can be detected as well as the lesion depth estimated.[10] These details provide insight into the extent of lesion involvement thus guiding clinical treatment decisions.

To date, most of the emerging caries detection optical technologies are well suited for examining caries at facial, lingual, incisal, and occlusal surfaces. The approximal surfaces between adjacent teeth are difficult to examine due to lack of visual access and limited space for emerging caries detection tools. We present a study involving OCT imaging of the approximal surfaces of extracted human teeth. Imaging was carried out using a catheter-style probe developed at the NRC-Industrial Materials Institute (NRC-IMI) in collaboration with the NRC-Institute for Biodiagnostics (NRC-IBD). The internal probe was rotated continuously and translated axially to generate depth images in a spiral pull-back fashion. We compare the results with those obtained from OCT imaging of individual samples where the approximal surfaces of extracted teeth are directly accessible with a lab-bench OCT setup. In particular, we compare and contrast the results with OCT data acquired using 1310 nm and 850 nm.

2. MATERIALS AND METHODS

2.1 Tooth Samples

Extracted human teeth (n=8, tooth 2.1 through to tooth 2.8 [F.D.I. system]) were collected from consenting and assenting patients undergoing tooth extractions for orthodontic or periodontal disease reasons. Tooth samples were collected using protocols approved by the research ethics boards of the institutions involved in the study. Following extraction, the teeth were rinsed well in deionized distilled water, any remaining soft tissue removed by scaling, and the samples sterilized by gamma irradiation (GammaCell 1000 Irradiator, dose of 103.05 Gy for 45 minutes). No further treatment was performed and the samples were preserved in sterile deionized distilled water until OCT imaging.

2.2 OCT Systems

2.2.1 Rotary Catheter Imaging System (1310 nm)

A 1310 nm rotary catheter imaging system developed at NRC-IMI in collaboration with NRC-IBD was used to image the approximal surfaces of the tooth samples. This system is adapted from a system developed for cardiovascular applications. This time-domain system includes an interferometer, an optical catheter probe 0.7 mm in diameter (Fig. 1), a guiding catheter specially designed to be inserted into the interproximal space between adjacent teeth, and a mechanical drive for rotating the optical probe while simultaneously translating the probe axially. The interferometer is a time domain (TD) system[11] capable of 2 000 A-scans/s over 4 mm. A swept source (SS) system capable of 20 000 A-scans/s over 3 mm (one side of the zero path delay location) with 30 revolutions/s has also been built, but was not available at the time of the measurements. In this paper, the results presented are thus derived from the TD system. The source is a super-luminescent diode (SLED) from Denselight (1.3 μm, 70 nm bandwidth) and provides a coherence length of 11 μm. The guiding catheter was specialized to be used in the approximal space of adjacent teeth. It had a distal tip tapered to 1.1 mm in diameter. The guiding catheter is required for the protection of the optical probe which rotates continuously. The optical probe was pulled back inside the guiding catheter along a distance of 4 mm, enough to cover the approximal surface of interest. Using a pullback speed of 250 μm/s and a rotation speed of 2.4 revolutions/s we obtained a resolution of 105 μm between frames and 15 μm between A-scans (computed at a nominal radius of 2 mm).

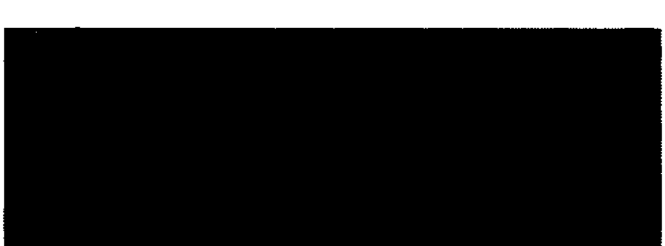

Fig. 1. Photograph of the OCT optical catheter probe for OCT imaging. For size reference, the background grids are 1 mm squares.

The probe spot size was 40 µm focalized at a distance of 1 mm from the rotation axis.

For OCT imaging with the rotary catheter system, the tooth samples were mounted upright in their anatomically correct positions with the tooth roots placed in dental rope wax. The 8 teeth formed the left quadrant of a partial mock upper maxillary arch containing permanent dentition (tooth 2.1 through to tooth 2.8). Adjacent teeth were mounted touching one another at the interproximal contacts. The teeth were measured in air without any water surrounding the arches. The guiding catheter was inserted from the facial direction into the interproximal space between adjacent teeth. The catheter was raised as high as possible such that it sat just inferior to the contact point of adjacent teeth (Fig. 2). The imaging pull-back data acquisition was in the lingual to facial direction. In between the measurements from the various OCT systems, the teeth were kept in a container of deionized filtered water to prevent the teeth from drying out.

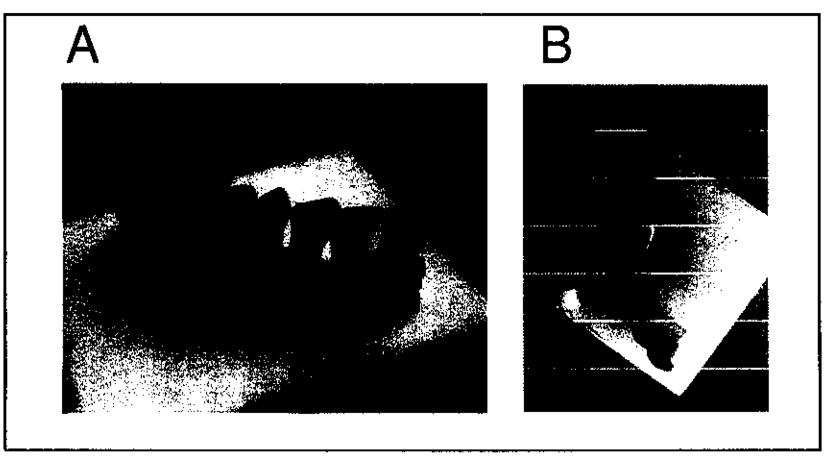

Fig. 2. Photographs of the OCT catheter probe placed in the interproximal space of two adjacent teeth. A) View from the side. B) View from above. The red laser light is used as a reference indicator to help localize the probe scanner location.

2.2.2 Galvanometer OCT Imaging System (1310 nm)

This system is also a time domain OCT system developed at NRC-IMI. It consists of a 1310 nm super-luminescent light emitting diode (SLED, $\Delta\lambda$ = 64.9 nm, FWHM, Pmax = 24 mW, coherence length = 12 µm; Covega Corporation, Jessup, MD) as the illumination source. A 2X2 optical fiber coupler separates the light into sample and reference arms. A collimator and 25 mm lens focuses the beam (diameter of 2.0 mm) on the sample and re-collects the reflected light. The axial resolution of the system is 12 µm which corresponds to the source's coherence length and the transverse resolution is 24 µm which results from the selected lenses. With the SLED at maximum power, 5-8 mW of light reaches the sample. The optical path length of the reference arm is varied by passing it through a parallelogram prism mounted on an oscillating galvanometer. The prism and galvanometer set-up allow for a scanning depth of 4 mm at a rate of 148 A-scans per second. A one-micron precision stepping motor driven X-Y stage (Danaher Motion, Westborough, MA) moves the beam around the sample. Software developed by NRC-IMI controls the stage, other hardware, and collection of data.

For measurements, each tooth sample was placed on its side with the approximal surface position angled roughly perpendicular to the OCT beam (Fig. 3). Due to the long scanning times, the sample was immersed in water to prevent it from drying out. The OCT beam was focused beyond the water surface onto the tooth surface. OCT scans of the region of interest was acquired with 5 µm step increments between A-scans along the incisal to cervical direction, with 100 µm between adjacent B-scans across the approximal surface.

2.2.3 OCT Imaging System at 850 nm

OCT images were recorded with a Humphrey OCT-2000 system (Humphrey Systems, Dublin, CA, USA) as described previously.[12] This system uses a super-luminescent light emitting diode with a central wavelength at 850 nm and a measured coherence length of ~15 µm (full-width at half-maximum) that provides the axial resolution of the OCT system. Two-dimensional images are formed by a straight-line collection of adjacent A-scans. Each OCT image consists of one hundred A-scans, each scan being 500 pixels deep with a measured spatial resolution of 5.5×10^{-3} mm/pixel. The length of the line was between 2.83-4.00 mm depending on the tooth thus resulting in a transverse resolutions of 28.3-

40.0 μm. The laser is focused to a thin line on the sample surface with a total optical power of 750 μW for all image sets. Sequential B-scans were acquired approximately 200 μm apart.

Samples were imaged in an upright position by affixing the apical root portion of the tooth to a microscope slide using dental rope wax. The approximal surface was again positioned perpendicular to the OCT beam (Fig. 4). The OCT-2000 system has an integrated camera for sample viewing and photographic acquisition during data collection.

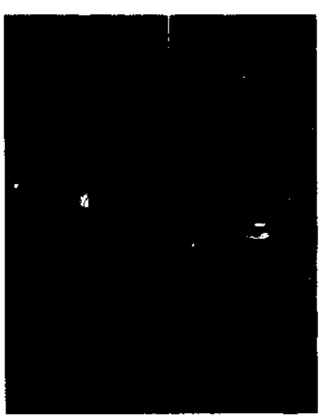

Fig. 3. Photograph of the sampling orientation for the 1310 nm OCT galvanometer imaging system.

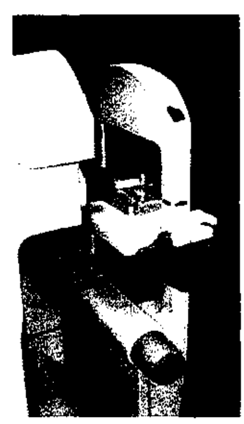

Fig. 4. Photograph of the sampling orientation for the Humphrey OCT-2000 850 nm OCT imaging system.

3. RESULTS AND DISCUSSION

For this study, three different OCT systems were used to acquire images from the approximal surfaces (i.e. mesial and distal surfaces) of the same set of samples. Table 1 summarizes the key parameters of each of these systems

Table 1: Summary of the OCT system parameters used to examine tooth samples.

	Rotary Catheter Imaging System	**Galvanometer Imaging System**	**Humphrey OCT-2000 Imaging System**
Central wavelength	1310 nm	1310 nm	850 nm
OCT source	SLED	SLED	SLED
Axial/depth resolution	11 μm	12 μm	15 μm
Step-size between A-scans	15 μm	5 μm	28.3 μm to 40.0 μm
Step-size between B-scans	105 μm	100 μm	200 μm
Beam spot size (transverse/lateral resolution)	40 μm	24 μm	10-20 μm
Depth scanned	4 mm	4 mm	3 mm (not all range is captured)
Time to scan 2-dimensional region of interest (relative to other systems used in this study)	fast	slow	very slow

We compared the data from the rotary catheter imaging system at 1310 nm to the data from the galvanometer system where the approximal surface is accessible in order to evaluate whether the features of interest could be observed with the catheter system. Furthermore, we chose to compare the data also with the 850 nm system as we have previously conducted extensive studies with the 850 nm system and are familiar with identifying incipient lesions from these images. In addition, the background noise level is lower with the 850 nm system compared with the 1310 nm systems thus facilitating the identification of regions of interest.

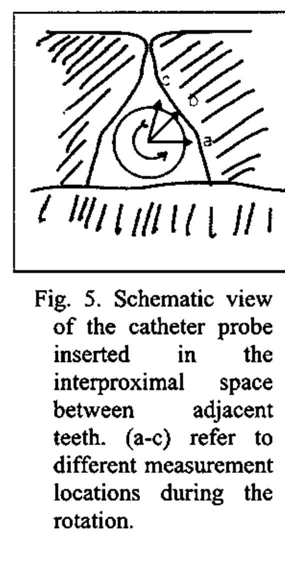

Fig. 5. Schematic view of the catheter probe inserted in the interproximal space between adjacent teeth. (a-c) refer to different measurement locations during the rotation.

The interproximal space between adjacent teeth presents an interesting challenge for caries management. This region is prone to trapped food particles and the build up of plaque therefore requiring attention through brushing and flossing. For caries diagnosis, dental clinicians do not have tools to visually access these regions therefore making diagnosis difficult. The interproximal space is limited at the bottom by the gingiva (gum tissue) and its surface forms a triangular shape with the adjacent teeth. The diameter of any probe to access this region limits the height at which the probe can be located between the teeth. The OCT imaging probe developed rotates continuously (from a to c and then to a again) as illustrated in the diagram (Fig. 5). The angle of incidence of the beam relative to the tooth surface remains relatively normal (perpendicular) for the lower portion of the tooth (a and b) but becomes increasingly oblique while the beam targets the upper surface of the tooth (c). The penetration of the OCT beam might not be as deep as in the lower portion of the tooth. Therefore, caution must be taken when making interpretation of the results in the upper portion of the teeth.

In Fig. 6, the approximal surfaces (distal and mesial) of two adjacent teeth, human central incisor and canine, are shown. Visual clinical examination of the extracted teeth reveals that there is evidence of early carious lesions. The lesion on the distal surface is larger in diameter, more advanced and stained brown. Also apparent are chalky white areas due to the deposition of calculus along the gumline where the enamel crown meets the root. The OCT image obtained when using the rotary catheter probe inserted into the interproximal space is shown in Fig. 7. On the left is the distal surface of tooth 2.2 and on the right is the mesial surface of tooth 2.3. In the centre, the concentric circles represent the imaging catheter probe along

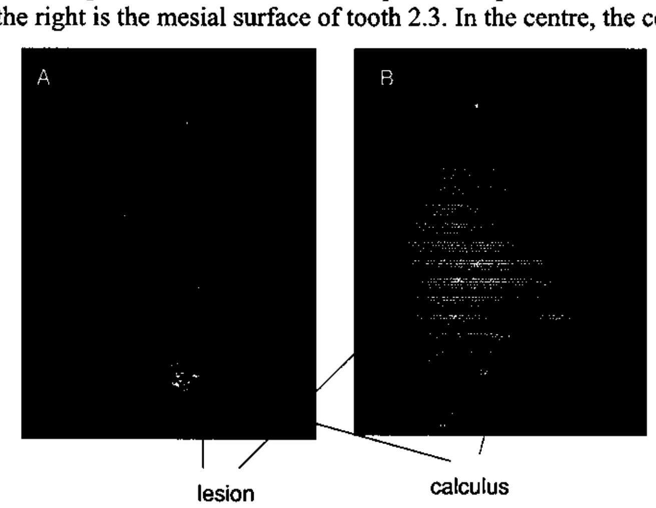

Fig. 6. Photographs of the (A) distal surface and (B) mesial surface of two adjacent teeth (tooth 2.2 and 2.3, respectively). Regions of early carious lesions are marked along areas of accumulated calculus.

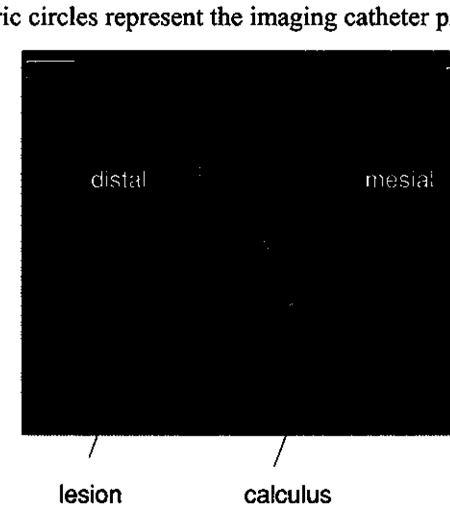

Fig. 7. OCT B-scan image acquired using the 1310 nm rotary OCT catheter probe inserted between tooth 2.2 (distal surface) and 2.3 (mesial surface).

with the inner and other walls of the guiding catheter that protects the OCT probe optics. The classical triangular shape of the interproximal space is apparent. In this mock setup, the gingival tissue is not present and thus not observed on the image. On the distal surface (left), increased scattering is observed at the enamel surface as well as into the depth of the enamel. This increased light back-scattering can be attributed to the presence of the early lesion. The shallow lesion on the opposing mesial surface is not well visible although the calculus deposit lower on the tooth surface is clearly observed. These observations on the mesial surface could be that the probe diameter limits access to the lesion that is positioned towards the top of the crown. Alternatively, as described above, the angle of the beam is oblique to the tooth surface and is not well suited for imaging the higher lesion. Future studies are aimed at reducing the probe diameter to gain access to the apex of the triangular space and possibly improved imaging of lesions below the contact point.

For comparison, the OCT images obtained with the galvanometer system on the exposed approximal surface is shown in Fig. 8. Since access is not the limiting issue in this measurement configuration, OCT images of the entire tooth surface is possible. This system has comparable axial OCT imaging resolution as the rotary system with measurements acquired at 3-fold higher transverse resolution and better depth penetration. The tooth crown and root morphology are clearly visible as is the dentinoenamel junction where the enamel crown meets the underlying dentin. With both surfaces, high light back-scattering intensities at the sites of the lesions are visible and it is clear that the lesion on the mesial surface is smaller than that on the distal surface. Also visible are the calculus deposits on both surfaces. Although the galvanometer system provides superior quality imaging with much anatomical and pathological detail, its open access configuration limits its clinical utility *in vivo*.

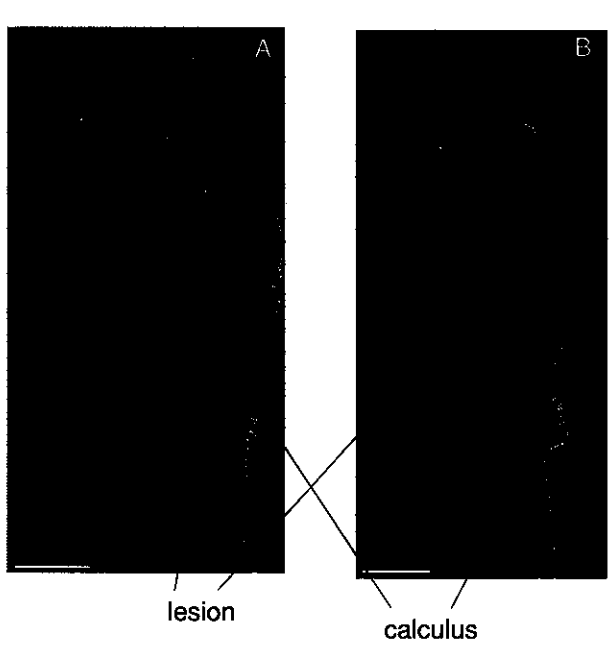

Fig. 8. OCT B-scan images acquired from the 1310 nm galvanometer system of the (A) distal surface and (B) mesial surface of two adjacent teeth (tooth 2.2 and 2.3, respectively). Regions of early carious lesions are marked along areas of accumulated calculus.

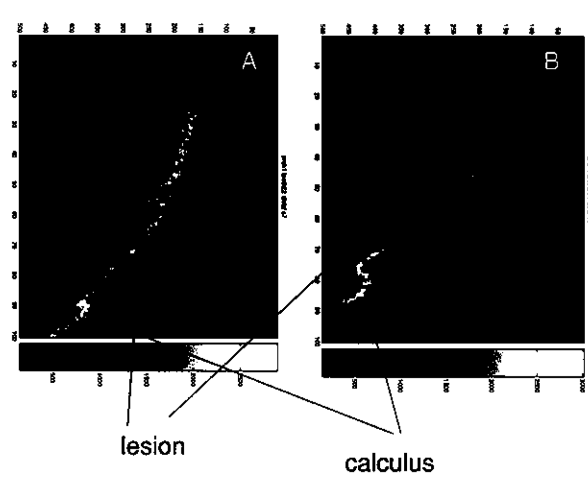

Fig. 9. OCT B-scan images acquired from the 850 nm system of the (A) distal surface and (B) mesial surface of two adjacent teeth (tooth 2.2 and 2.3, respectively). Regions of early carious lesions are marked along areas of accumulated calculus.

Finally, in Fig. 9 we present the OCT images obtained from the 850 nm system. The depth penetration of this system is lower than the 1310 nm systems, however, the images of the early carious lesions have good resolution. The overall background speckle noise level of these images is lower. This makes it easier to discern the lesion edges and lesion depths, two parameters that would be clinically relevant. The shallower depth penetration and requirement for open access configuration also restricts the use of this wavelength and setup for clinical use.

In conclusion, we have successfully demonstrated the first (to our knowledge) OCT images acquired from the interproximal space using a catheter probe. The images reveal tooth morphology, areas of early carious lesions as well as evidence of calculus in the interproximal space. Future developments aimed at decreasing the OCT probe diameter as well as increasing the depth of field will provide improved images that can potentially be useful for clinical caries assessment *in vivo*.

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