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ISBN
978-1-5106-3197-7

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Publication Date
2020-02-01

DOI
10.1117/12.2550982

Peer reviewed

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Nai-Yuan Chang, Yihua Zhu, Donald Curtis, Oanh Le, Vincent Yang, Wiliiam A. Fried, Jacob C. Simon, Prajna Banan, Cynthia L. Darling, Daniel Fried, "SWIR, thermal and CP-OCT imaging probes for the in vivo assessment of the activity of root caries lesions," Proc. SPIE 11217, Lasers in Dentistry XXVI, 1121708 (19 February 2020); doi: 10.1117/12.2550982

SPIE.

Event: SPIE BiOS, 2020, San Francisco, California, United States

SWIR, Thermal and CP-OCT imaging probes for the *in vivo* assessment of the activity of root caries lesions

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ABSTRACT

New imaging technologies are needed for the clinical assessment of lesions on root surfaces. It is not sufficient to simply detect caries lesions; methods are needed to assess lesion depth, structural composition and activity to determine if chemical intervention has the potential to be effective and if remineralization has occurred. Lesions were monitored using CP-OCT during lesion dehydration to assess the lesion structure and any shrinkage. Thermal imaging at 6-10 μm wavelengths and short wavelength-IR imaging at 1450-1750-nm were used to monitor thermal emission during lesion dehydration to assess lesion activity. Imaging probes were custom fabricated for clinical use. We present the first clinical results of a small feasibility study employing CP-OCT, thermal and SWIR imaging to assess lesion activity *in vivo* on thirty test subjects with suspected root caries lesions.

Keywords: root caries, CP-OCT, lesion activity, thermal imaging, SWIR imaging

1. INTRODUCTION

Root caries is an increasing problem with our aging population and likely to be an increasing concern because of an increase in number of people maintaining teeth [1-3]. Tooth loss is the most significant oral health-related negative variable of quality of life for the elderly [4]. Clinical diagnosis of root caries is highly subjective and is based on visual and tactile parameters. In contrast to coronal caries, root caries lacks a valid diagnostic standard, such as radiography [5]. Moreover, early root caries lesions are much more difficult to detect than the early incipient white spot lesions seen with coronal caries. There are often no clinical symptoms with root caries, although pain may be present in advanced lesions. Traditional methods of visual-tactile diagnosis for root caries can result in a correct diagnosis, but not until the lesion is at an advanced stage [5]. In addition, investigators have not developed a reliable relationship of appearance with lesion activity [6-8]. Even though most experts agree that active root lesions are soft, tactile hardness assessments remain subjective and lack reliability [6]. Multifactorial root caries scoring systems have been developed with mixed success [9, 10]. More recently, the International Caries Detection and Assessment System (ICDAS) coordinating committee and Ekstrand et al. proposed clinical scoring systems for assessing root caries lesion activity [9, 11]. Criteria include: color (light /dark brown, black); Texture (smooth, rough); Appearance (shiny or glossy, matte or non-glossy); Tactile (soft, leathery, hard); Cavitation (loss of anatomical contour); and proximity to the gingival margin [12]. However, such clinical methods for root caries lesion activity assessment lack histological validation and are composed of visual and tactile exams, which are prone to subjective bias and interference from staining [13]. Histological analyses for lesion assessment such as transverse microradiography (TMR) and polarized light microscopy (PLM) require destruction of the tooth and are not suitable for use *in-vivo*. Incorrect diagnosis can result in under treatment or over treatment.

Several studies have demonstrated that CP-OCT can be used to quantify changes in the demineralization of enamel and dentin and measure the internal structure and depth of lesions with high-resolution. CP-OCT studies have successfully measured demineralization in simulated caries models in dentin and on root surfaces (cementum) [14-16]. CP-OCT can be used to accurately discriminate demineralized dentin from sound dentin and cementum [14]. CP-OCT has also been used to measure remineralization on dentin surfaces and to detect the formation of a highly mineralized layer on the lesion surface after exposure to a remineralization solution [16]. Cementum has lower reflectivity than dentin in OCT images, making it possible to easily discriminate the remaining cementum thickness

Lasers in Dentistry XXVI, edited by Peter Rechmann, Daniel Fried, Proc. of SPIE Vol. 11217,
1121708 · © 2020 SPIE · CCC code: 1605-7422/20/$21 · doi: 10.1117/12.2550982

[14, 16]. OCT has also been used to help discriminate between noncarious cervical lesions and root caries *in vivo* [17]. Arrested root caries lesions typically form an outer layer of highly mineralized dentin that reduces the permeability of the lesion that limits further mineral loss. Furthermore, we have demonstrated the unique ability of CP-OCT to nondestructively determine the thickness of the highly-mineralized transparent surface zone formed on the outside surface of dentinal lesions during remineralization [15, 16, 18]. Therefore, we postulate that CP-OCT is well suited for detecting structural differences in active and arrested lesions. Several studies have shown that the unsupported collagen matrix of the demineralized cementum and dentin in active root lesions manifests considerable shrinkage with loss of water [3, 14]. OCT is well suited for the accurate measurement of dimensional changes *in vivo*. In a recent study we showed that the shrinkage can also be measured during drying by measuring the contraction of the thickness of the demineralized dentin in addition to the change in the position of the lesion surface [3]. We fabricated autoclavable probes with an integrated air-nozzle to fit on the CP-OCT handpiece to measure shrinkage *in vivo* during forced air-drying. CP-OCT can also be used to assess shrinkage, lesion depth, integrated reflectivity over the lesion depth and the surface zone thickness. Therefore, the lesion structure and shrinkage measured with CP-OCT can both be used to assess lesion activity.

Significant changes in surface porosity occurs when a root surface lesion is arrested due to remineralization. Since the heat of water vaporization is large, the use of forced air to evaporate water from dentin pores near the lesion surface induces a large drop in the lesion temperature that can be imaged with a thermal camera. Arrested lesions are less permeable since mineral has filled many of the pores resulting in less water loss and they undergo smaller temperature changes from forced air-drying. The optical changes associated with water loss have been investigated *in vitro* via thermal, fluorescence, and near-IR imaging for lesions on enamel surfaces [19-21]. The only clinical study that has been carried out employing optical methods to assess lesion activity via forced air-drying used fluorescence on smooth surface enamel lesions [22]. The organic scaffold and dentinal tubules are occupied by mostly water when hydrated [23]. The capacity of water retention of dentin increases with the increase in severity of demineralization [24]. Kaneko et al. and Zakian et al. carried out thermal imaging studies using an infrared camera and an air-jet for evaporation on occlusal and smooth natural tooth enamel surfaces [19, 25] to detect lesions. Lee et al. [18] demonstrated that thermal imaging was highly effective *in vitro* on assessing the activity of simulated and natural lesions on root surfaces. Compact and inexpensive high-resolution thermal cameras are now available for intraoral imaging.

Another approach to assessing lesion activity is to use short wavelength IR imaging (SWIR). Several studies have shown that SWIR imaging at wavelengths from 1450-1750-nm can be used to assess lesion activity on coronal surfaces due to the large change in lesion contrast during drying [26, 27]. SWIR images can also be used to show high contrast images of calculus and demineralization on root caries lesions on extracted teeth[28]. In a recent study, SWIR imaging was effective in assess changes in the activity of simulated lesions on dentin however SWIR imaging was not as effective on natural root caries lesions on extracted teeth [18].

In this study, thirty test subjects with at least one suspected active root caries lesion were imaged with CP-OCT, SWIR and thermal imaging during the drying of one of the lesions with air for thirty seconds to assess the potential of these three novel approaches for assessing the activity of lesions on root surfaces *in vivo*.

2. MATERIALS AND METHODS

2.1 Participant Recruitment and Procedures

Thirty test subjects at the UCSF comprehensive clinics were recruited for this study (UCSF IRB 18-24558). The test subjects were aged 18-90 and had one root caries lesion that was accessible to imaging and was determined to be active based on conventional assessment. Each lesion was imaged with a cross-polarized USB camera with a dental mirror and the color, texture (roughness) and softness were assessed. Two 3D cross polarization images of the lesion were acquired while it was wet and after it had been dried for 30 seconds with air at 10-psi. In addition a 2D image (b-scan) was recorded while the lesion was dried for 30 seconds. The lesion was wetted and thermal images were recorded for 30 seconds during drying. Images were also acquired using SWIR imaging at 1450-1750-nm as the lesion was dried for 30 seconds.

2.2 SWIR Reflectance (1450-1750-nm)

A high sensitivity, InGaAs, micro-SWIR camera (SU640CSX) measuring only 32 x 32 x 28 mm from Sensors Unlimited (Princeton, NJ), with a 640x512-pixel focal plane array and 12.5-µm pixel pitch was used to capture SWIR images from 1450-1750-nm. A SLS201L Stabilized Tungsten-Halogen lamp from Thorlabs (Newton, NJ) with a 1450-nm longpass filter and a 1 mm in diameter low-OH optical fiber was used as the light source for reflectance. A lens assembly consisting of 1 inch in diameter f=75 and 60 mm lenses along with an adjustable aperture was attached to a 3D printed handpiece equipped with a 10 mm aluminium mirror with channels for air and the 1 mm optical fiber. The distal end of the 1 mm fiber was inserted into a Teflon plug to provide diffuse illumination. Air at 10 psi was connected to the probe as shown in Fig. 1 to prevent fogging of the handpiece window and to facilitate dehydration of the lesion.

The handpiece body was printed with standard black resin from Formlabs (Somerville, MA) using Form 2 and 3 printers. A cap was also printed using biocompatible Dental LT resin which was held in contact with the tooth surface. All parts of the probe with the exception of the Dental LT cap was covered with polypropylene film for infection control as shown in Fig. 1. Image acquisition was carried out using a custom program using Labview™ from National Instruments (Austin, TX). See paper 11217-18 in this proceedings.

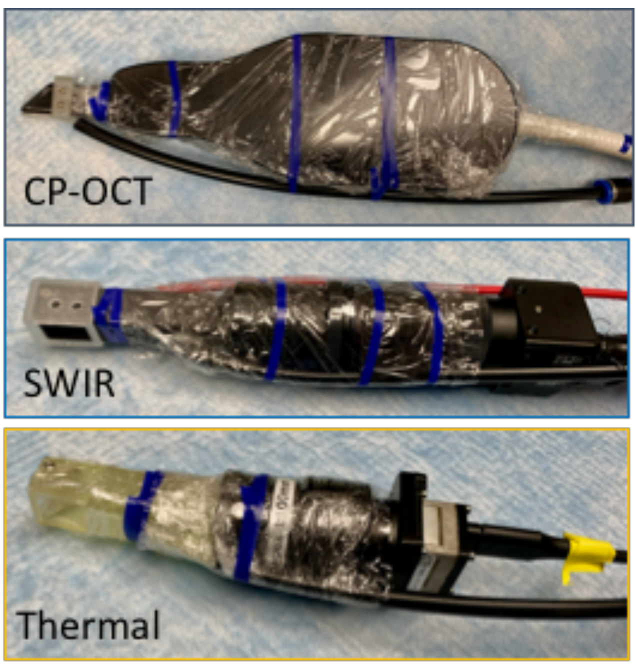

Fig. 1. The three imaging probes used to image each of the root caries lesions.

2.3 Cross Polarization Optical Coherence Tomography (CP-OCT)

The cross-polarization OCT system used for this study was purchased from Santec (Komaki, Aichi, Japan). This system acquires only the cross polarization image (CP-OCT), not both the cross and co-polarization images (PS-OCT). The Model IVS-3000-CP utilizes a swept laser source; Santec Model HSL-200-30 operating with a 30 kHz a-scan sweep rate. The Mac-Zehnder interferometer is integrated into the handpiece which also contains the microelectromechancial (MEMS) scanning mirror and the imaging optics. It is capable of acquiring complete tomographic images of a volume of 6 x 6 x 7 mm in approximately 3 seconds. The body of the handpiece is 7 x 18 cm with an imaging tip that is 4 cm long and 1.5 cm across. This system operates at a wavelength of 1321-nm with a bandwidth of 111-nm with a measured resolution in air of 11.4 µm (3 dB). The lateral resolution is 80-µm ($1/e^2$) with a transverse imaging window of 6 mm x 6 mm and a measured imaging depth of 7-mm in air. The polarization extinction ratio was measured to be 32 dB. An appliance made of Dental LT resin was placed on the distal end of the OCT scanning handpiece and the handpiece was covered with polyethylene film for infection control. Air at 10 psi was connected to the probe as shown in Fig. 1 to prevent fogging of the mirror and to facilitate dehydration of the lesion.

2.4 Thermal Imaging Camera

Thermal images were captured using a FLIR Boson 640 (Wilsonville, Oregon) thermal camera that uses an uncooled vanadium oxide microbolometer with a 12 µm pixel pitch, a 640 x 512 array and a thermal sensitivity of 50 mK. The spectral range is 7.5 - 13.5 µm. The size of the camera itself is only 21 x 11 x 11 mm equivalent to a 4.9 cm^3 volume. The camera was equipped with the 24 mm focal length lens and an additional 100 mm focal length planoconvex ZnSe lens attached to a handpiece 3D-printed using a Formlabs 2 printer (Somerville, MA) as shown in Fig. 1. The handpiece was printed using biocompatible and autoclavable Dental SG resin and a 12.5 mm aluminum right angle mirror was attached at the distal end of the handpiece. An air nozzle is attached to the appliance to provide air to dehydrate the lesion area at 10 psi. Thermal captures occurred in a 30 second time window at 4 frames per second. Image acquisition was carried out using a custom program using Labview. The resolution of each captured frame was 293 x 277 pixels. See paper 11217-17 in this proceedings.

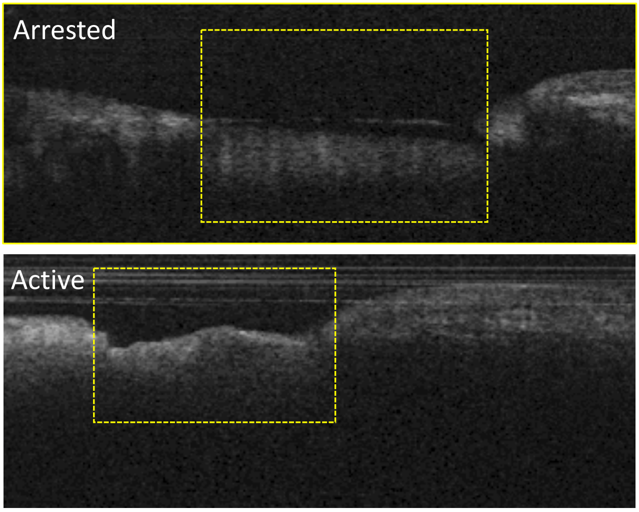

Fig. 2. Two b-scan CP_OCT images of root caries lesions with "arrested" and without "active" transparent surface zones visible at the surface of the lesions. Lesions in yellow box. From same teeth shown in Fig. 3.

3. RESULTS AND DISCUSSION

In this study thirty root caries lesions were imaged on thirty test subjects. This was the first time that we used an appliance on the OCT scanner to provide dehydration of the lesion and it worked well. The air also prevented condensation on the OCT window which had been a problem in past OCT imaging studies in which we had to have an assistant blow air on window during imaging. We did have considerable difficulty holding the handpiece steady during imaging and we will have to determine whether we are able to successfully show lesion shrinkage during lesion dehydration. We were able to acquire high quality OCT images of the root caries lesions, resolve the transparent surface zones that were present and see visible changes in the root caries lesions during dehydration. Two OCT b-scans acquired from two of the lesions are shown in Fig. 2. A transparent surface zone was visible on one of the lesions which suggests that the area of that lesion is likely arrested. In contrast, there is no surface zone visible near the surface in the CP-OCT b-scan of the other lesion that is shown in Fig. 2 and on most of the other lesions imaged during the study.

In the original study we had not planned to include SWIR imaging during dehydration since the method was not as effective for natural root caries lesions on extracted teeth as it was for simulated lesions on dentin. In our preliminary assessment of its performance in this study it appeared to be effective for only a few lesions and dehydration for 30 seconds did not appear sufficient to dehydrate most lesions.

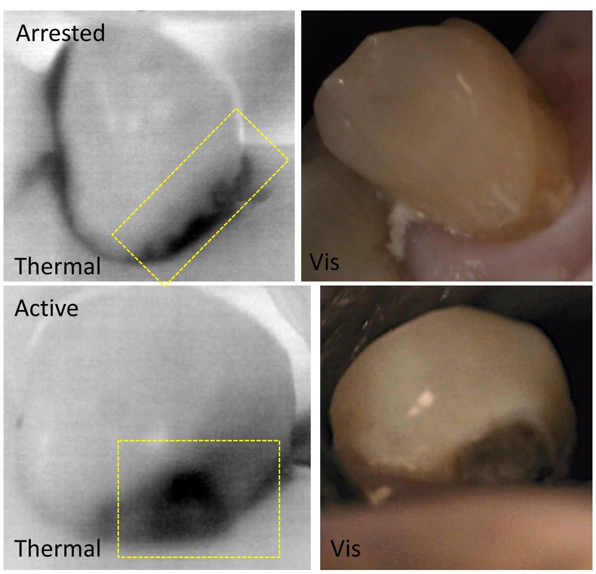

Fig. 3. Two thermal and visible images of root caries lesions with "arrested" and without "active" transparent surface zones visible at the surface of the lesions. Lesions in yellow box.

To the best of our knowledge this was the first clinical study involving the thermal imaging of caries lesions and thermal imaging appears to show great potential. Most of the lesions were visible in the thermal images and the time course of the thermal emission from the lesion area during dehydration was distinctly different from the sound regions of the tooth. Matching color and thermal images are shown in Fig. 3 for two of the lesions that are shown in the CP-OCT scans of Fig. 2. The lesion in the top images appeared arrested in the CP-OCT scans with a surface layer visible and the bottom lesion appeared active. There were some initial complications. For example, for one of the first few test subjects, we noticed that an air pressure of 5 psi was too low and the test subjects breathing interfered with the measurements. Subsequently, we raised the air pressure to 10 psi and the fluctuations due to breathing were less noticable.

In summary, based on the initial results of this pilot study, thermal and CP-OCT imaging appear highly promising for the clinical assessment of lesion activity on root surfaces. The imaging data will be analyzed over the next few months and we hope to confirm this initial assessment and publish a more complete account of this study.

4. ACKNOWLEDGEMENTS

The authors would like to acknowledge the support of TRDRP Grant 27IP-0015, NIDCR/NIH grants R01-DE027335, F30-DE027264 and F30-DE026052.

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