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A SWIR imaging handpiece for the clinical assessment of lesion activity via dehydration. Preclinical Assessment

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Abstract

New imaging methods are needed to assess the activity of caries lesions on tooth surfaces. Recent studies have shown that changes in the contrast of lesions during dehydration with air at SWIR wavelengths can be used to determine if lesions are active or arrested. In this study changes in the reflectance of caries lesions during dehydration with air was monitored at 1500-1750-nm on extracted teeth using an imaging system with an InGaAs camera, a light source and a 3D printed handpiece with an integrated air nozzle suitable for clinical use. Lesion structure was also assessed with optical coherence tomography and microCT for comparison. This small preclinical study demonstrated that a 3D printed appliance with integrated air for dehydration can be used to acquire SWIR dehydration curves similar to those acquired previously for benchtop imaging systems.

Keywords

SWIR imaging; caries detection; reflectance imaging; lesion activity

1. INTRODUCTION

Caries lesions can be arrested by the preferential deposition of mineral at the lesion surface that inhibits diffusion into the lesion and reduces the rate of water loss [1–3]. Since arrested lesions do not need further intervention, an accurate assessment of lesion activity is paramount for clinical diagnosis.

Many lesions have been arrested or do not require intervention. Even so, it is difficult to identify active lesions with current diagnostic methods. Accurate assessment of lesion activity, depth, and severity is important to determine whether intervention is necessary. Gold standards for lesion assessment such as transverse microradiography (TMR) and polarized light microscopy (PLM) either require destruction of the tooth, or in the case of microCT are unsuitable for use *in-vivo*. New non-destructive diagnostic tools are needed that can assess lesion activity with a single measurement (time-point). Effective employment of new optical diagnostic technologies that can exploit the changes in the light scattering of the lesion have great potential for diagnosing the present state of the lesions. Therefore, the development of new methods, such as short wavelength infrared (SWIR) imaging, are needed for the clinical assessment of lesion activity to avoid unnecessary cavity preparations.

When lesions become arrested by mineral deposition, or remineralization, in the outer layers of the lesion, the diffusion of fluids into the lesion is inhibited. Hence, the rate of water diffusion out of the lesion reflects the degree of lesion activity. Previous studies have demonstrated that the optical changes due to the loss of water from porous lesions can be exploited to assess lesion severity and activity with fluorescence, thermal, and SWIR imaging [4–10]. Since arrested lesions and developmental defects (fluorosis) are less permeable to water due to the highly mineralized surface layer, changes in the rate of water loss can be related to changes in lesion structure and porosity. We have investigated optical methods for assessing water diffusion rates from lesions since the porosity of the outer layers of active lesions is significantly greater than arrested lesions. This can be indirectly measured via SWIR reflectance methods [11–13]. Normal enamel is transparent at SWIR wavelengths, whereas early demineralization causes increased SWIR reflectance due to scattering. Water in the pores at the surface of the lesion absorbs the incident SWIR light, particularly at wavelengths greater than 1450 nm, reducing surface scattering and lesion contrast. Loss of that water during dehydration produces a marked increase in reflectivity and lesion contrast.

The only clinical study that has been carried out using optical methods to assess lesion activity via forced air-drying employed fluorescence on smooth surface enamel lesions [7]. The purpose of this study is to develop and evaluate a SWIR reflectance probe suitable for lesion activity measurements *in vivo*. Measurements were performed on extracted teeth with lesions on tooth occlusal and interproximal surfaces. Higher resolution OCT and microCT images of lesion structure were used as a gold standard to assess lesion activity for comparison.

2. MATERIALS AND METHODS

2.1 Sample Preparation

Twelve extracted teeth were selected with occlusal and interproximal lesions for participation in this study. Teeth were collected from patients in the San Francisco Bay area with approval from the UCSF Committee on Human Research. The teeth were sterilized using gamma radiation and stored in 0.1% thymol solution to maintain tissue hydration and prevent bacterial growth.

The teeth were imaged using Microcomputed X-ray tomography (μ CT) with a 10- μ m resolution. A Scanco μ CT 50 from Scanco USA (Wayne, PA) located at the UCSF Bone Imaging Core Facility was used to acquire the images.

2.2 Design and Fabrication of SWIR Dehydration Imaging Probe

The probe was designed in Fusion 360 from Autodesk (San Francisco, CA). The reflectance probe body utilized black resin to reduce artifacts from unwanted scattering in the probe assembly. A side view of the reflectance probe body is shown in Fig. 1A. The reflectance fiber comes in from the back of the probe, and light is diffusely scattered to the sample. The bottom of the reflectance probe is designed to be attached to the camera, and the camera view is reflected off an aluminum mirror fitted to a 45-degree angle attached to the top of the

probe. There is an air nozzle near the mirror to prevent fogging of the mirror. The air nozzle can also be used to dry the lesion to increase lesion contrast and potentially assess lesion activity [8–10].

2.3 SWIR Dehydration Measurements

Each tooth was immersed by hand in a water bath for 30 seconds while being vigorously shaken to enhance water diffusion. After the sample was removed from the water bath, an image was captured as an initial reference image and the air spray was activated. Each measurement consisted of capturing a sequence of images at 1 frame per second for 240 seconds. For each measurement, the air nozzle and the light source were centered on the region of interest (ROI) which encompasses the entire enamel/dentin sample. The dehydration setup was completely automated using Labview™ (National Instruments, Austin, TX). A SLS201L Stabilized Tungsten-Halogen lamp from Thorlabs (Newton, NJ) with a 1500-nm longpass filter and a 1 mm in diameter low-OH optical fiber was used as the light source for reflectance. The SWIR reflectance images were captured using a 12-bit Model GA1280J (Sensors Unlimited, Princeton, NJ) with a 1280 x 1024 pixel format and 15- μm pixel pitch. A lens assembly consisting of 1 inch in diameter $f=200$ 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 25 psi was connected to the probe as shown in Fig. 1 for dehydration of the lesion. The handpiece body was printed with standard black resin from Formlabs (Somerville, MA) using Form 2 and 3 printers. For clinical use 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. 1B. Image acquisition was carried out using a custom program using Labview™ (National Instruments, Austin, TX).

2.4 Optical Coherence Tomography (OCT)

An IVS-2000-HR-C OCT system purchased from Santee (Komaki, Aichi, Japan) was used for this study. This system utilizes a swept laser source and a handpiece with a microelectromechanical (MEMS) scanning mirror and the imaging optics. It is capable of acquiring complete tomographic images of a volume of 5 x 5 x 5 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 1312-nm with a bandwidth of 173-nm with a measured resolution in air of 8.8 μm (3 dB). The lateral resolution is 30- μm ($1/e^2$) with a transverse imaging window of 5 mm x 5 mm and a measured imaging depth of 5-mm in air.

3. RESULTS AND DISCUSSIONS

Twelve lesions were imaged on extracted teeth. The lesions were chosen based on microCT images of each tooth and three lesions were chosen for each group: arrested and active interproximal and arrested and active occlusal. If a highly mineralized surface zone was

present on the microCT image of the lesion the lesion was considered arrested. OCT images were also taken of tire arrested lesions confirming that a transparent surface zone was present. If there was no obvious highly mineralized or transparent surface zone present, the lesion was considered active. SWIR reflectance dehydration measurements for two of tire interproximal lesions are shown in Fig. 2. The active lesion changes very rapidly and most of tire changes occurred in the first 60 seconds. Mean dehydration curves for the four lesion types are shown in Fig. 3. For active lesions the overall intensity change, I , is greater and the intensity change is more rapid. To compare tire dehydration curves between each sample group, the curves were fitted to a sigmoid functions, where a - c are coefficients and $I(t)$ is the intensity value at time (t) in seconds. The Levenberg-Marquardt algorithm was used to estimate the best fit of each curve to the equation. The overall growth rate (OGR) of the function was given by a/b [8, 9].

$$I(t) = \frac{a}{1 + e^{\frac{c-t}{b}}} + d$$

Each curve was fit using Igor Pro from Wavemetrics (Portland, OR) and the OGR was calculated. The OGR was compared between both active and arrested sample groups using a one-tailed t-test, Fig. 4. With a P value of 0.036 the difference in OGR between both active and arrested samples was statistically significant ($P < 0.05$).

This small preclinical study demonstrated that a 3D printed appliance with integrated air for dehydration can be used to acquire SWIR dehydration curves similar to those acquired previously by benchtop imaging systems. This appliance has been attached to a small micro-SWIR InGaAs camera as shown in Fig. 1 and is currently being used for a small clinical study involving the activity of root caries (see paper 11217-8 of this proceedings) and another clinical study of the activity of occlusal caries on primary teeth.

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Fig. 1.
(A) The 3D printed imaging probe body and (B) the fully assembled probe with miniature InGaAs array ready for *in vivo* imaging.

Fig. 2. SWIR reflectance images for active and arrested interproximal lesions at different timepoints. The intense spot in the active lesion at $t=0$ is specular reflection.

Fig. 3.
Mean dehydration curves for occlusal and interproximal lesions (n=3 each group).

Fig. 4. Correlation between NIR reflectance dehydration measurement and the thickness of the transparent surface layer measured by PS-OCT. $r^2 = 0.42$.