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A thermal imaging handpiece for the clinical assessment of lesion activity on root surfaces via dehydration

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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 thermal imaging of lesions on root surfaces during dehydration with air can be used to determine if the lesions are active or arrested. In this study changes in the thermal emission of root caries lesions on extracted teeth during dehydration with air was monitored using an imaging system with a miniature thermal camera and a 3D printed handpiece with an integrated air nozzle suitable for clinical use. This study evaluated the performance of the thermal camera for imaging root caries on extracted teeth prior to its use for *in vivo* studies. There was a significant difference in the thermal response of sound and root lesion areas of human teeth under dehydration at constant airflow.

Keywords

thermal imaging; caries detection; reflectance imaging; lesion activity

1. INTRODUCTION

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 [1]. 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 [1]. In addition, investigators have not developed a reliable relationship between lesion appearance and activity [2–4]. Even though most experts agree that active root lesions are soft, tactile hardness assessments remain subjective and lack reliability [2]. Multifactorial root caries scoring systems have been developed with mixed success [5, 6]. 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 [5, 7]. 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 [8]. However, such clinical methods for root caries lesion activity assessment lack histological validation and are composed of only visual and tactile exams, which are prone to subjective bias and interference from staining [9]. 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. If a decision to restore is made prematurely when remineralization was feasible, the patient is committed to a restoration, or replacement restorations, that can become progressively larger. If the lesion is active and intervention is delayed, often the patient will require a root canal or extraction.

Although the penetration depth of near-IR light is limited in dentin compared to enamel, high quality images of early root caries and demineralization in dentin are feasible [14]. CP-OCT has been used successfully to measure demineralization in simulated caries models in dentin and on root surfaces (cementum) [12, 15, 16]. 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]. OCT has also been used to help discriminate between noncarious cervical lesions and root caries *in vivo* [17]. Kaneko et al. and Zakian et al. [18, 19] demonstrated that lesions on coronal surfaces could be differentiated from sound enamel in thermal images. We recently demonstrated that thermal imaging via dehydration can be used to assess lesion activity on both enamel [20] and dentin surfaces. In previous studies, thermal imaging during lesion dehydration was more successful than near-IR imaging for assessing lesion activity on root and dentin surfaces [21]. In this study we built a handheld thermal imaging probe with a miniature thermal camera and a 3D printed handpiece with an integrated air nozzle suitable for clinical use. We evaluated the performance of the handheld thermal imaging probe for imaging root caries on extracted teeth prior to use for *in vivo* studies.

2. MATERIALS AND METHODS

2.1 Sample Preparation

Teeth (n=16) containing root lesions extracted from patients in the San Francisco Bay Area were collected, cleaned, sterilized with gamma radiation, and stored in a 0.1% thymol solution. These teeth were then mounted on 1.2 x 3 cm rectangular blocks of black orthodontic composite resin with the outward tooth lesion surface facing upwards.

2.2 Handheld Thermal Imaging System

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 integrated 24 mm focal length lens and an additional 100 mm focal length planoconvex ZnSe lens was attached to a handpiece 3D-printed using a Formlabs 2 printer (Somerville, MA) as shown in Fig. 1. The handpiece was printed using the standard black resin and a right angle mirror was attached at the distal end of the handpiece. An air nozzle was attached to the appliance to provide air to dehydrate lesion and sound areas at a set airflow. Image acquisition was carried out using a custom program using LabviewTM from National Instruments (Austin, TX).

For this study, 16 extracted teeth containing root lesions stored in 0.1% thymol solution prior to imaging were used. Samples were removed from the solution and placed under the window of the handpiece in contact for thermal capture. The resolution of each captured frame was 293 x 277 pixels. Airflow over the samples was set at 5 psi. Frames were captured at 4 frames per second for a period of 60 seconds. Thermal images acquired at different time points over a period of 60 seconds of drying are shown in Fig. 2.

2.3 Analysis of Thermal Emission Curves

Figure 3 provides a flowchart of the steps taken in analyzing the thermal images. For each sample, a 5x5 pixel lesion area and corresponding 5x5 sound area were identified as regions of interest (ROI). These two areas were tracked over the total duration of time for intensity changes. For each 5x5 area, the intensity of all pixels within that area was averaged at each time point.

Thermal curves were inspected and found to have a sharp dip in intensity, followed by a gradual asymptotic growth to a final intensity level. This behavior corresponds to the evaporation of water, cooling the surface of the tooth, and then gradual warming back to ambient temperature. To simplify analysis, the curves were split in two at the minimum intensity. The minimum intensity is where the intensity changes from a negative to a positive slope and is representative of the coolest temperature the sample reaches over the experimental time. The corresponding time and intensity at that point are noted as $t_{\min}$ and $I_{\min}$, respectively. The maximum intensity, $I_{\max}$, is the intensity reached after complete thermal drying. These three values are shown on the sample curve in Fig. 4, which is a sample thermal curve of one lesion area of one sample. The intensity values over time after this cutoff were normalized, smoothed using a moving average over 5 time points, and fitted to a three-parameter logistic growth curve. The fit equation is: $I = 1/(1+\exp(a*(t-b)))+c$, where “a” is the growth coefficient. It characterizes the growth in intensity over time.

Another important value is integrated intensity. It is a representative measure of heat leaving the tooth at the region of interest. This value can be found by integrating the area of the curve above the intensity versus time graph, but below the maximum intensity reached. The area is represented in Fig. 4 as Q .

Contrast was calculated over the 60 seconds of drying and is a measure of the visibility of the lesion against the sound surface. Contrast is calculated by taking the difference in intensities between the sound and lesion ROIs and dividing the result by the intensity of the sound ROI. In other words, $(I_S - I_L)/I_S$ for each timepoint.

Growth coefficient, minimum and maximum intensities, Q , and growth start time values were compared between sound and lesion areas using paired t-tests. If $p < 0.05$, then the difference between data was considered significantly different. Tests were carried out using Graphpad Prism (San Diego, CA).

3. RESULTS AND DISCUSSION

A comparison of the images for the 16 samples indicated that there were significant differences ($P < 0.05$) for the growth coefficients, minimum intensities, Q and growth start times between sound and lesion areas, while there was no significant difference for the maximum intensity. Further *in vitro* studies will be carried out comparing active and arrested root caries lesions. Moreover, we have just completed a clinical study on 30 test subjects in which root caries lesions were imaged *in vivo* using this imaging handpiece along with cross polarization optical coherence tomography (CP-OCT). The thermal imaging appeared to work well *in vivo*, and changes in the thermal emission of the lesions were clearly visible. For the clinical study the handpiece was printed with Formlabs high-temperature Dental SG resin which is biocompatible and autoclavable. The results of the clinical study will be submitted for publication in the near future.

Lesion activity is an important characteristic to consider, because it determines whether treatment should be given or withheld. 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 undertreatment or overtreatment. If a decision to restore is made prematurely when remineralization was feasible, the patient is committed to a restoration and often replacement restorations can become progressively larger. If the lesion is active and intervention is delayed, often the patient will require a more invasive and expensive restorative procedure.

There was a significant difference in the thermal response of sound and root lesion areas of human teeth under dehydration at constant airflow. Future studies will attempt to discern between active and arrested lesion areas and understand how active lesions respond to treatment *in-vivo* under clinically relevant timescales.

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Fig. 1.
3D printed prototype appliance for use with the CP-OCT handpiece. The window is centered over the lesion and forced air is delivered through the cylindrical shaped channel to the window.

Fig. 2. Thermal images over time (0, 7.5, 15, 30, and 60 seconds drying elapsed) show the behavior of the lesion compared to the corresponding sound surfaces.

Fig. 3.
Outline of steps taken in the processing of the thermal images.

Fig. 4.

A plot of intensity vs time for the thermal emission showing $I_{\min}$, $I_{\max}$, Q and growth start times.