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The Relationship of Dehydration Rate and Transparent Surface Layer Thickness for Coronal Lesions on Extracted Teeth

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Abstract

Transparent remineralized surface zones found on natural caries lesions may reduce the permeability to water and plaque generated acids. Near-IR (NIR) reflectance imaging coupled with dehydration can be used to measure changes in the fluid permeability of lesions in enamel and dentin. Previous work demonstrated a negative association between the surface zone thickness and the rate of dehydration in simulated enamel lesions. In this study, the rates of dehydration and thickness of transparent surface layer of coronal lesions of extracted teeth were measured and correlated. Reflectance imaging at NIR wavelengths from 1695–1750 nm, which coincides with higher water absorption and manifests the greatest sensitivity to contrast changes during dehydration measurements, was used to image these enamel lesions. The remineralized surface layer thickness was determined using optical coherence tomography (OCT).

Keywords

dental caries; NIR reflectance imaging; lesion dehydration; lesion permeability

1. INTRODUCTION

The majority of newly discovered carious lesions are frequently localized to the occlusal pits and fissures of the posterior dentition and the proximal contact sites between teeth, where they are more difficult to detect. Clinicians mostly rely on tactile and visual examination to determine whether dental decay is active or arrested [1]. If the lesion appears smooth, hard, and dark, it is assumed that it is arrested [2]. However, this method is subjective and unreliable. The challenge lies in that many lesions might be arrested or do not require intervention, and that active lesions are difficult to identify with current diagnostic methods. Accurate assessment of lesion activity, depth, and severity is important to determine whether intervention is necessary. Effective utilization of new optical diagnostic technologies taking advantages of 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 NIR reflectance dehydration imaging, are needed for the clinical assessment of lesion activity and to avoid unnecessary cavity preparations.

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When lesions become arrested due to 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 used to assess lesion severity and activity with QLF, thermal, and SWIR imaging [3–9]. Conversely, arrested lesions and developmental defects (fluorosis) often possess a highly mineralized surface layer, where the rate of water loss is less due to related changes in lesion structure and porosity. We have investigated the use of NIR reflectance methods to indirectly assess water diffusion rates from lesions since the porosity of the outer layers of active lesions is significantly greater than arrested lesions [10–12]. Normal enamel is transparent in NIR wavelengths, whereas early demineralization causes increased NIR reflectance due to scattering. Water in the pores at the surface of the lesion absorbs the incident NIR light, particularly at wavelengths such as 1450 nm and beyond, reducing surface scattering and lesion contrast. Loss of that water during dehydration produces a marked increase in reflectivity and lesion contrast.

New technologies are also needed to determine whether lesions are active and expanding, partially arrested and undergoing remineralization, or fully arrested and remineralized in clinical settings. Optical Coherence Tomography (OCT) may be capable of this task. Previous works have demonstrated that arrested lesions exhibit a well-defined surface zone of reduced reflectivity that can be clearly resolved in OCT images [13–15]. OCT provides high speed and high-resolution measurements of the reflectivity from each layer of the lesion, and is able to detect the formation of a zone with increased mineral density and reduced light scattering due to remineralization.

The purpose of this study is to continue our previous work in developing a method to assess lesion activity by assessing lesion activity of lesions on extracted human premolar and molars (*ex vivo*) [16]. We hypothesize that the thickness of the highly mineralized transparent surface zone formed during remineralization correlates with the lesion permeability and activity in human enamel. We correlated the results from NIR reflectance dehydration measurements and OCT measurements and found that minor changes in surface layer thickness may lead to major changes in fluid permeability in remineralized enamel lesions.

2. MATERIALS AND METHODS

2.1 Extracted Tooth Samples

Fifty extracted human premolar and molars with coronal lesions determined by a clinician were obtained. The teeth were sterilized with gamma radiation and stored in 0.1% thymol. Figure 1 shows the workflow of the study design employed.

2.2 NIR Reflectance (NIR-R) Dehydration Measurements

Each sample was placed in a mount connected to a high-speed XY-scanning motion controller system (Newport, Irvine, CA) ESP301 controller and 850G-HS stages, coupled with an air nozzle and a light source as previously described [7]. Each sample was immersed in the water bath for 30 seconds while being 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. The air pressure was set to 30 psi and the computer-controlled air nozzle was positioned 5 cm away from the sample. Each measurement consisted of capturing a sequence of images at 4 frames per second for 60 seconds. The dehydration setup was completely automated using LabVIEW software (National Instruments, Austin, TX).

A Model SU320KTSX InGaAs focal plane array (Sensor-Unlimited, Princeton, NJ) with a spectral sensitivity range from 900 to 1750 nm, a resolution of 320 × 256 pixels, and an InfiniMite lens (Infinity, Boulder, CO) was used to acquire all the images during the dehydration process. Light from a 150 W fiber-optic illuminator FOI-1 (E Licht Company, Denver, CO) was directed at the sample at an incident angle of approximately 30° from surface normal of the tooth occlusal surface to reduce specular reflection and the source to sample distance was fixed at 5 cm. A FEL LP series long-pass filter at 1695 nm (Thorlabs, Newton, NJ) was used. NIR reflectance images were processed and automatically analyzed using a dedicated program constructed with LabVIEW software. A region of interest (ROI) encompassing the whole sample was used. The intensity difference between the final and initial images, $\Delta I_{(t=60)}$, was calculated using $I_{60} - I_0$, where I_{60} is the mean intensity at t = 60 seconds and I_0 is the mean intensity prior to turning on the air nozzle. Prism 7 (GraphPad Software Inc., La Jolla, CA) was used for regression analysis.

2.3 Optical Coherence Tomography (OCT)

A prototype polarization diversity-detection OCT system (Axsun Technologies, Billerca, MA) with an integrated dental handpiece capable of acquiring high speed 3D scans of the occlusal surface of an entire tooth (8(X) x 8(Y) x 7(Z) mm) was used for this study. The system utilized an Axsun Technologies swept source engine operating at a 100 kHz scan rate and a MEMS scanner for 3D scans. The Axsun engine, fiber interferometer and polarization diversity setup, and MEMS controller were packaged in a console 250 by 300 by 150 mm. The host computer used was an Intel NUC miniPC based on a dual-core i3–7100U 2.4GHz processor with 8GB RAM. B-scan scan images were acquired at over 100 fps with 66μm transverse and 7μm depth resolution. See paper #10857–13 in this conference for more detail regarding this system.

3. RESULTS AND DISCUSSIONS

3.1 NIR Dehydration Measurements

NIR reflectance dehydration measurements for the samples are shown in Fig. 2. Results were analyzed by clinical decisions (clinically active or clinically arrested, denoted as $\mathbf{\Delta I}_{Active}$ and $\mathbf{\Delta I}_{Arrested}$, respectively) and by the thickness of TSL (denoted as $\mathbf{\Delta I}_{TSL<50}$, $\mathbf{\Delta I}_{TSL<75}$, $\mathbf{\Delta I}_{TSL<120}$). In general, the dehydration curves exhibited a sharp positive slope within 10 seconds of dehydration with the exception of samples having TSL thickness of < 50 μm, which exhibited slower increase but higher final intensity values. Quantitatively, in the clinical decision analysis, $\mathbf{\Delta I}_{Active} = 19.76 \pm 2.40$ (mean ± SD), which is marginally higher than $\mathbf{\Delta I}_{Arrested} = 19.37 \pm 1.43$, or effectively no difference ($t = 0.51$; $p > 0.05$). When the dehydration rate (ΔI) was analyzed based on the thickness of TSL, the result is $\mathbf{\Delta I}_{TSL<50}$

$= 26.88 \pm 10.48$, $\mathbf{\Delta I}_{TSL<75} = 18.12 \pm 7.76$, $\mathbf{\Delta I}_{TSL<120} = 15.13 \pm 4.29$ with significant differences amongst groups (1-way ANOVA: $F = 8.49$; $p < 0.05$), with the exception of TSL < 75 µm and TSL < 120µm groups (Tukey's MCT mean diff. = 2.96, $p > 0.05$). These results suggest a negative correlation between dehydration rate and transparent surface zone thickness.

3.2 OCT Measurements

Sample OCT B-scans are shown in Figure 3. As expected, samples with active lesions determined by dehydration rate measurement showed higher reflectivity on the lesion surface with no visible formation of a surface zone. Samples with arrested lesions have a visible transparent surface zone of varying thickness. Figure 4 shows the correlation between NIR reflectance dehydration measurement and TSL thickness measured by OCT. The plot shows a negative trend of decreasing permeability, or decreasing ΔI, as the thickness of the transparent surface layer increases. However, the variability of permeability was greater when the transparent surface layer was thinner compared to when the transparent layer was thicker. An explanation for this might be the inherent variation of the enamel structures such as enamel rod orientation, the rate and location at which minerals are deposited, and the remineralization environment prior to extraction. In all, the results suggest that the permeability decreased with increasing transparent surface layer thickness. Furthermore, small increases in transparent surface layer thickness of < 50 µm lead to large permeability changes. The teeth will be sectioned and examined with polarized light microscopy (PLM) or examined intact with µCT to confirm the presence of a highly mineralized surface zone. Additional studies will be aimed to assess the feasibility for integrating NIR-R dehydration and OCT as a diagnostic tool to aid clinician in determining lesion activity.

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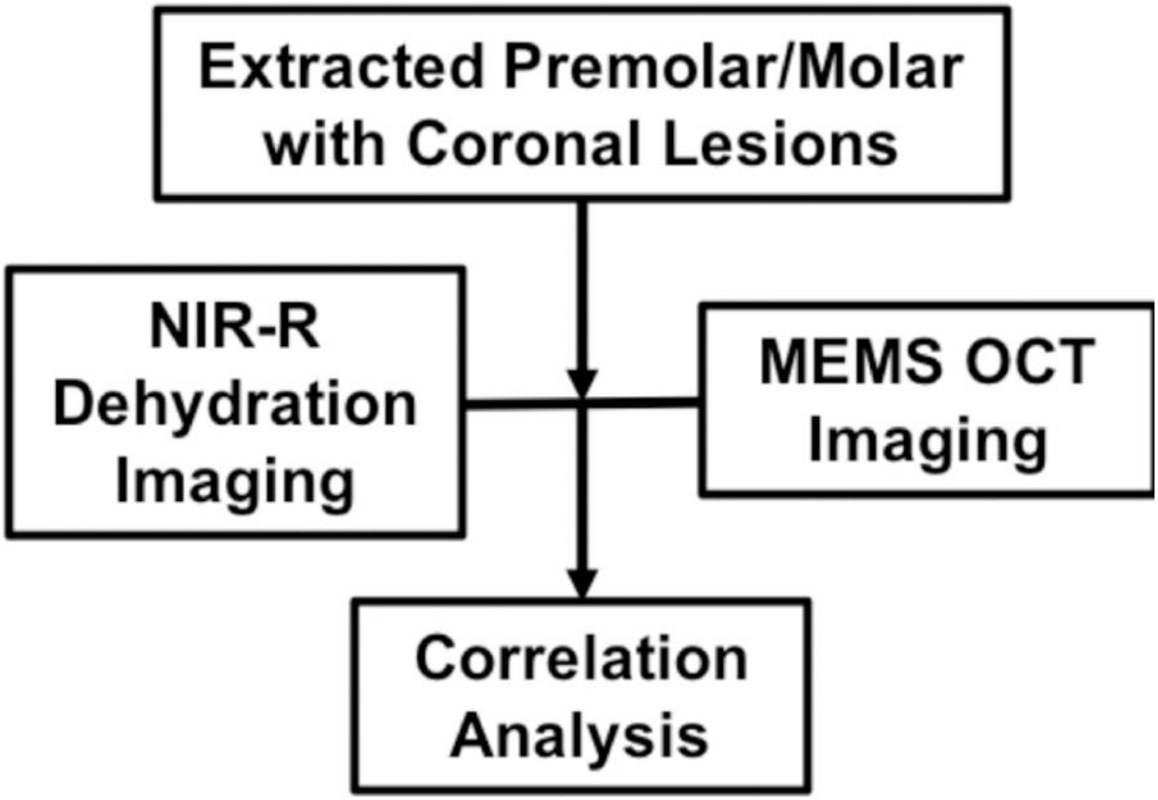

Fig. 1.
Workflow of the experimental setup.

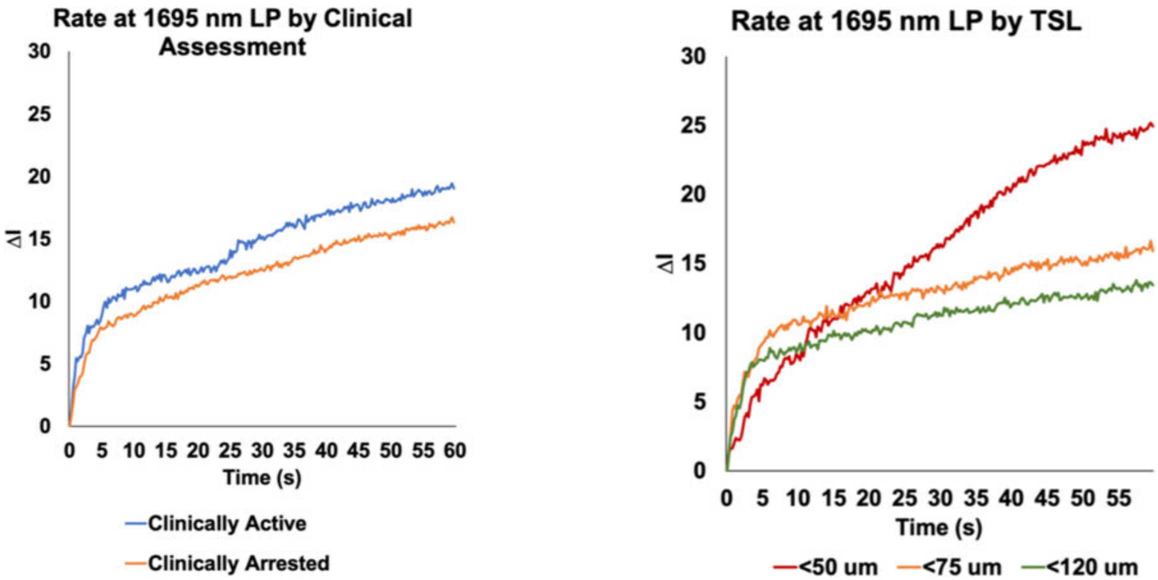

Fig. 2.

Average dehydration curves from 1695-nm LP. *Left*: Dehydration curves compared on the basis of clinical assessment. *Right*: Dehydration curves compared based on presence of a transparent surface layer (TSL) thickness of <50, <75, and <120 μm.

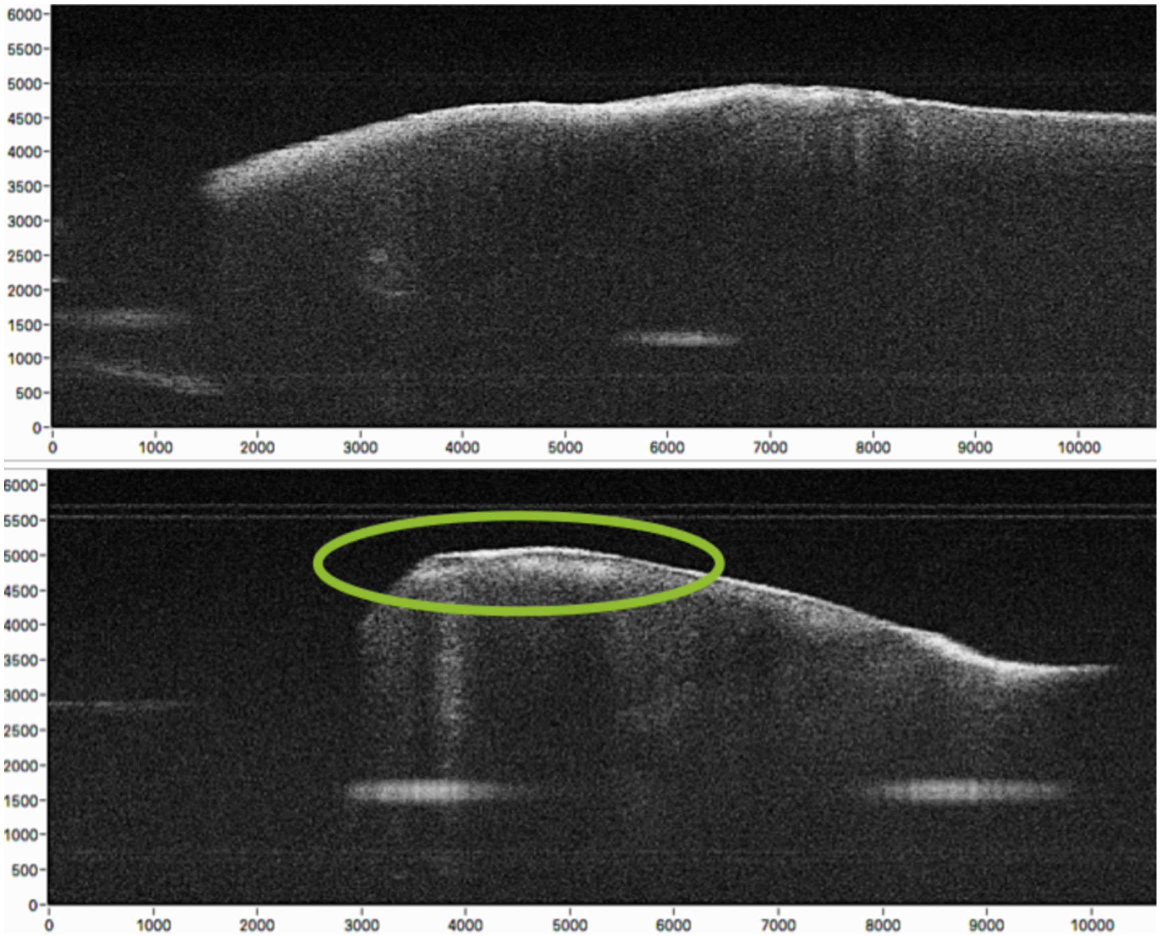

Fig. 3.
A sample OCT B-scan of a molar with an active lesion (top) with no formation of transparent surface layer and a molar with an arrested lesion (bottom) with a clear formation of transparent surface layer (green oval). Dimensions measured in μm.

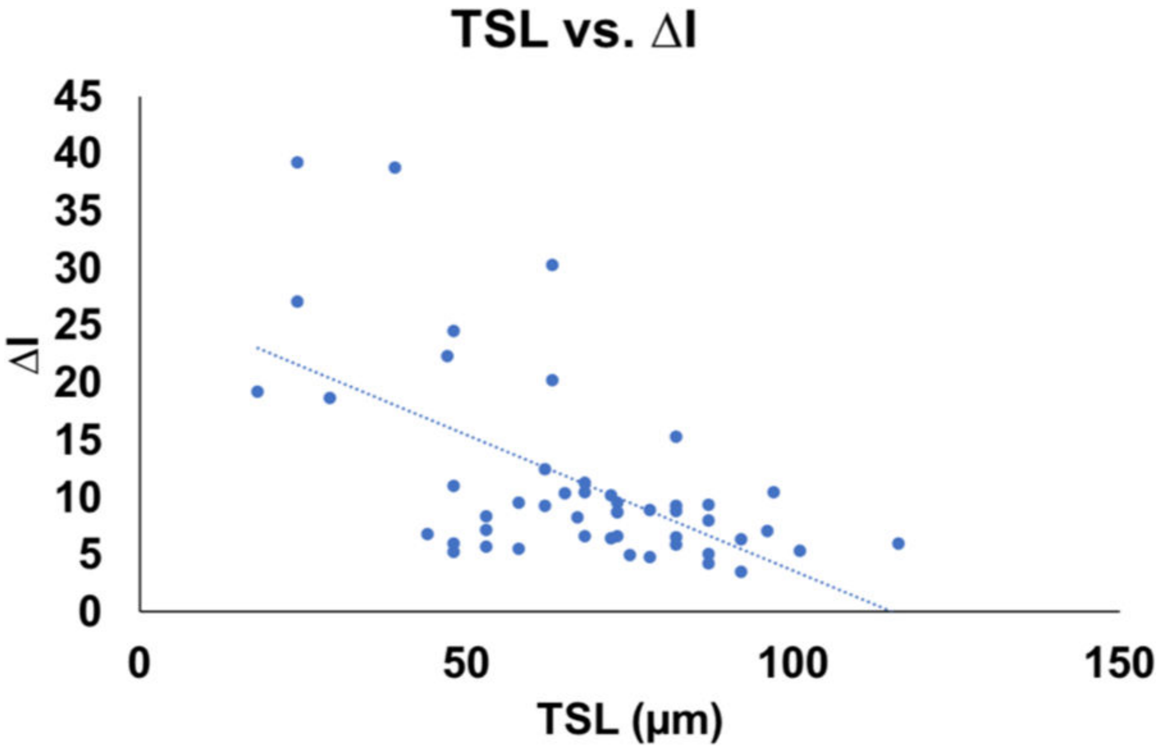

Fig. 4.
Correlation between NIR reflectance dehydration measurement and the thickness of the transparent surface layer measured by OCT, $r = -0.49$, $p < 0.05$.