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Near-IR imaging of cracks in teeth

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Abstract

Dental enamel is highly transparent at near-IR wavelengths and several studies have shown that these wavelengths are well suited for optical transillumination for the detection and imaging of tooth decay. We hypothesize that these wavelengths are also well suited for imaging cracks in teeth. Extracted teeth with suspected cracks were imaged at several wavelengths in the near-IR from 1300-1700-nm. Extracted teeth were also examined with optical coherence tomography to confirm the existence of suspected cracks. Several teeth of volunteers were also imaged *in vivo* at 1300-nm to demonstrate clinical potential. In addition we induced cracks in teeth using a carbon dioxide laser and imaged crack formation and propagation in real time using near-IR transillumination. Cracks were clearly visible using near-IR imaging at 1300-nm in both *in vitro* and *in vivo* images. Cracks and fractures also interfered with light propagation in the tooth aiding in crack identification and assessment of depth and severity.

1. INTRODUCTION

Cracks in teeth are an important problem in dentistry, they may cause a large range of symptoms and lead to the loss of healthy tooth structure [1-3]. Early detection and diagnosis is important to limit further crack growth. Cracks can originate from coronal tooth structure or from within the root and they may occur in both horizontal and vertical directions on the crown and/or root. There are 5 classification for cracks in teeth: craze line, fractured cusp, cracked tooth, split tooth, and vertical root fracture [1].

Near-IR reflectance and transillumination and optical coherence tomography (OCT) are new imaging techniques operating in the wavelength region from 1300-1700-nm which are capable of imaging caries lesions with high contrast [4-9]. We have found that 1300-nm yields the highest contrast for transillumination while wavelengths with higher water absorption 1450-nm and 1500-1700-nm yield the highest contrast for near-IR reflectance. Transillumination with visible light is typically used to help locate cracks. Since the tooth is most transparent at 1300-nm we hypothesize that near-IR transillumination imaging is ideally suited for imaging cracks in teeth.

Optical coherence tomography can be used to acquire tomographic images of the internal structure of teeth and cracks are sometimes visible. Imai et al. [10] demonstrated that OCT

at 1300-nm can be used to show that cracks have penetrated through the enamel into dentin. Shemesh et al. [11] showed that OCT can potentially be used to detect vertical root fractures using a inter-catheter rotating –pullback scanning probe. Ultrasound can also potentially be used to locate cracks [12].

We have shown in previous studies that crack formation and propagation can be imaged in real-time during laser irradiation using near-IR transillumination [13, 14]. In this study we deliberately used laser irradiation conditions that created large thermal stresses to produce cracks and imaged the propagation of those cracks using near-IR transillumination.

2. MATERIALS AND METHODS

2.1 Sample Preparation

Human teeth were collected (CHR approved) and sterilized with gamma radiation. Teeth were visually examined and those that scored ICDAS 1 or 2 were selected. Teeth were mounted in black orthodontic acrylic blocks. Samples were stored in a moist environment of 0.1% thymol to maintain tissue hydration and prevent bacterial growth.

Tooth sections approximately 3-mm thick were prepared from extracted sound human 3rd molars that were stored in water with only 0.1% thymol added to inhibit bacteria and fungal growth. Surfaces were serially polished to a finish of 0.1- μ m using embedded diamond polishing discs.

2.2 Digital Microscopy

Images of the tooth occlusal surfaces were examined using a digital microscopy/3D surface profilometry system, the VHX-1000 from Keyence (Elmwood, NJ) with the VH-Z25 lens with a magnification from 25 to 175 $\times$. Images are acquired by scanning the image plane of the microscope and reconstructing a depth composition image with all points at optimum focus displayed in a 2D image.

2.3 Near-IR Transillumination Images

A 150-W fiber-optic illuminator FOI-1 E Licht Company (Denver, CO) with a low profile fiber optic with dual line lights, Model P39-987 (Edmund Scientific, Barrington, NJ) was used with each light line directed at the cemento-enamel junction (CEJ) beneath the crown on the buccal and lingual sides of each tooth. Light leaving the occlusal surface was directed by a right angle prism to the SU320 InGaAs camera equipped with a Navitar (Rochester, NY) SWIR-35 lens, a 75-mm plano-convex lens LA1608-C Thorlabs (Newton, NJ) and a 90-nm wide bandpass filter centered at 1300-nm, BP1300-90 Spectrogon, (Parsippany, NJ).

2.4 Laser Generated Crack Imaging

A 48-series 20 W CO₂ laser Synrad (Mukilteo, WA) operated at 10.6 μ m, was used to irradiate tooth samples with intensities from 0-6 Watts. The setup showing the respective positions of the tooth section, laser, light-source, and camera and lens is shown in Fig. 1. A NoblePeak Vision Triwave Imager, Model EC701 (Wakefield, MA) was used that employs a Germanium enhanced complementary metal oxide semiconductor (CMOS) focal plane

array sensitive from 400-1600-nm with a larger array (640×480) and smaller pixel pitch (10- μ m pixels) for higher resolution with a near-IR 50 mm lens (F1.4) the SOLO from Sensors Unlimited. Light from a 150-W fiber-optic illuminator FOI-1 E Licht Company (Denver, CO) coupled to an aperture and a 90-nm bandpass centered at 1310-nm (filter # BP-1300-090-B) Spectrogon US Inc., Parsippany, NJ in series with a FB1300-12-FWHM (12-nm) Thorlabs (Newton, NJ) was used to illuminate the samples. This setup was similar to those used in prior imaging studies [13, 14].

3. RESULTS AND DISCUSSION

3.1 Near-IR Transillumination Imaging

Several extracted teeth with suspected cracks were examined using near-IR transillumination. Cracks typically show up with high contrast due to the high transparency of enamel. Figure 2 shows two teeth with several small cracks located through the highly transparent enamel around the central core of the more highly scattering dentin. More serious cracks/fractures can be easily located, Fig. 3 shows three teeth with larger cracks/fractures. These more serious cracks greatly interfere with light transmission through the enamel resulting in partition of the light into distinctive sectors in the tooth. The teeth in Fig. 3 all contain restorations that greatly contribute to stress and the likelihood of fracture. A good example of a large fracture can be seen in the center tooth of Fig. 3. A fracture runs from the top of the tooth right down the center to the other side and the right side of the tooth appears brighter than the left side of the tooth. The tooth on the right is interesting because it has a triangular shaped enamel section on the bottom right hand corner which is optically isolated by two fractures and the composite in the center. We have observed cracks/fractures similar to these examples during our *in vivo* near-IR imaging studies. Those studies are described in Paper# 8929-12 in these proceedings.

3.2 Laser Generated Crack Imaging

Human tooth sections of approximately 3-mm thickness were irradiated by a cw carbon dioxide laser with energies up to 6 W. The cw laser pulses were used to deliberately generate thermal damage and thermal stress to generate cracks that could be followed as they propagated through the transparent tooth enamel.

Thermal damage and dehydration caused changes in enamel opacity. Figure 4 shows four images acquired sequentially in time which show the formation and propagation of two cracks. Many of the cracks terminate at the enamel-dentinal junction. However, with the very high thermal stress generated by longer laser irradiation times, some cracks will penetrate into the dentin. Laser irradiated areas were also examined using a digital microscope that is capable of acquiring both depth composition images (all surfaces in focus) and 3D images. Figure 5 shows images taken of one of the samples that was irradiated with several watts producing several cracks. The first image shows both the surface of the irradiated section and the exposed side that was imaged. The 2nd image labeled “surface” shows the rim of fused enamel around the crater produced by the laser along with a large number of cracks radiating outwards. Close examination of the cracks in the enamel surface indicate that they follow both the incremental growth lines in the enamel

along with the prism boundaries—the scalloped shaped features on the left side of Fig. 5c. It is also very interesting that the prism boundaries have enhanced contrast in the zone of high thermal damage near the tooth surface. Protein and water are concentrated at the prism boundaries and they have most likely been removed in these areas. Increased scattering by the “exposed” prisms may contribute to the increased opacity of the thermally modified enamel. Figure 6 contains images of another section in which a very large crack was generated which penetrated deeply into the dentin of the tooth section. Close examination at higher magnification shows that the crack does not follow the path or direction of the dentinal tubules.

We also examined many of the cracks on the extracted teeth with optical coherence tomography, however it was difficult to assess penetration to the DEJ. In the previous study of Imai et al. [10], cracks were clearly visible penetrating through the DEJ, however the images shown are for areas on the tooth where the remaining enamel thickness appeared to be less than a mm thick.

In summary, this study shows that near-IR transillumination at 1300-nm is valuable for imaging cracks and fractures due to the high transparency of enamel. Cracks and fractures also interfered with light propagation in the tooth aiding in crack identification and assessment of depth and severity.

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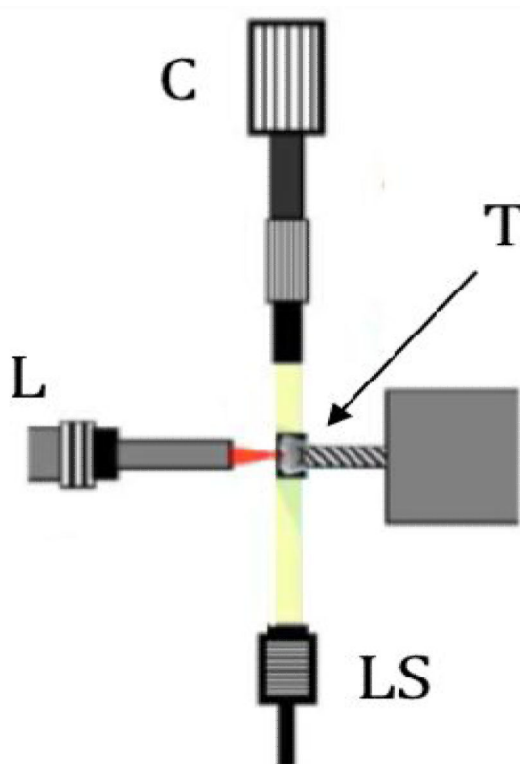


Fig. 1. Laser-Induced Crack Imaging Setup (C) Imaging camera with zoom lens, (L) laser, (LS) fiber-optic illuminator, and (T) tooth section.

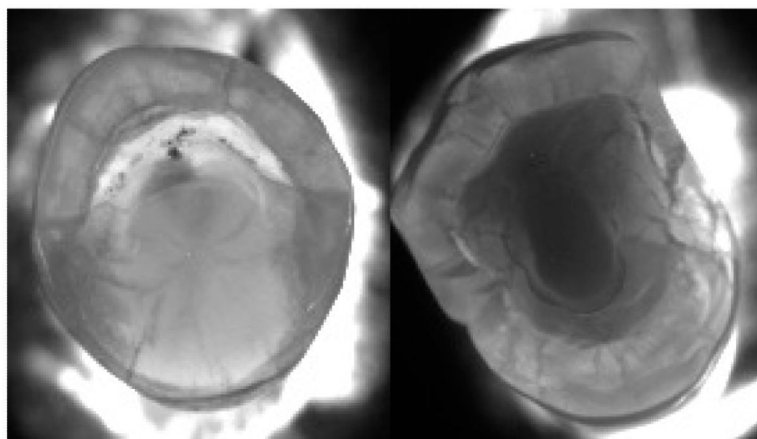


Fig. 2.
Near-IR transillumination images acquired at 1300-nm of two extracted teeth with cracks.

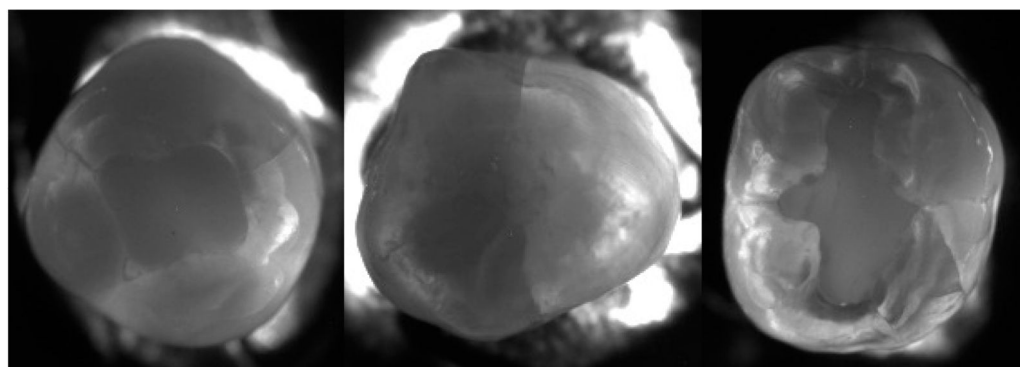


Fig. 3.
Near-IR transillumination images acquired at 1300-nm of three extracted teeth with suspected fractures.

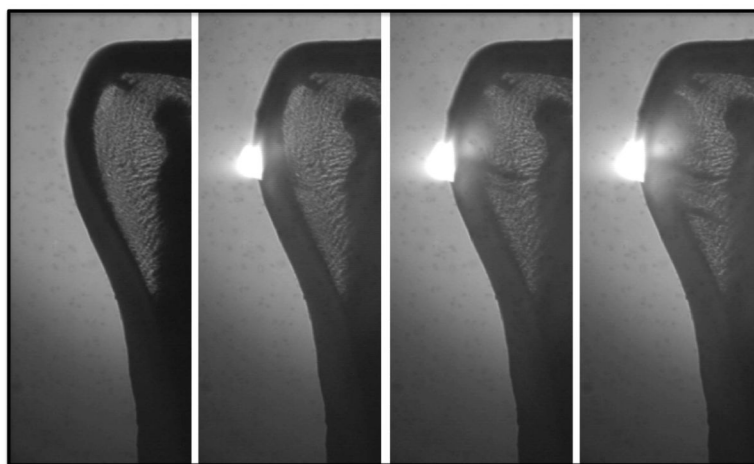


Fig. 4. Sequential images acquired during laser irradiation of one of the samples (increasing time from left to right). Note the glow of the laser heated zone and the two cracks angling down from the heated zone.

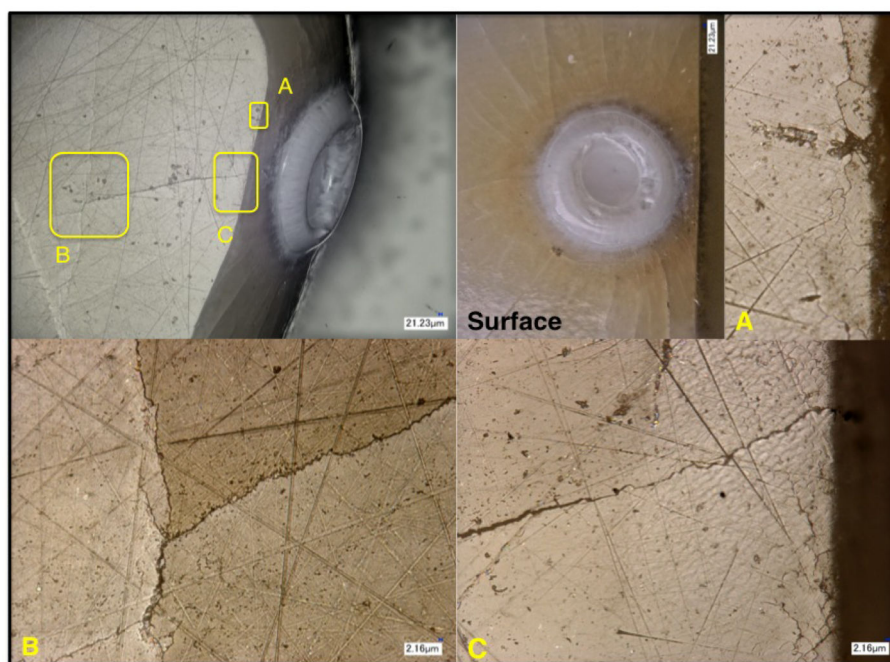


Fig. 5.
(upper left) Depth composition image showing both the laser spot of the tooth edge and the side of the tooth where the cracks were imaged. The three boxes labeled a-c are expanded in the three images and they show cracks and other features on the enamel surface.

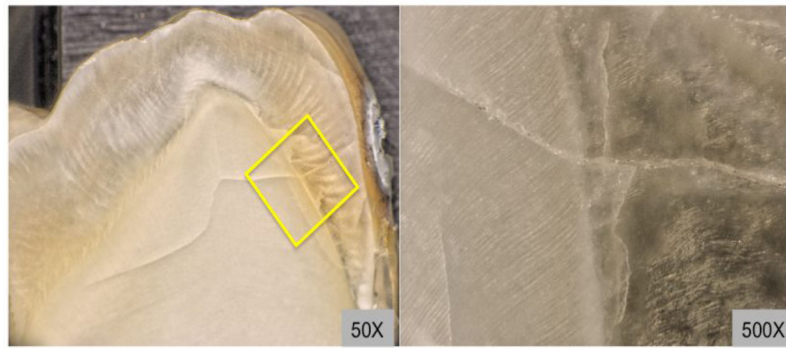


Fig. 6. Images of a sample with a very large crack that penetrated deep into dentin and almost completely through the sample. Examination of crack near the dentinal-enamel junction at higher magnification indicates that it does not follow the path of the tubules.