Dental Depth Profilometry using Simultaneous Frequency-Domain Infrared Photothermal Radiometry and Laser Luminescence for the Diagnosis of Dental Caries

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ABSTRACT

Frequency-domain infrared photothermal radiometry is introduced as a dynamic dental diagnostic tool and its main features are compared with modulated laser luminescence for quantifying sound and carious enamel or dentin. Dental caries found in the fissures or grooves of teeth is very difficult to diagnose or quantify with the present clinical techniques. Visual examination and dental radiographs do not detect the presence of decay until there has been significant carious destruction of the tooth. A high-spatial-resolution dynamic experimental imaging set-up, which can provide simultaneous measurements of laser-induced frequency-domain infrared photothermal radiometric and luminescence signals from defects in teeth, was developed.[1] Following optical absorption of laser photons, the new set-up can monitor simultaneously and independently the non-radiative (optical-to-thermal) conversion (infrared photothermal radiometry), and the radiative de-excitation (luminescence emission) in turbid media such as hard dental tissue.

This work is intended to show the complementarity between modulated luminescence and photothermal frequency scans in detecting carious lesions in teeth. A sound extracted molar with a dentin-enamel interface was introduced to examine the depth profilometric abilities of the method. Occlusal surfaces of teeth with potential areas of demineralization or carious destruction in the fissures were examined and compared to the signals produced by the sound enamel establishing the depth profilometric abilities of the method. The significance to clinical dentistry lies in the potential of this technique to detect and monitor early carious lesions in the pits and fissures of teeth.

Keywords: dental infrared photothermal radiometry, photothermal imaging and luminescence, carious teeth, pit and fissure caries, diagnosis of dental caries

1. INTRODUCTION

In recent years rapidly increasing research activities have been reported centered on laser-induced luminescence as a probing technique for the detection and quantification of physical and chemical processes associated with carious dental enamel. In general, luminescence suffers from low signal levels and thus in most cases dyes are used to enhance sensitivity[2]. Under laboratory conditions, the results appear satisfactory, yet the use of dyes makes the method difficult for clinical applications. In this work, frequency-domain infrared photothermal radiometry (FD-PTR) and modulated laser luminescence are introduced as complementary dynamic dental diagnostic tools for quantifying sound and defective (carious) enamel or dentin. FD-PTR is a growing technology for the nondestructive evaluation (NDE) of sub-surface features in opaque materials.[3,4] It has also shown promise in the study of excited-state dynamics in active optically transparent solid-state (laser) materials[5]. The technique is based on the modulated thermal infrared (blackbody or Planck-radiation) response of a medium, resulting from radiation absorption and non-radiative energy conversion followed by temperature rise. The generated signals carry sub-surface information in the form of a temperature depth integral. As a result, PTR has the ability to penetrate and yield information about an opaque medium well below the range of optical imaging. Owing to this ability, pulsed-laser PTR has been extensively used with turbid media such as tissue[6,7] to study the sub-surface deposition localization of laser radiation, a task which is difficult for optical methods due to excessive scattering. Very recently, dental applications of pulsed

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PTR focused on the examination of dentin and enamel have been reported.[8,9] These preliminary studies have examined the temperature behavior of dental tissues, their tolerance to optical-to-thermal energy conversion and deposition, and their ablation threshold by high-fluence pulsed lasers. Unfortunately, the high-fluence deposition and wideband nature of pulsed photothermal detection, coupled with laser-pulse jitter and the high noise content inherent to all thermal (incoherent) signal techniques, prohibits the non-destructive application of this PTR mode to dental imaging, at least in competition with luminescence and other imaging diagnostics. FD-PTR, on the other hand, exhibits much higher SNR than its pulsed counterpart[10] and can monitor a fixed probed depth with the use of a single modulation frequency. The current experimental method is based on low-fluence photothermal radiometric detection microscopy[11], which detects the emission of infrared radiation from a heated region of the sample without thermally altering it. A temperature oscillation due to modulated heating causes a variation in the thermal emissions, which is monitored using an infrared detector. By changing the laser-beam modulation frequency, the region of the specimen that contributes to the image is also varied.

Infrared radiometric and luminescence images of flat enamel surfaces from teeth with sub-surface lesions (cracks) were obtained at a fixed laser-intensity modulation frequency [1]. A dentin-enamel interface was examined for quantitative comparison with enamel-generated signals. Simultaneous radiometric and luminescence frequency scans for the purpose of depth profiling were performed. Futhermore teeth with potential pit and fissure caries were examined and the dynamic nature of the method was evaluated.

2. EXPERIMENTAL METHOD

The experimental setup for performing simultaneous FD-PTR and luminescence studies is shown in Figure 1. A 488-nm wavelength cw Innova 100 Ar^+ laser from Coherent is modulated by an external acousto-optic modulator (AOM) at frequency $f=\omega/2\pi$, where ω is the angular modulation frequency. The laser beam is then focused with a high performance lens onto a sample to a radial (1/*e*) spot size of approximately 30μm in reflection, at an incident power of 0.1W. The blackbody radiation from the optically excited sample is collected, collimated, and focused to a fine spot size by two axially aligned reflecting objectives onto a liquid-nitrogen-cooled HgCdTe (Mercury-Cadmium-Telluride) detector. The HgCdTe detector is a photoconductive element, which undergoes a change in resistance proportional to the intensity of the incident infrared radiation. It has an active square size area of 50μm x 50μm and a spectral bandwidth of 2-12μm. Its quantum efficiency increases with decreasing temperature, so the detector is operated at a cryogenic temperature of 77K. An anti-reflection (A-R)-coated germanium window with a transmission bandwidth of 2-14μm is mounted in front of the detector to block any visible radiation from the pump laser. Before being sent to the digital lock-in amplifier, the photothermal radiometric signal is amplified by a pre-amplifier with a frequency bandwidth dc-1MHz especially designed for operation with the HgCdTe detector. Since both the modulated heating source and the detector are localized, they can be scanned across the sample. To perform PTR imaging the sample is moved in a raster fashion. This process of data acquisition, storage, and scanning is automated. For the simultaneous measurement of luminescence and PTR signal, a germanium window was placed between the path of the two reflective objectives. The germanium window was utilized so that wavelengths up to 900nm would be reflected and the infrared radiation would be transmitted to the second reflecting objective focused onto the infrared-detector. The reflected spectrum was focused onto a photodetector of spectral bandwidth 300 nm-1.1 μm. A cut-off colored glass filter was placed in front of the photodetector to suppress scattered laser light and the spectrally integrated enamel luminescence following excitation by the 488-nm laser light[12] was monitored. In order to test if any experimental components showed fluorescence a measurement with a mirror as a sample was performed. The result was negative (no signal).

Following optical absorption of laser photons, the experimental set-up can monitor simultaneously and independently the non-radiative (optical-to-thermal) conversion *via* infrared photothermal radiometry, and the radiative de-excitation *via* luminescence emission. With this experimental set-up two types of experiments can be performed. The first is imaging, where the sample coordinates are scanned at a constant frequency. The second experiment is dynamic, performed at one location on the sample. It generates depth-dependent information by scanning the laser-beam modulation frequency ("a frequency scan").

3. RESULTS AND DISCUSSION

3.1 Dentin Enamel Interface

To study the dynamic nature (i.e. feature structures dependent on modulation frequency) of both luminescence and photothermal methods, frequency scans in the range 10 Hz-10 kHz were performed at different positions along a dentin-enamel interface of a cross-sectioned extracted molar as shown in Figure 2. Position 1 is dentin, position 2 is enamel of 0.5mm thickness over the dentin, position 3 is enamel of thickness 1mm, position 4 is enamel of thickness 1.5mm and position 5 is enamel of 2mm thickness. Figure 3 shows the simultaneous photothermal and luminescence frequency scans for the five positions on the tooth. Dentin (pos. 1) exhibits low luminescence amplitude (Fig 3a) as compared to the enamel signal (pos. 5). Positions 2 and 3 are similar at low luminescence frequencies but differ at high frequencies**.** At the low frequency end the luminescence level (signal) of positions 2 and 3 is close to the dentin level (pos. 1). Positions 4 and 5 exhibit higher luminescence signifying a region where only the enamel is detected. The luminescence phases (Fig 3b) coincide for all positions at the low frequency end. At high frequencies there are some small variations. The PTR signal contains more detailed information. Position 1 exhibits high signal in both amplitude (Fig. 3c) and phase (Fig. 3d). Position 2 is interesting because the dentin layer underneath the enamel is seen as a minimum (interference) in the phase. This clearly shows the profilometric nature of PTR, manifested as a thermal wave interference pattern in the range 100Hz-10kHz. Positions 3, 4 and 5 behave similarly showing that a semi-infinite region has been reached for the enamel. Such a method (interpretation of frequency scans) can be useful for future applications since the absence of enamel or the demineralization of enamel can determine an early carious lesion.

The frequency scans can be further used for analysis of optical properties of both enamel and dentin. A quantitative theoretical two-lifetime rate model of dental luminescence was advanced and two characteristic lifetimes were measured.[1] The results have been used in a newly developed quantitative theoretical model for characterizing the radiometric frequency-domain response.[13] Simultaneous radiometric and luminescence frequency scans and images of case studies with teeth ranging between sound and carious are being examined, showing the diagnostic complementarity of the novel integrated frequency-domain instrumentation.

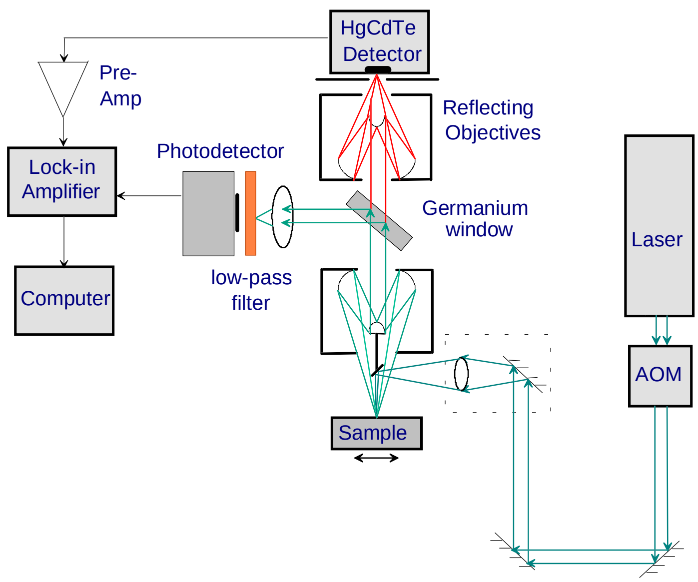


Figure 1: Frequency-domain photothermal radiometric (FD-PTR) and luminescence imaging instrumentation.

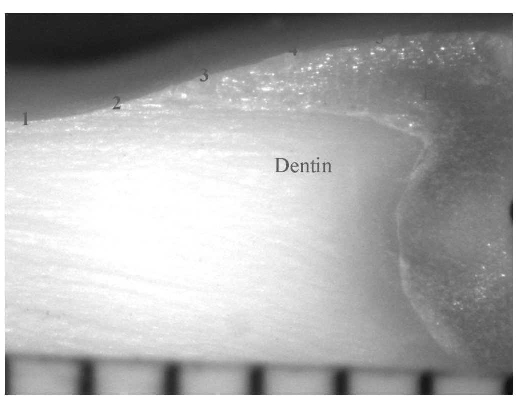


Figure 2: Cross section of dentin-enamel interface of an extracted molar

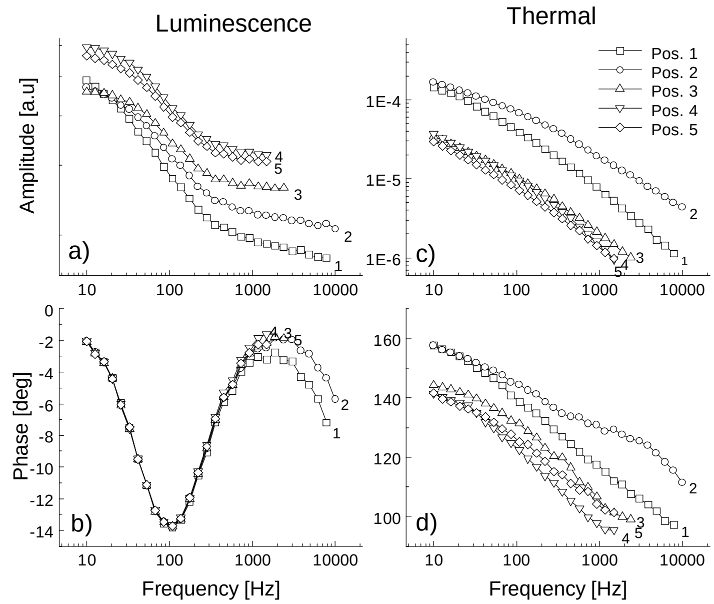


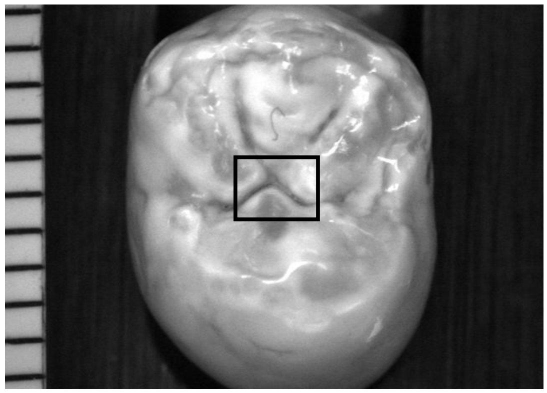
Figure 3: Simultaneous luminescence and FD-PTR frequency responses at five positions as shown in Figure 2. a) luminescence amplitude scan; b) luminescence phase scan; c) PTR amplitude scan; and d) PTR phase scan.

3.2 Carious Teeth

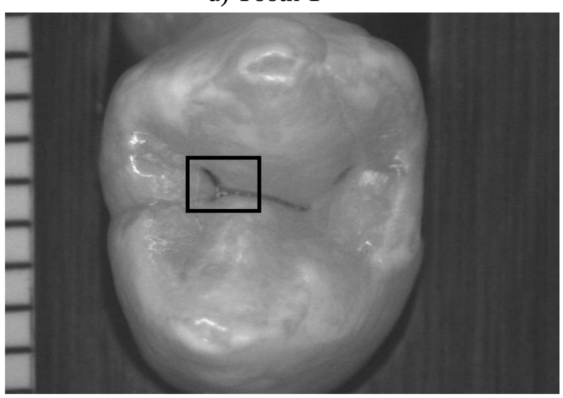
Three extracted molars and bicuspids being stored in water were selected as samples. The samples bore no visible caries on their buccal or lingual surfaces. The teeth were disinfected with Hibitane (2% chlorhexidine), washed with water and any surface pellicle or stain was removed using a rubber cup prophylaxis with coarse grit prophy paste. The samples were then stored in a humid environment with distilled water to avoid dehydration and contamination. These regions on the occlusal surfaces were chosen as areas of potential demineralization or dental caries. Each tooth was examined visually by two dentists using air and a dental explorer to lightly probe the surfaces. Tooth 1, shown in Figure 4a, is a maxillary bicuspid with well-formed and well-coalesced occlusal pits and fissures. There is some evidence of hypermineralization of the enamel possibly due to some mild fluorosis. Visual examination determined that this tooth has no caries and should not be treated. Tooth 2 (Figure 4b), is a maxillary bicuspid and has stained fissures especially in the distal pit. Visual examination determined that the stained fissure is not carious and it does not need to be treated. Tooth 3 (Figure 4c), is a maxillary third molar. It has a stained distal pit on a maxillary third molar with visible signs of decay. There are demineralized areas over the wall of the fissure. This tooth should be observed and perhaps the occlusal fissures opened and restored. Before irradiation, the teeth were dried.

Figure 5 shows the modulated photothermal results for each tooth. Tooth 1 seems to be a tooth with no caries since the photothermal amplitude is low and the luminescence amplitude is high. The photothermal phase decreases linearly at high frequencies indicating minimal levels of inhomogeneity (possibly damage). The luminescence phase at high frequencies exhibits a maximum, which corresponds to the response of healthy enamel[1]. For Tooth 2 the photothermal amplitude is an order of magnitude greater than the photothermal amplitude from Tooth 1. This is an indication that there may be a defect beneath the enamel surface that requires restoration. The luminescence amplitude shows no obvious trends and behaves similarly to Tooth 1. The luminescence phase perhaps gives some indication of caries due to the fact that at the high frequency there is no clear maximum. In addition, the photothermal phase is higher perhaps due to the recessed geometry of the tooth surface. Finally, Tooth 3 has the highest photothermal and lowest luminescence amplitude. This is an indication of the presence of a large carious lesion involving the enamel and dentin requiring restorative treatment. Both the photothermal and luminescence phase of Tooth 3 are more similar to Tooth 2 than Tooth 1. From this investigation, we can establish a diagnosis and treatment approach for teeth 1 and 3. Tooth 1 has a healthy intact enamel surface requiring no treatment. Tooth 3 has a defect or carious lesion beneath the enamel surface of the occlusal pit. This is because the anticorrelation between luminescence and photothermal signal amplitudes is consistent. For Tooth 2 the interpretation or diagnosis is more complicated because the luminescence amplitude at high frequencies is not monotonically decreasing as the tooth severity increases. Perhaps in such an occasion relying mostly on the photothermal signal is more advantageous due to the higher dynamic range of the method.

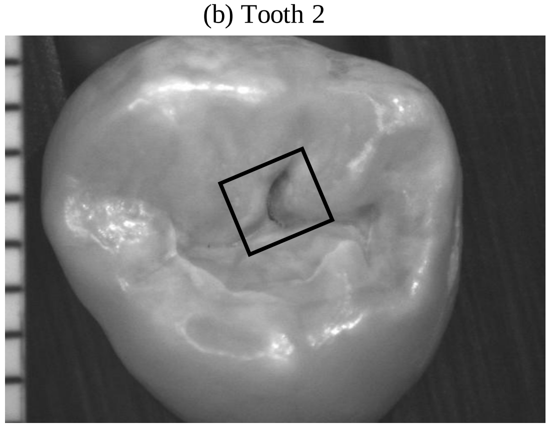
The teeth were then cross-sectioned to perform histological studies. Figure 6 shows the cross-section of Tooth 1. The tooth has a shallow pit with no evidence of caries or demineralization around the walls. Tooth 1 would not require any type of restorative intervention. Figure 7 shows the cross-section of Tooth 2. There is a large area of demineralized enamel surrounding the pit. The enamel is not entirely demineralized and there is at least 100μm of intact enamel adjacent to the dento-enamel junction. The enamel surface is not homogenous which could contribute to the higher photothermal phase lag than is seen in tooth 1. This pit should be restored or watched very closely using intensive preventive therapy to ensure that the demineralization does not grow to involve the dentin. Figure 8 shows the cross-section of Tooth 3. There is a broad area of demineralized enamel surrounding the fissure. There is also carious destruction of the outer third of the dentin indicating the immediate need for restorative treatment. These results are consistent with the photothermal and luminescence results.



a) Tooth 1



(b) Tooth 2



c) Tooth 3

Figure 4: Optical images of extracted molars investigated with the square box indicating the region of examination. a) Tooth 1, b) Tooth 2 and c) Tooth 3.

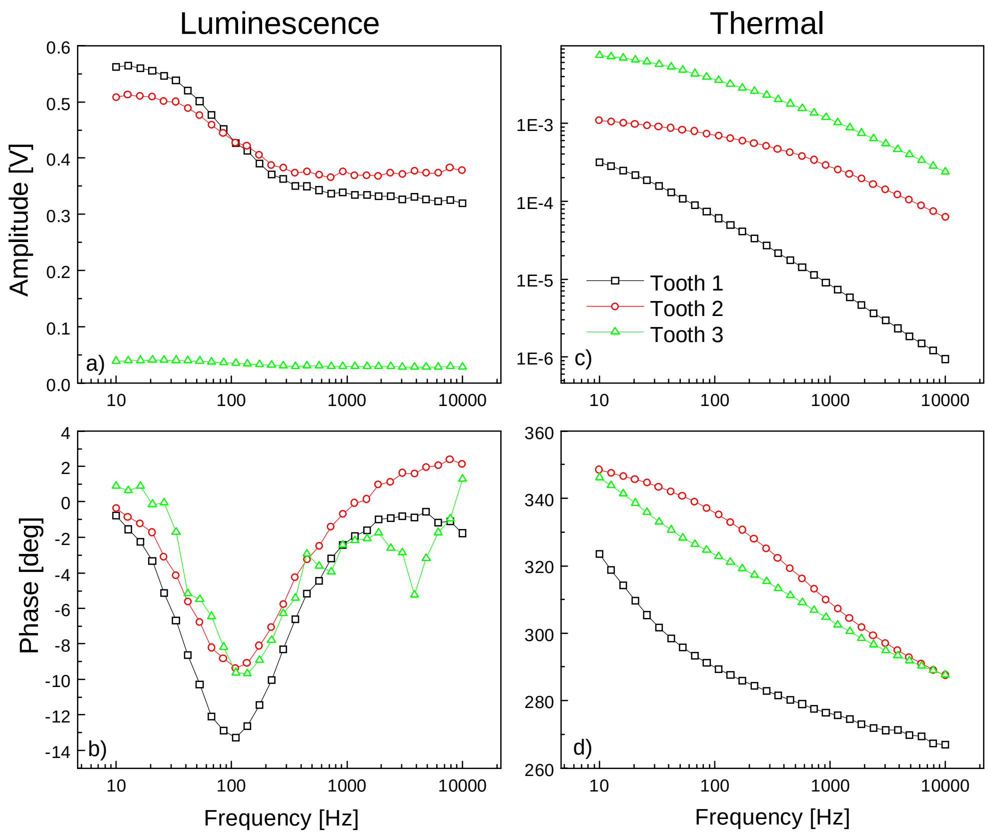
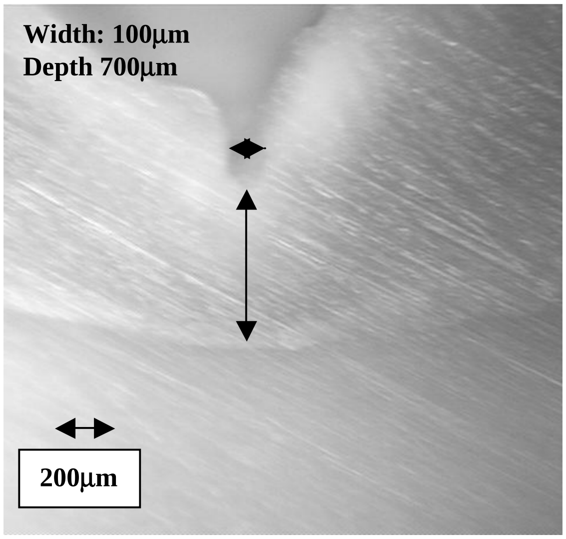


Figure 5: Simultaneous luminescence and FD-PTR frequency responses for Tooth 1, 2 and 3. a) luminescence amplitude scan; b) luminescence phase scan; c) PTR amplitude scan; and d) PTR phase scan.



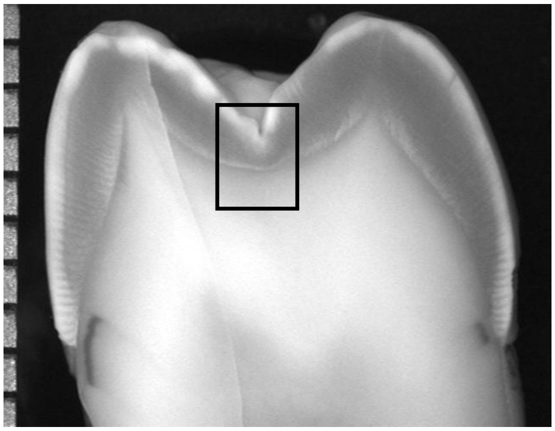


Figure 6: Tooth 1 cross-section at the irradiated region.

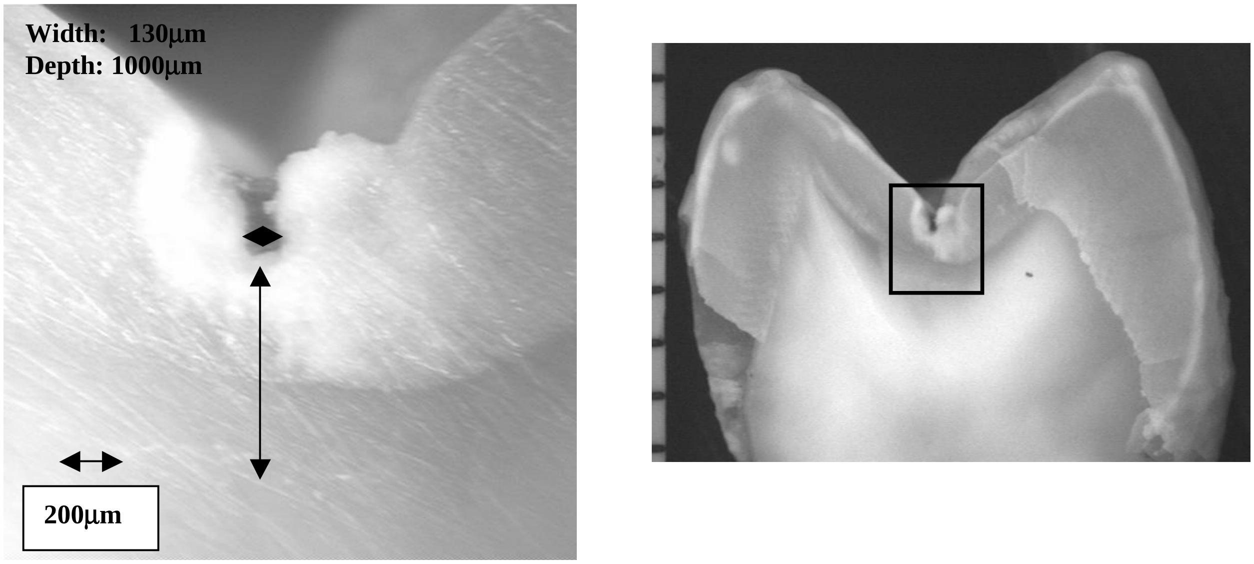


Figure 7: Tooth 2 cross-section at the irradiated region.

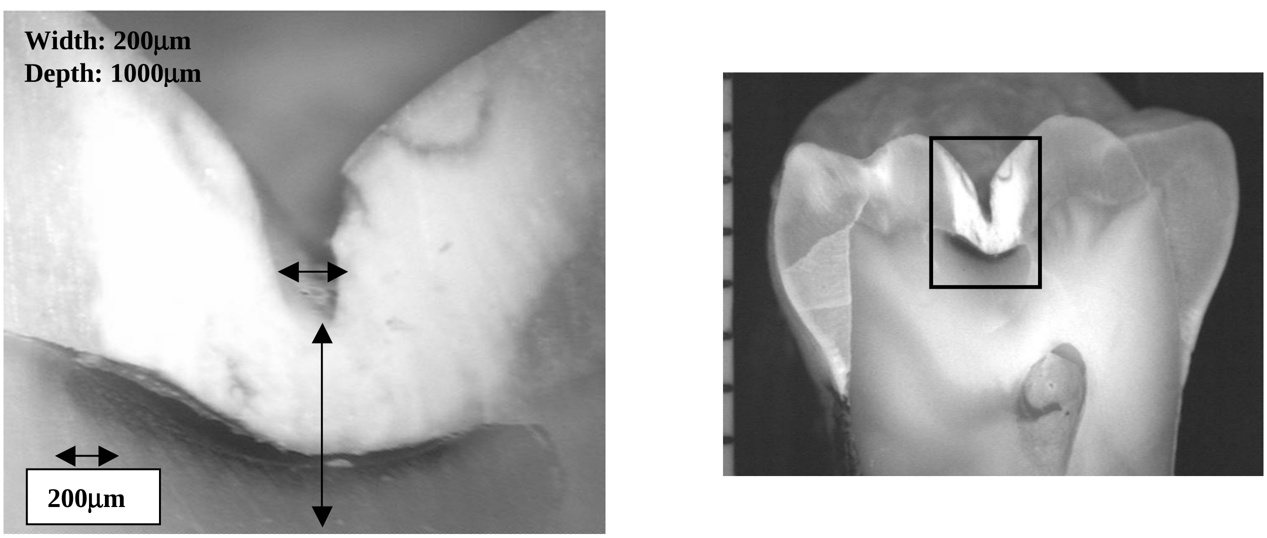


Figure 8: Tooth 3 cross-section at the irradiated region.

4. CONCLUSIONS

Frequency-domain infrared photothermal radiometry (FD-PTR) was introduced as a non-destructive, non-intrusive method for evaluating sound and carious teeth. The complementarity between modulated luminescence and PTR has proved important for distinguishing severe subsurface damage or demineralization. Several advantages of FD-PTR imaging were found including much superior dynamic range of the amplitude signal with regard to the defect state of dental enamel and depth profilometric capabilities. Future work can be pursued in developing criteria for early carious tooth diagnosis using simultaneous modulated luminescence and PTR.

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