Novel Dental Depth Profilometric Imaging using Simultaneous Frequency-Domain Infrared Photothermal Radiometry and Laser Luminescence

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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 conventional laser luminescence for quantifying sound and defective (cracked) enamel. 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, has been developed[1]. Following optical absorption of laser photons, the new 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.

Keywords: dental infrared photothermal radiometry, photothermal imaging, and luminescence

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. Another promising approach is laser-scanned fluorescence (or luminescence). This technique can detect early carious lesions[3] by producing surface images, which are subsequently enhanced via standard image processing techniques[4]. Nevertheless, the relatively low signal-to-noise ratio (SNR) limits the contrast and the diagnostic ability of laser fluorescence. 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 (cracked) enamel. This work is intended to show the complementarity between modulated luminescence and photothermal frequency scans and imaging. As a first test for investigating the sensitivity and spatial resolution of the methodology as applied to dental tissues, cracked and sound enamel samples were chosen. The significance to dentistry lies on the conclusions regarding the potential of this technique to monitor dental lesions at the early stages of carious decay where lateral and sub-surface spatial resolution on the order of the crack sizes and sub-surface depths investigated in this work (100-300 μm) may be required.

FD-PTR is a growing technology for the nondestructive evaluation (NDE) of sub-surface features in opaque materials.[5,6] It has also shown promise in the study of excited-state dynamics in active optically transparent solid-state (laser) materials[7]. The technique is based on the modulated thermal infrared (blackbody or Planck-radiation) response of a medium, resulting from radiation absorption, non-radiative energy conversion and excited-to-ground-state relaxation, 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[8,9] to study the sub-surface deposition localization of laser radiation, a task which is difficult or impossible for optical methods due to excessive scattering. Very

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recently, dental applications of pulsed PTR focused on the diagnostics of dentin and enamel have been reported.[10,11] 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[12] and 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[13], 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. The temperature modulation allows for thermal energy to reach the surface diffusively from a depth approximately equal to a thermal wavelength, $\lambda_{th}(f) = 2\pi\sqrt{\alpha / \pi f}$, where α is the material thermal diffusivity [cm^2/s] and f is the laser beam modulation frequency. Scatterers located within a fraction of a thermal wavelength from the source dominate the contrast of radiometric images. In this way, when the thermal wavelength is varied, e.g. 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. Furthermore, 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.

2. MATERIALS AND METHODS

2.1. Sample Preparation

Extracted molar teeth 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 roots were removed and each tooth was sectioned in half. At that point, the dentin was removed from the inner half of the section until very little remained, leaving specimens of between one and two millimeters in thickness. The samples were then stored in a humid environment with distilled water to avoid dehydration and contamination. Before irradiation, the teeth were dried and the surfaces examined to identify the regions of cracks and fissures. These regions were chosen as good candidates for near surface and sub-surface crack investigation. An extracted molar with a dentin-enamel interface was also investigated. The interface was created by cross-sectioning the extracted molar on a 20-degree angle.

2.2. Experimental System

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-Isomet 1201E-1) at frequency $f=\omega/2\pi$, where ω is the angular modulation frequency. The laser beam is then focused with a high performance lens (Gradium GPX085) onto a sample to a 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 (Ealing 25-0522X36 and 25-0506X15) onto a liquid-nitrogen-cooled HgCdTe (Mercury-Cadmium-Telluride) detector (EG&G Judson J15D12-M204-S050U). 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 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 (Stanford Research System Model SR850), the photothermal radiometric signal is amplified by a pre-amplifier with a frequency bandwidth dc-1MHz (EG&G Judson Model PA-300), 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 (Newport 818-BB-20). A cut-off colored glass filter (Schott OG570) was placed in front of the photodetector to surpress scattered laser light and the spectrally integrated enamel luminescence following excitation by the 488-nm laser light[14] 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").

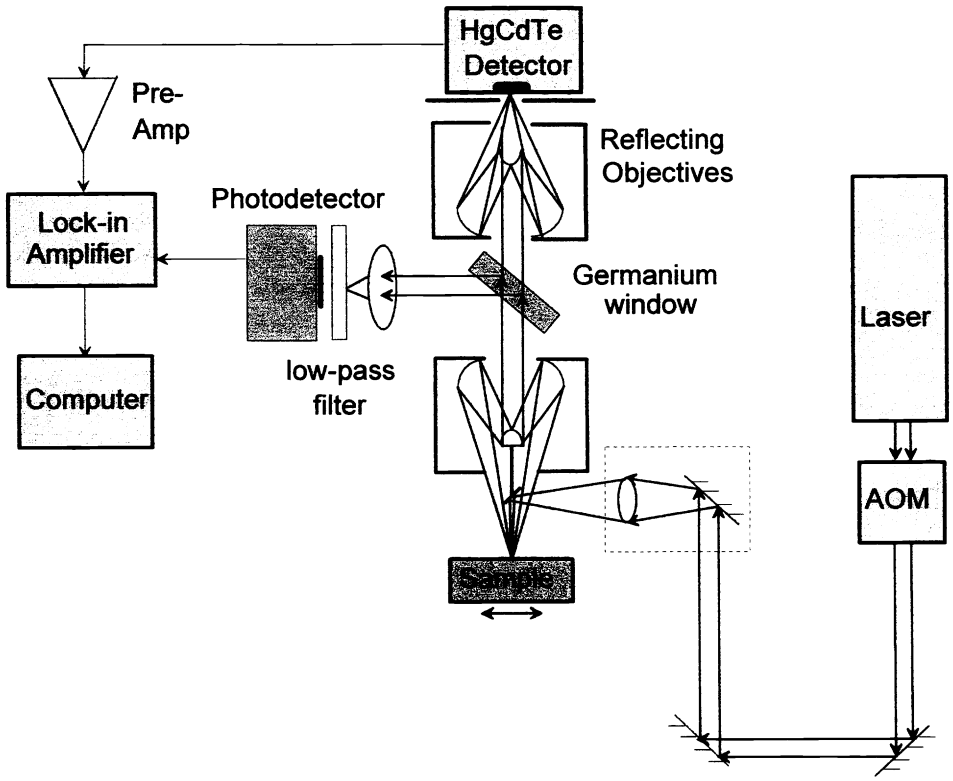

Figure 1: Frequency-domain photothermal radiometric (FD-PTR) and luminescence imaging instrumentation. HgCdTe: Mercury-Cadmium-Telluride infrared detector; AOM: acousto-optic modulator.

3. RESULTS AND DISCUSSION

3.1 PTR and luminescence imaging

Simultaneous PTR and luminescence images were obtained at different modulation frequencies and in all reported images, the signal ranges between high (black) and low (light gray). A flat enamel slice with a single 15μm wide transverse crack, 2mm thick and 6mm x 10mm in size is imaged at f=20 Hz. The aim is to show the intrinsic features of, and anti-correlation between, PTR and luminescence images. The results of a 0.5mm x 0.5mm image of the flat enamel slice with a

near vertical sub-surface crack are shown in figure 2. The luminescence image (fig. 2a) seems to be sensitive to the presence of the crack; in the cracked region the luminescence signal is low (light gray) whereas in the (nearly) intact region the luminescence is relatively high (gray). Within the crack region, luminescence photon emission of several wavelengths characteristic of the enamel chromophores is essentially absent due to the material structural destruction. As a result most of the incident energy decays nonradiatively, yielding a strong photothermal radiometric signal. Conversely, in the intact part of the enamel the luminescence is significantly enhanced, while the photothermal contribution is decreased. The two images together represent the expected balance of excited-state energy release between a radiative (luminescence) and a nonradiative (thermal-decay) dynamic process. The PTR image is the result of thermal-wave generation in the tooth and thus consists of two channels; amplitude and phase, Fig. 2 (b-d). In turbid media these channels carry thermal transport information within approximately one thermal centroid below the surface. The thermal diffusion centroid is determined as the "center-of-mass" among thermal diffusion length, $\mu = \lambda_{th}/2\pi$, optical absorption depth and optical scattering mean-free-path in the bulk of the material. Photothermal amplitude is generally more sensitive to surface property variations, such as the reflectance, whereas phase is largely insensitive to the optical properties of the surface and probes a larger depth range[15] into the material. In figure 2(b) the PTR amplitude exhibits two "hot spots" in the defective enamel. These two spots are also seen in phase, figure 2(c), confirming that the extend of these regions of the crack is deeper into the enamel. From optical observation of the tooth after the scan it is estimated that the penetration of the crack spots is 300μm.

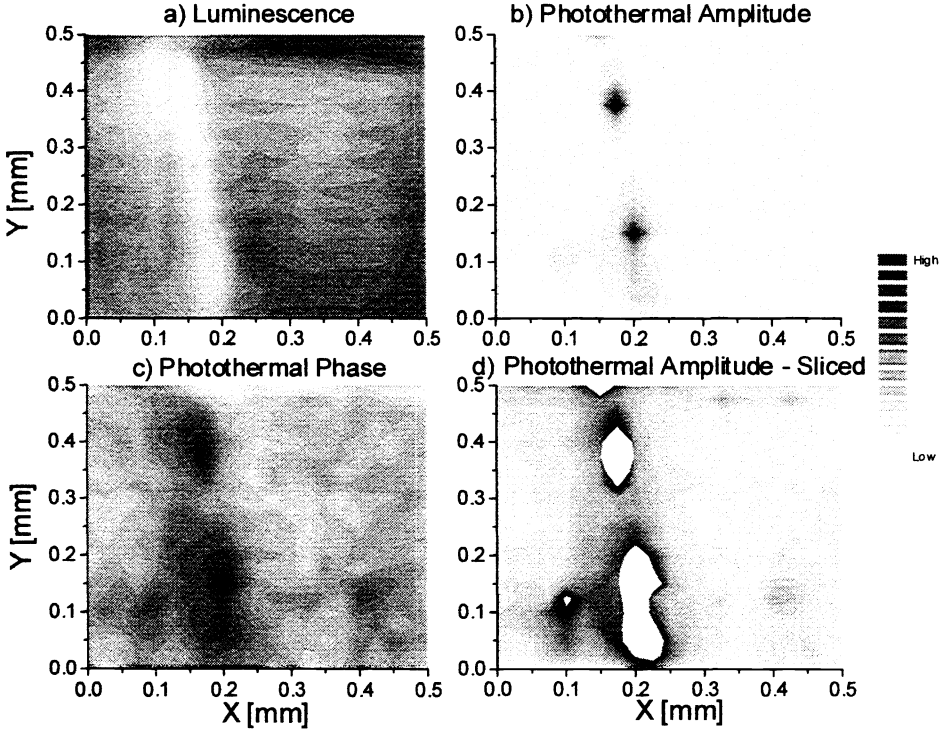

Figure 2: Simultaneous luminescence and FD-PTR images at f=20 Hz. a) luminescence amplitude; b) PTR amplitude; c) PTR phase; and d) PTR amplitude with peaks sliced off.

The luminescence image, figure 2(a), however, shows the crack damage to be uniform throughout the extend of the crack. This is probably due to the influence of enhanced optical scattering at the crack leading to photon diffusion and "blurring" of the luminescence emission from dental enamel and points to the major difference between the two imaging principles: *PTR images depth profiles of sub-surface heat sources; luminescence does not, but is affected by image "blurring" due to photon scattering at the crack. It turns out it is also affected by photon emission delay processes which are characteristic of the material (enamel).* Figure 3 further points to the other major difference between the two techniques: *the superior dynamic range of the PTR amplitude.* For this reason, the image in figure 2(b) is sliced to allow the visualization of other features, the PTR intensity of, which is much lower than the peaks of the defect regions. The sliced image is seen in figure 2(d), whose features are now comparable to the PTR phase, Fig. 2(c). On the contrary, the luminescence amplitude is essentially

continuous along the crack and shows neither the detailed morphology of the cracked region, nor any similarly great signal variations from the surrounding regions.

Scanning imaging at different frequencies manifests the dynamic character of modulated imaging (PTR and luminescence). Furthermore, the depth profilometric character of PTR can be assessed in terms of defective enamel information obtained from different depths[1] and also in terms of enamel absence and presence of dentin. These aspects are illustrated by examining a molar tooth with a dentin-enamel interface as shown in figure 3; the interface shown by the curved centerline. A 2mm x 4mm region (as outlined in figure 3) was imaged at two frequencies, f=10Hz and f=500Hz.

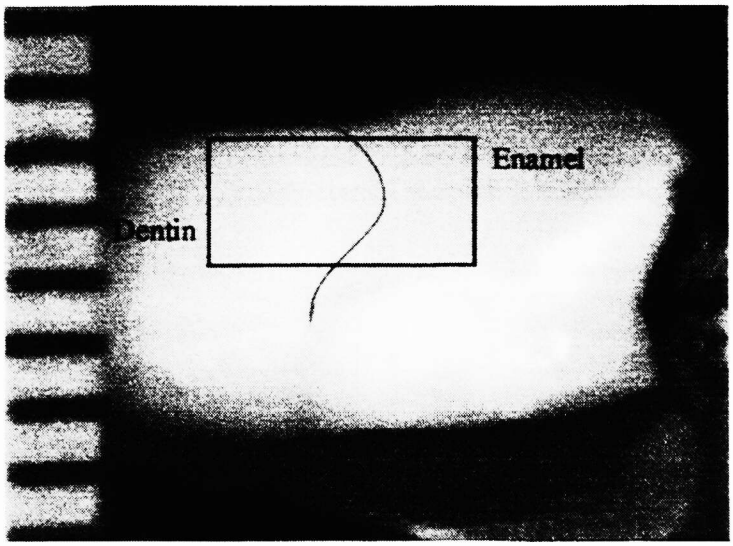

Figure 3: Top view of dentin-enamel interface of an extracted molar.

The simultaneous PTR and luminescence images are shown respectively in figures 4, and 5. In figure 4(a) the luminescence amplitude signal is low (light gray) for dentin and high (black) for enamel. The interface is similar to the optical interface seen in figure 3. The luminescence phase (Fig 4b), is low and there is no distinction between dentin and enamel. The PTR amplitude and phase are seen in Figs. 4(c) and 4(d), respectively. At f=10 Hz the information obtained photothermally is from deep (mm-range) into the enamel. Here, again, a comparison with the broader features of Fig. 4(a) shows the expected general anti-correlation of signal amplitudes *and* the higher localization of the PTR feature morphologies, consistent with excitation and/or luminescence photon scattering (image blurring). The PTR phase image shows a direct correlation with the amplitude image and similarly localized features. The additional details on the dentin and enamel region of the phase image are due to the lower dynamic range of the phase channel. The most striking features of the PTR images is the dentin-enamel interface, which differs from the luminescence one, as seen in both amplitude and phase. The broadly anti-correlated luminescence image does not show clear details of the dentin structure. At the higher modulation frequency f=500 Hz (figure 5) the same defect region is examined and PTR information about interface region closer to the surface is obtained. At this sub-surface level the dentin region appears more resolved in the PTR amplitude. Comparing the phase, Fig. 5(c) with its lower-frequency counterpart, Fig. 4(c), it becomes apparent that the lower frequency image is associated with deeper bulk features, whereas the higher frequency images closer to the surface. At f=500 Hz the PTR images show the best delineation of the very-near surface morphologies of the interface. This amounts to enhanced image resolution compared to Figure 4, and is expected photothermally, as the wavelength of the thermal wave that interacts with the dentin-enamel interface decreases and the thermal emission becomes more localized. The luminescence phase seems to be exhibiting a profilometric nature. At the higher frequency (fig 5b) the interface of dentin-enamel is clearly shown. The sequence of Figs. 4 and 5 shows that modulated luminescence imaging yields integrated bulk information. *A major advantage of dental PTR imaging is the localization of features, largely due to the relative insensitivity of this technique to photon scattering.*

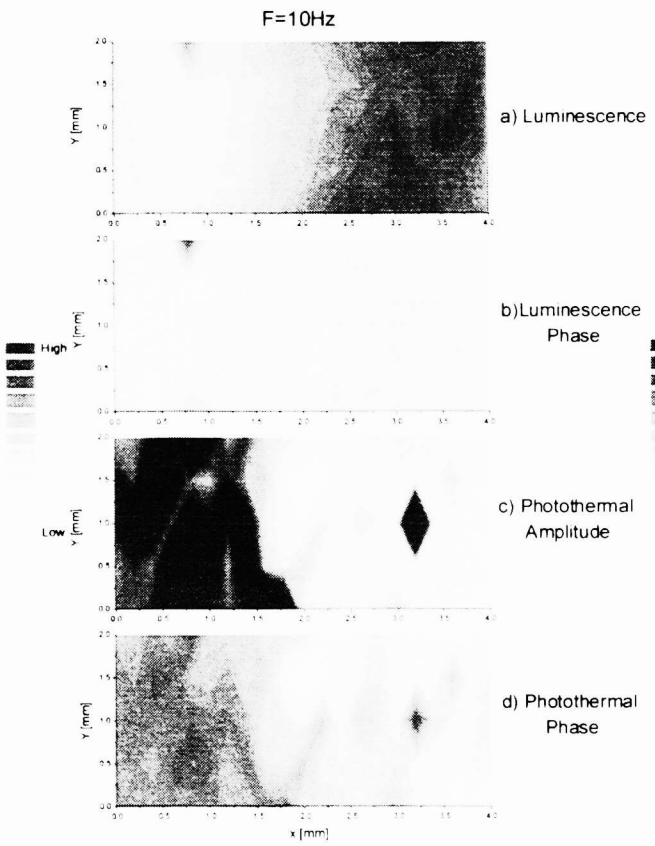

Figure 4: Simultaneous luminescence and FD-PTR images at f=10 Hz. a) luminescence amplitude; b) luminescence phase; c) PTR amplitude; and d) PTR phase.

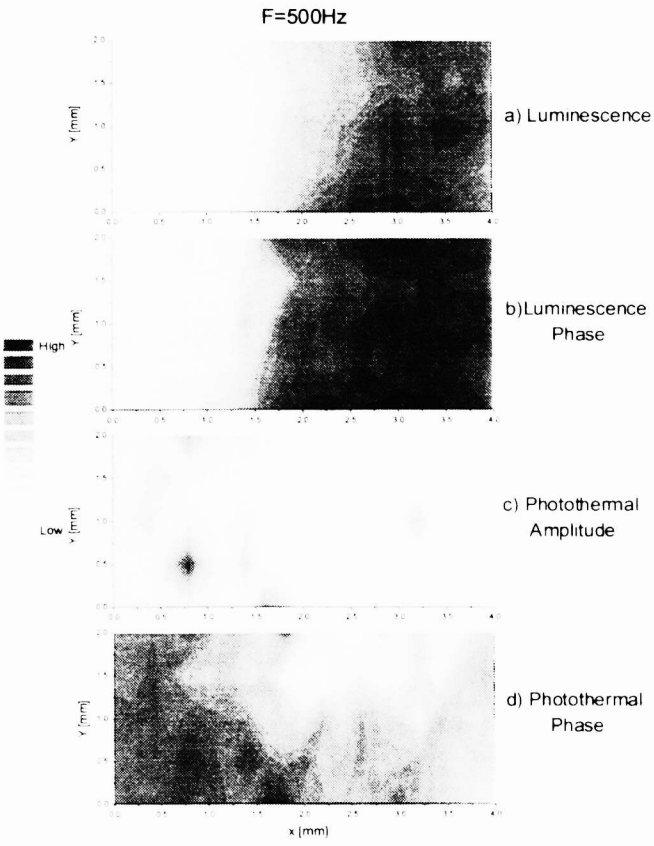

Figure 5: Simultaneous luminescence and FD-PTR images at f=500 Hz. a) luminescence amplitude; b) luminescence phase; c) PTR amplitude; and d) PTR phase.

3.2 Frequency scans

From the luminescence and photothermal images of figs. 4 and 5, it is seen that both dental enamel luminescence and PTR are capable of dynamic imaging, i.e. feature structures depend strongly on modulation frequency. To study these effects, frequency scans in the range 10 Hz-10 kHz were performed at different positions along the dentine-enamel interface dental enamel as shown in figure 6. Figure 6 is the side view of the dentin enamel interface shown in figure 3. Position 1 is dentin, position 2 is enamel of 0.5mm thickness with 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 7 shows the simultaneous photothermal and luminescence frequency scans for the five positions on the tooth. As expected from the results obtained in figures 4 and 5, dentin (position 1) exhibits low luminescence amplitude (fig 7a). Positions 2 and 3 show similar characteristics at the high luminescence frequency but differ at the low frequencies. The luminescence level is closer to dentin. Positions 1 and 2 are at a higher luminescence region signifying a region where only the enamel is detected. The luminescence phase does not show any apparent differences between the positions at the low frequency end. At the high frequencies there are some small variations. The PTR signal contains more detailed information. Position 1 exhibits high signal in both amplitude (Fig. 7c) and phase (Fig. 7d). Position 2 is interesting because the sublayer of dentin underneath the enamel is seen as a minimum (interference) in the phase. This clearly shows the profilometric nature of PTR. Position 3, 4 and 5 behave similarly showing that a semi-infinite region has been reached for the enamel. Such a method can be very useful for future application since the absence of enamel or deterioration of enamel can determine an early carious region.

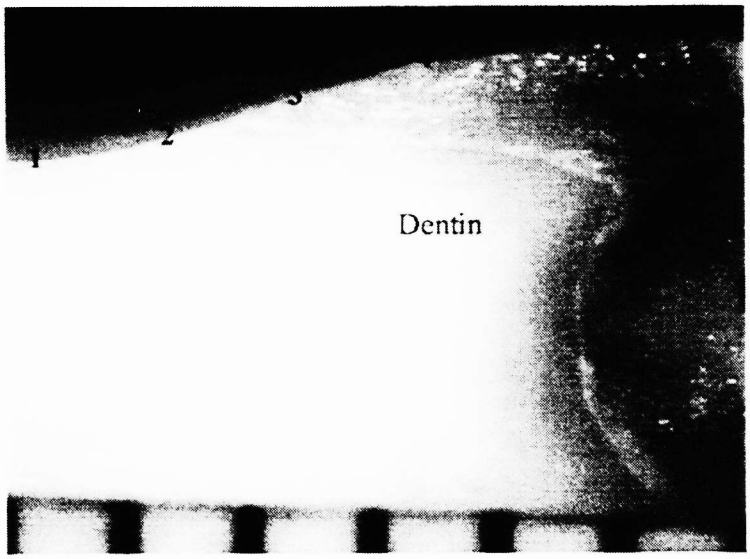

Figure 6: Side view of dentin-enamel interface of the extracted molar shown in figure 4.

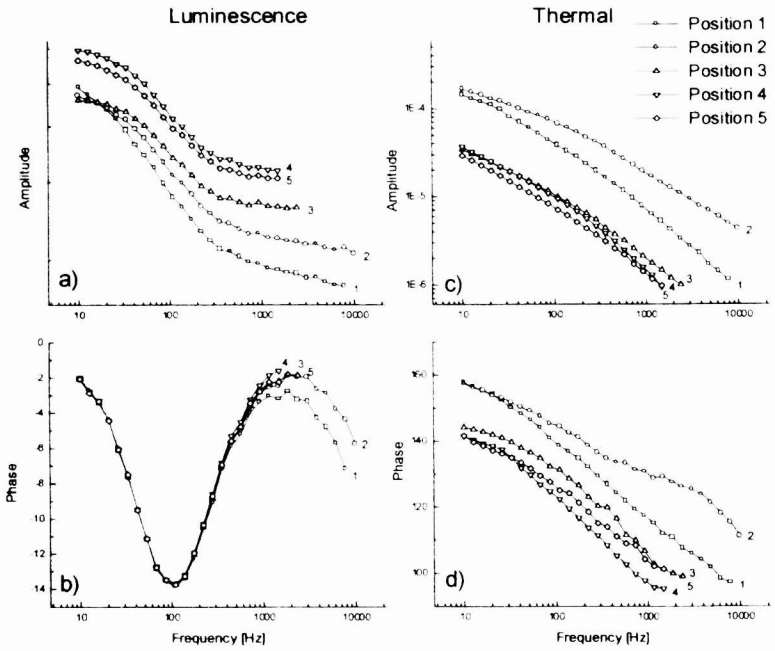

Figure 7: Simultaneous luminescence and FD-PTR frequency responses at five positions as shown in figure 6. a) luminescence amplitude scan; b) luminescence phase scan; c) PTR amplitude scan; and d) PTR phase scan.

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[1] and the two characteristic lifetimes were measured. The results are currently been used in a newly developed quantitative theoretical model for characterizing the radiometric frequency-domain response. 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.

4. CONCLUSIONS

Frequency-domain infrared photothermal radiometry (FD-PTR) was introduced as a non-destructive, non-intrusive method for evaluating sound and defective tooth enamel, and was shown to be a complimentary imaging technique to luminescence. 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, superior feature localization and resolution, and depth profilometric capabilities. The major findings of this work are i) radiometric images are complementary to (anti-correlated with) luminescence images, as a result of the nature of the two physical signal generation processes; ii) the radiometric amplitude exhibits much superior dynamic (signal resolution) range to luminescence in distinguishing between intact and cracked sub-surface structures in the enamel; iii) the radiometric signal (amplitude and phase) produces dental images with much better defect localization, delineation and resolution; iv) radiometric images (amplitude and phase) at a fixed modulation frequency are depth profilometric, whereas luminescence images are not.

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REFERENCES

1. L. Nicolaides, A. Mandelis and S. H. Abrams, "Novel dental dynamic depth profilometric imaging using simultaneous frequency-domain infrared photothermal radiometry and laser luminescence", J. Biom. Opt. (January 2000).
2. V. D. Rijke and J.J ten Bosch, "Optical quantification of caries like lesions in vitro by use of fluorescent dye", J. Dent. Res. 69, 1184-1187 (1990).
3. J. Baron, K. Zakariasen and B. Patton, "Detecting CO_2 laser effects by 3D image scanned laser fluorescence", J. Dent. Res. 72, special issue #1060, 236 (1993).
4. C. D. Gonzalez, K. Zakariasen, D. N. Dederich and R. J. Pruhs, "Potential preventive and therapeutic hard tissue applications of CO_2 and Nd:YAG and Argon lasers in dentistry: A review", J. Dent. Child May-June, 196-207 (1996).
5. M. Munidasa, T.C., A. Mandelis, S. K. Brown, and L. Mannik, "Non-destructive depth profiling of laser processed Zr-2.5Nb alloy by infrared photothermal radiometry", J. Mat. Sci. Eng. **A** 159, 111-118 (1992).
6. G. Walther, "Photothermal nondestructive evaluation of materials with thermal waves" in *Progress in photothermal and photoacoustic science and technology*, Mandelis A ed., Vol. 1, pp. 205-298 Elsevier, N.Y (1992).
7. A. Mandelis, M. Munidasa, and A. Othonos, "Single-ended infrared photothermal radiometric measurements of quantum efficiency and metastable lifetime in solid-state laser materials: the case of ruby (Cr^{3+}:Al_2O_3)", IEEE J. Quant. Electron. 29, 1498-1504 (1993).
8. A. J. Welch and M. J. C. van Gemert eds., *in Optical-thermal response of laser-irradiated tissue*, Plenum, N.Y (1995).
9. S. A. Prahl, A. I. Vitkin, U. Bruggemann, B. C. Wilson, and R. R. Anderson "Determination of optical properties of turbid media using pulsed photothermal radiometry", Phys. Med. Biol. 37, 1203-1217 (1992).
10. D. Fried, W. Seka, R.E Glena, and J. D. B. Featherstone, "Thermal response of hard dental tissues to 9- through 11-μm CO_2-laser irradiation", Opt. Eng. 35, 1976-1984 (1996).
11. D. Fried, S. R. Visuri, J. D. B. Featherstone, J. T. Walsh, W. Seka, R.E. Glena, S. M. McCormack, and H. A. Wigdor, " Infrared radiometry of dental enamel during Er:YAG and Er:YSGG laser irradiation", J. Biomed. Opt. 1, 455-465 (1996).
12. A. Mandelis, "Signal-to-noise ratios in lock-in amplifier synchronous detection: A generalized communications systems approach with application to frequency-, time-, and hybrid (rate-window) photothermal measurements", Rev. Sci. Instrum. 65, 3309-3323 (1994).
13. L. Nicolaides, M. Munidasa and A. Mandelis, "Thermal-wave diffraction tomographic microscopy", Djordjevic and Reis (eds): Topics On Non-Destructive Evaluation Series Vol 3, pp 65-69 (1998).
14. F. Sundstrom, K. Fredriksson, S. Montan, U. Hafstorm-Bjorkman and J. Strom, "Laser-induced fluorescence from sound and carious tooth substance: Spectroscopic studies", Swed. Dent. J. 9, 71-80 (1995).
15. G Busse, "Optoacoustic and photothermal inspection techniques", Appl. Opt. 21, 107 (1982).