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Dental biothermophotonics: How photothermal methods are winning the race with X-rays for dental caries diagnostic needs of clinical dentistry

A. Mandelis[1], R. Jeon[1], A. Matvienko[1], S.H. Abrams[2], and B.T. Amaechi[3]

[1] Center for Advanced Diffusion-Wave Technologies, University of Toronto, 5 King's College Road, Toronto, ON M5S 3G8, Canada
[2] Four-Cell Consulting, Toronto, Canada
[3] Department of Community Dentistry, University of Texas Health Science Center at San Antonio, San Antonio, TX 78229-3900, USA

Abstract. Recent trends in biothermophotonics of teeth are presented. The presentation is centered on the development of clinical-level frequency-domain photothermal radiometry and modulated luminescence to address issues associated with the early diagnosis of demineralization caries in human teeth. Biothermophotonic principles and applications to the detection of the carious state in human teeth as embodied by laser photothermal radiometry are presented and further supported by modulated luminescence. The emphasis is on recent developments with regard to abilities of these techniques to diagnose interproximal lesions between teeth, etching with phosphoric acid and with an artificial demineralization gel in order to simulate early demineralization, as well as demineralization and remineralization of dental crown enamel and root dentin. These are lesions which normally go undetected by X-ray radiographs. Comparisons with X rays, Micro-Computed Tomography (μ-CT) and Transverse Micro-Radiography (TMR) are discussed. A theoretical model involving coupled diffuse photon density and thermal-wave fields is developed and applied to frequency scans from demineralized artificial lesions to produce quantitative values for optical and thermophysical parameters of teeth as well as the thickness of the induced lesion.

1 Biothermophotonics of hard tissues: Applications to dental caries

Nowadays with the widespread use of fluoride, the prevalence of caries, particularly smooth surface caries has been considerably reduced [1], but the development of a non-invasive, non-contacting technique which can detect early demineralization on or beneath the enamel surface is essential for the clinical management of this problem. A novel biothermophotonic technique based on photothermal radiometry (PTR) has been introduced. Modulated thermal infrared (black-body or Planck) radiation is emitted from hard dental tissue, resulting from laser radiation absorption and non-radiative energy conversion followed by a small temperature rise. In PTR applications to turbid media, such as hard dental tissue, depth information is obtained following optical-to-thermal energy conversion and transport of the incident laser power in two distinct modes: conductively, from a near-surface distance ($50 \sim 500 \mu$m) controlled by the thermal diffusivity of enamel; and radiatively, through blackbody emissions from considerably deeper regions commensurate with the optical penetration of the diffusely scattered laser-induced optical field (several mm) [2].

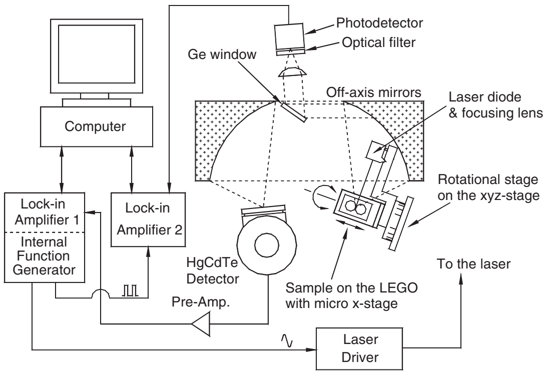


Fig. 1. Schematic diagram and a picture of experimental set-up for combined PTR and LUM monitoring.

2 Experimental apparatus

Fig. 1 shows the experimental setup for combined frequency-domain PTR and luminescence (LUM) probing. Two semiconductor lasers with wavelengths 658 nm (80 mW; Mitsubishi ML120G21), and 670 nm (500 mW, Sony SLD1332V) were used as the sources of both PTR and LUM signals. A diode laser driver (Coherent 6060) was used for the lasers and was triggered by the built-in function generator of the lock-in amplifier (Stanford Research SR830), modulating the laser current harmonically. The laser beam was focused on the sample with a high performance lens (Gradium GPX085) to a spot size of approximately 150–170 μm or larger when necessary. The laser and the sample holder were equipped with rotational stages, so as to be able to set arbitrary relative positions among the sample, the source and the detector. The modulated infrared PTR signal from the tooth was collected and focused by two off-axis paraboloidal mirrors onto a Mercury Cadmium Telluride (HgCdTe or MCT) detector (EG&G Judson J15D12-M204-S050U). For the simultaneous measurement of PTR and LUM signals, a germanium window was placed between the paraboloidal mirrors so that wavelengths up to 1.85 μm (Ge bandgap) would be reflected and absorbed, while infrared radiation with longer wavelengths would be transmitted. The reflected luminescence was focused onto a photodetector of spectral bandwidth 300 nm $\sim$ 1.1 μm (Newport 818-BB-20). A cut-on colored glass filter (Oriel 51345, cut-on wavelength: 715 nm) was placed in front of the photodetector to block laser light reflected or scattered by the tooth. For monitoring the modulated luminescence, another lock-in amplifier (EG&G model 5210) was used. Both lock-in amplifiers were connected to, and controlled by, the computer via RS-232 ports. Two kinds of experiments were performed. One was a frequency scan to examine the frequency dependence of the PTR and the LUM signals from 1 Hz to 1 kHz. The other type of experiment measured the PTR and the LUM signals along a spatial coordinate on the tooth surface at a fixed frequency.

3 Interproximal lesion detection

3.1 Mechanical lesions

Interproximal lesions have been examined by PTR and LUM. Lesions were created either with very fine burs, and artificial caries agents in the contact area of a pair of teeth which were mounted on LEGO bricks. This set up allowed the teeth to be separated and remounted onto the exact position after creating the artificial lesions. Intact or treated human teeth were examined with PTR at various relative angles of the laser source and the detector using a specially designed rotational stage. Dental bitewing radiographs were also taken to determine whether dental X-rays could identify these defects. Extracted human teeth were mounted on LEGO

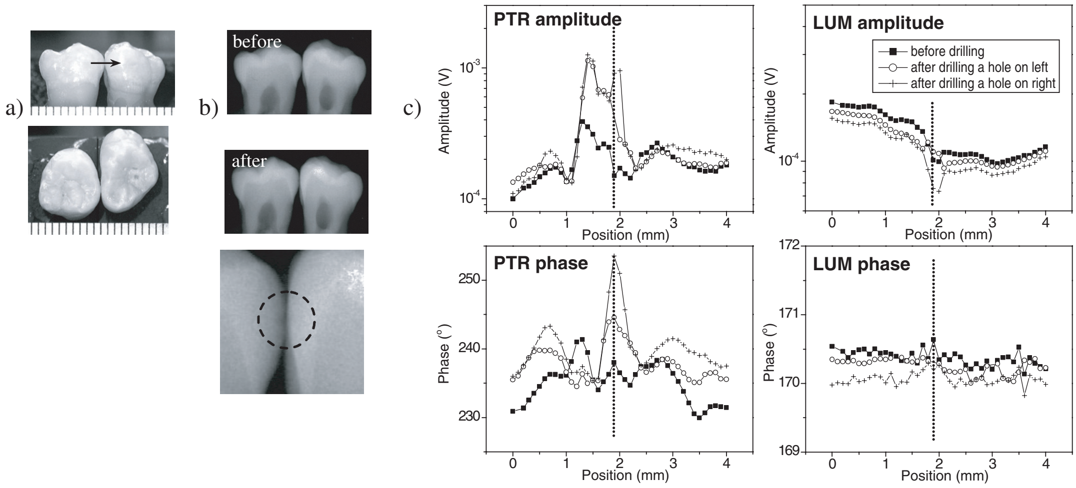


Fig. 2. Photographs and experimental results of an interproximal artificial lesion (mechanical hole) detection. (a) front, and top views of the teeth; (b) X-rays before and after drilling holes; (c) PTR and LUM amplitude and phase signals across the scan line at 30 Hz.

bricks so that a pair of teeth was in point contact, Fig. 2(a). The samples with mechanical holes were stored in saline solution and removed from the container just before the experiments, rinsed thoroughly with tap water for more than 20 seconds, and then left in air for 20 minutes to be dried properly. After the experiments, these samples were immediately placed in the container. However, for long term treatments (hours to days) of samples with a demineralization-remineralization solution, after several tests, humidity control was found to be important in reproducing signal baselines because teeth would be exposed to the dry air for a long time during treatment. To ensure similar humidity environments for all samples, a humid tight box was used with distilled water in Petri dishes for providing samples with humidity without direct water contact. Each pair of teeth was mounted on the LEGO bricks and was scanned at 30 Hz from the left to right across the interproximal contact spot as shown with arrows in Fig. 2(a) and Fig. 3(a). These samples were scanned and radiographed at every step of machining or treatment with an artificial caries agent. In order to see if small artificial holes could be detected by PTR and/or LUM, a 1/4 mm fine dental bur was used to make holes with approximately 1/4 mm depth on the sides of both teeth at the contact location. As shown in Fig. 2(b), the left side hole was deeper than that on the right side, so it could be visible on the X-ray image. PTR and LUM signals are shown in Fig. 2(c). PTR amplitudes are clearly higher after the sequential drilling of holes, to the left and to the right of the contact point at 1.2∼2.3 mm. PTR phases showed large changes around the holes at 1.5∼2.5 mm, too. In the PTR phase, some signal changes also appeared at regions away from the drilled holes, 0∼1.5 mm and 2.5∼4 mm. It is hypothesized that microcracks might have been created due to drilling and caused more extensive damage. The PTR amplitude also showed similar behavior. The LUM amplitude and phase didn't show clear differences around the holes because the LUM is essentially a surface phenomenon while the PTR delivers deep sub-surface information [3]. LUM amplitude and phase showed slight decreases at all scans, possibly because LUM is very sensitive to humidity changes.

3.2 Artificial demineralized lesion detection by PTR and LUM

Another sample set was treated by a demineralization-remineralization solution (2.2 mM Potassium Phosphate, monobasic (KH_2PO_4), 50 mM Acetic acid (NaOAc), 2.2 mM of 1M Calcium Chloride (CaC_{l2}), 0.5 ppm Fluoride (F-), and Potassium Hydroxide (KOH) for balancing the pH at 4∼4.5). After the first 16-hour treatment, PTR amplitude and phase increased almost an order of magnitude in the vicinity of the interproximal area, even though the laser incidence

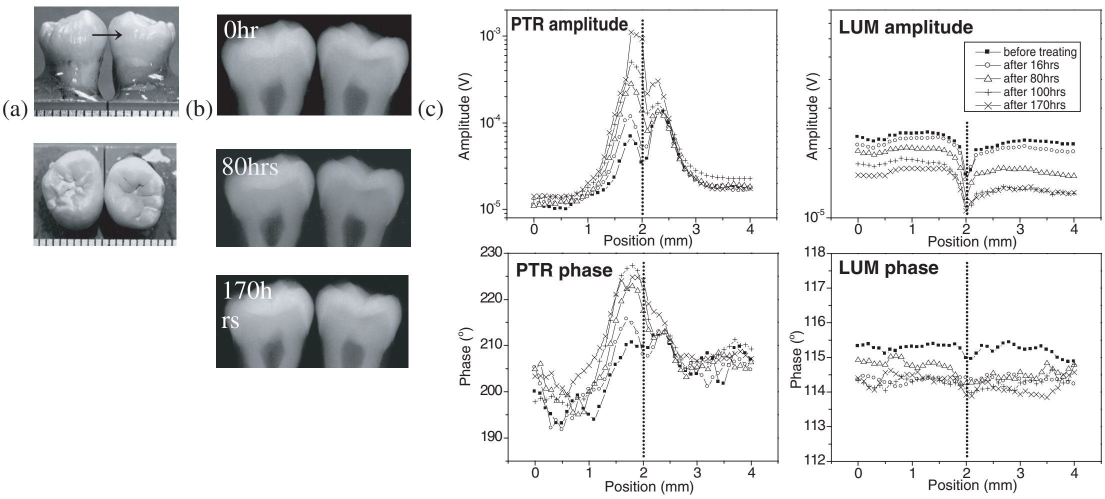
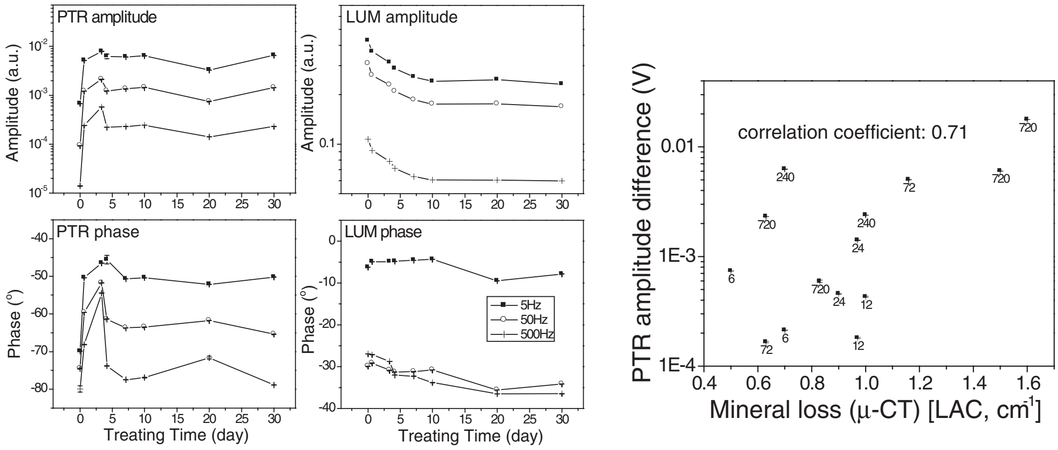


Fig. 3. A pair of teeth with an interproximal artificial lesion (demineralization-remineralization treatment) (a) front, and top views of the teeth; (b) X-rays before and after treatment for 80 hrs and 170 hrs; (c) PTR and LUM amplitudes and phases across the scan line at 30 Hz.

angle near the interproximal region was grazing, almost parallel to the approximal interface. Fig. 3(b) shows X-rays before and after treatment for 80 hours and 170 hours, but X-rays appear to be insensitive to the treatment. On the contrary, both PTR amplitude and phase showed clearly monotonic increases after each treatment while LUM was nearly insensitive but for the slight rigid shift (decrease) of the curves across the scanned region due to humidity changes. However LUM showed almost no change around the treated contact point. Slight rigid signal amplitude decreases across the entire scanned region were observed, presumably due to dehydration of the enamel affecting the entire surface. In these experiments both buccal and occlusal scans exhibit similar levels of sensitivity to the creation of the demineralized lesions. Fig. 4(a) shows signal changes with treatment time at 5, 50 and 500 Hz. These data were extracted from frequency scans following each treatment time. PTR amplitude and phase increased quite steeply after the first 16-hour treatment; beyond that, they increased marginally until 80 hours of treatment. Both signal channels decreased somewhat after 100 hours, remaining essentially flat thereafter. The higher the frequency, the steeper the decrease observed after 80 hours in both PTR amplitude and phase. It is noted that our LUM signal amplitudes also exhibited the steepest rate of descent at early demineralizing times, consistent with the rate of steepest ascent of the PTR signals. All the samples exhibited this behavior which may be due to partial saturation interaction between the solution and the enamel or partial remineralization of the enamel surface over time. After all the measurements, micro-Computed Tomography (μ-CT), Transverse Micro-Radiography (TMR) and Scanning Electron Microscopy (SEM) were used to measure the mineral loss (μ-CT and TMR) and the treatment lesion depth (TMR) as well as to obtain high-resolution cross sectional images around the location (SEM). No recognizable lesion was observed in either μ-CT and TMR images. Only the top-down SEM images on an untreated enamel surface and a treated surface showed differences. From these results, it seems that the treatment caused only a shallow surface demineralization and could not create a subsurface lesion deep enough to be visible to μ-CT or TMR. However, TMR and μ-CT could compute the mineral losses (110.8-905.4 vol% μm with TMR, 0.36-1.6 cm-1 LAC with μ-CT) and the lesion depths (5.9-31.0 μm with TMR) for these samples. The best correlation between these two methods and the PTR/LUM signals was obtained between the PTR amplitude differences vs. mineral loss with μ-CT which yields a correlation coefficient of 0.71 shown in Fig. 4(b). It was hard to find a relationship between mineral loss (or lesion depth) and treatment time for both TMR (correlation coefficient: 0.44) and μ-CT (correlation coefficient: 0.41). This is not only because of the small number of samples, since for treatments up to 10 days there were only



(a) (b)

Fig. 4. (a) An interproximal sample with demineralized lesion created by the buffer solution. Typical PTR/LUM signal kinetics vs. treatment time at 5, 50 and 500 Hz for a sequentially treated single tooth. (b) Correlation between PTR amplitude differences and μ-CT mineral loss measurements.

2 samples per treatment time. It was found that the mineral losses and the lesion depths after the full 30-day treatment were too widely distributed to yield meaningful mean and standard deviation values. This wide distribution of mineral loss from teeth has also been reported by de Josselin de Jong et al. [4]. On the other hand, Eggertsson et al. [5] mentioned that creating chemical caries lesions on natural surfaces of extracted teeth had proved to be quite difficult which might be related to either high concentration of fluoride in the superficial enamel layers or to organic debris tenuously adhering to the tooth. This implies that extracted human teeth may have widely different surface mechanical and chemical properties with the result that some can be easily treated chemically while others cannot. Consistently with these observations, it follows that optical and thermophysical properties of dental enamel would also be expected to vary widely among healthy teeth.

In conclusion, trends in biothermophotonics in frequency-domain depth-profilometric dental applications have been presented. PTR has been assessed to be capable of detecting artificial interproximal lesions in human teeth. Mechanical holes and etched surfaces by phosphoric acid in the interproximal region, which are too small to appear in dental radiographs, exhibited clear differences in PTR signals. Modulated luminescence was also measured simultaneously, but it exhibited a lower degree of sensitivity to these interproximal lesions and higher dependency than PTR on the hydration state of the surface. The demineralized interproximal spots created by a saturated acidic buffer after continuous exposure from 6 hours to 30 days were examined by PTR and LUM. The PTR amplitude increased more than 300% after treatment with the acidic buffer for 80 hours and the PTR phase also changed 5$\sim$13 degrees at 30 Hz. Dental bitewing radiographs were also taken to determine whether X-rays could identify these lesions as well, but they showed no sign of lesion even for samples treated for 30 days. After completing all the experiments, μ-CT, TMR and SEM analyses were performed to compare and potentially correlate the PTR signals to depths of lesions and density changes. Only SEM images of the treated surface showed slight changes, while cross sectional images showed no visible lesions. Therefore, PTR has been shown to exhibit higher sensitivity to early demineralization lesions than standard dental x-rays and the potential to be a reliable non-invasive tool for the detection of early interproximal carious lesions.

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