Depth profilometric case studies in caries diagnostics of human teeth using modulated laser radiometry and luminescence

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Simultaneous measurements from human teeth of photothermal radiometric (PTR) and luminescence (LM) signals induced by an intensity modulated laser have been performed to assess the feasibility of detecting deep lesions and near-surface cracks, to examine the effects of varying enamel thicknesses, the presence of fillings, and stains on the surface of teeth. A commercial dc luminescence monitoring instrument (DIAGNOdent by KaVo) was also used to examine a set of teeth for comparison purposes with PTR and LM. PTR amplitude signals from carious regions and from thin enamel were higher than those from healthy regions and thicker enamel. A crack produces a peak in the PTR amplitude scan, as well as a sudden change in the luminescence amplitude at the corresponding point. At low frequencies (5 Hz), the PTR amplitude showed high sensitivity to a deep (about 2 mm) lesion, while at high frequencies (700 Hz) it was more sensitive to surface cracks. It was concluded that by selecting proper modulation frequencies of the laser, measurements of PTR and LM signals could be used as a dental diagnostic technique with a small, inexpensive, low-power (<30 mW) semiconductor laser as a light source emitting in the optical window range of hard tissue (650–1000 nm). © *2003 American Institute of Physics.* [DOI: 10.1063/1.1516242]

I. INTRODUCTION

In the past few decades with the advent of water fluorination, the prevalence of caries, especially smooth surface caries, has been reduced greatly.[1] For example, a 50% reduction was documented for 17 year olds over the period 1971–1985, however, a greater reduction in smooth surface caries has resulted in an increase in the proportion of primary caries in susceptible pits and fissures.[1] Therefore, the development of (preferably noncontacting) techniques and instruments that can detect early caries or tiny lesions on the tooth surface or in the very-near subsurface has been an active area of research. The use of lasers is considered to be promising in this area, and some instruments have been developed and commercialized, such as the DIAGNOdent,[2,3] which can distinguish carious and healthy teeth using unmodulated laser excitation and dc luminescence collection from a tooth.

In recent years, a novel dynamic dental depth profilometric imaging technique, which can provide simultaneous measurements of laser-induced frequency-domain infrared photothermal radiometric and luminescence signals from defects in teeth has been developed.[4] In this work, several teeth were examined with various types of near-surface and deep-subsurface lesions (a subsurface caries, a crack, enamel thickness variations, and a surface stain). The behavior of photothermal radiometric (PTR) and luminescence (LM) signals in the presence of these defects and features was studied and the potential for the combined PTR and LM signals to be used as a depth profilometric diagnostic methodology has been assessed.

II. SAMPLE PREPARATION AND EXPERIMENTAL SETUP

Extracted teeth were stored in saline solution separately in vials before the experiments. Each sample tooth in the study was removed from the vial and was rinsed thoroughly with clean water for 20 s and then was dried with pressurized air before commencing the experiment. Then, the tooth was placed on the sample stage and the laser was turned on for a few minutes (thermalization time) before starting the measurements.

Figure 1 shows the experimental setup. A 659 nm Mit-

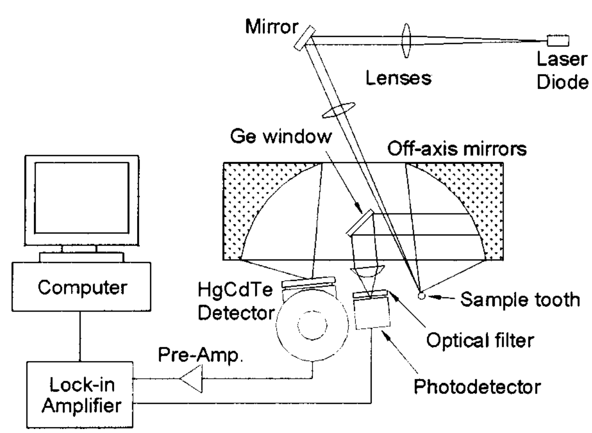

FIG. 1. Schematic diagram of the experimental setup.

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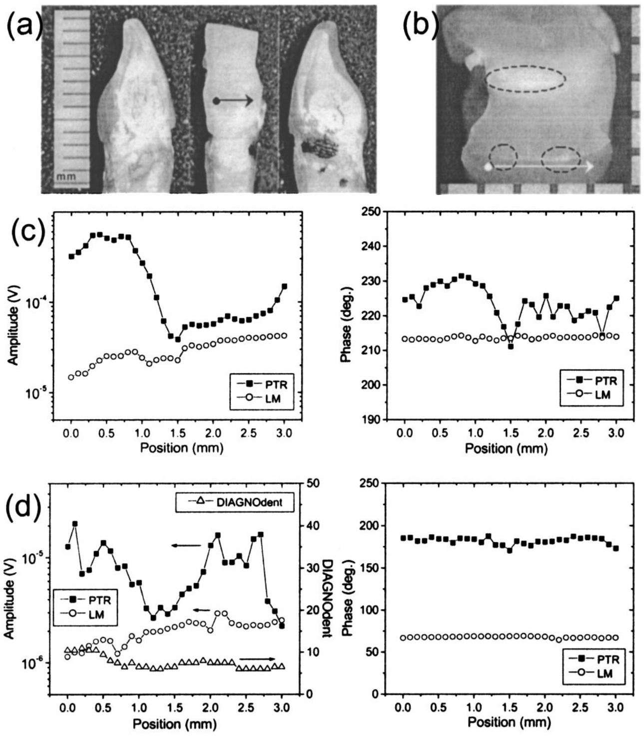

FIG. 2. Photographs and experimental results of sample tooth A. (a) left, front, and right views of the tooth; (b) cross section at the scanning line shows a deep demineralized lesion (dotted region in the middle) and surface cracks (dotted shapes at the bottom); (c) PTR and LM amplitude and phase signals across the scanned line at 5 Hz; and (d) PTR and LM amplitude and phase signals at 700 Hz and DIAGNOdent readings (amplitude curves).

subishi ML 1016R-01 (maximum power: 30 mW) semiconductor laser was modulated by the laser diode controller (Coherent 6060) and the built-in function generator of the lock-in amplifier (Stanford Research SR830). The laser beam was focused on the sample with a high-performance lens (Gradium GPX085) to a spot size of approximately 55 μm. Modulated PTR and LM were induced by means of harmonically modulating the current of the laser diode. The modulated infrared photothermal radiation (PTR signal) from the tooth was collected and focused by two off-axis paraboloidal mirrors onto a HgCdTe detector. Before being sent to the lock-in amplifier, the PTR signal was amplified by a preamplifier (EG&G Judson PA-300). For the simultaneous measurement of LM and PTR signals, a germanium window was placed between the parabolic mirrors, which was utilized so that wavelengths up to 1.85 μm (Ge band gap) 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–1.1 μm (Newport 818-BB-20). A cut-on colored glass filter (cut-on wavelength: 695 nm, Andover 695FG07-50S) was placed in front of the photodetector to suppress laser light reflected or scattered by the tooth. For ac luminescence monitoring, a different lock-in amplifier (EG&G model 5210) was used.

III. RESULTS AND DISCUSSION

Several teeth were examined with the simultaneous PTR and LM techniques at a fixed frequency. Most measurements were performed at 5 Hz. 700 Hz modulation was used with some teeth. Among a large reservoir of extracted teeth, four were chosen that exhibited lesions of interest to this study: deep-subsurface caries, surface cracks, variable enamel morphology, and fillings and stains, all of which could be easily diagnosed and classified by a dental clinician. After each set of measurements, the tooth was cross sectioned and photographed for histological validation of the PTR and LM signals.

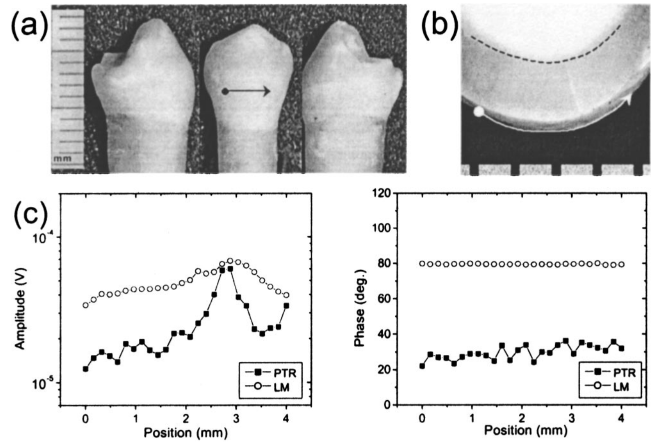

FIG. 3. Photographs and experimental results of sample tooth B. (a) left, front, and right views of the tooth; (b) cross section of the scan position; and (c) PTR and LM amplitude and phase signals across the scanned line at 5 Hz.

A. Case 1: Deep subsurface caries diagnosis

As shown in Fig. 2(a), sample "A" is a thoroughly carious tooth (left side) opposite to broken enamel (right side). Figure 2(b) shows a deep lesion in the middle of the dentin, probably a demineralized extension of the carious region on the left side of the tooth. On the right-hand side of Fig. 2(b) each segment of the graduated scale (broken line) is equivalent to 1 mm. The arrow in Fig. 2(a) shows the direction and extent of the laser scan across the intact surface of the tooth overlying the carious subsurface. The results are shown in Figs. 2(c) and 2(d). From the onset to the middle of the scan in Fig. 2(c), the PTR amplitude is high (5×10^{-5}–5×10^{-4} V range) consistent with the presence of the deep-subsurface lesion at approximately 2.5 mm below the tooth surface. The LM amplitude shows a similar but less dramatic structure than the PTR amplitude. It peaks and dips at the same locations, but its magnitude increases continuously beyond the visible boundary of the lesion. This is likely due to differences in the light scattering properties of the dentin and the lesion. The PTR phase shows strong spatial dependence and a similar shape to the PTR amplitude, while the LM phase shows almost no variation. The low-frequency insensitivity of the LM phase to the subsurface dental structure has been noted in our earlier report.[4]

B. Case 2: Surface crack detection

Two samples were examined in this case. One is the tooth in case 1, probed with the modulation frequency of 700 Hz. At low frequencies, both PTR and LM show greater

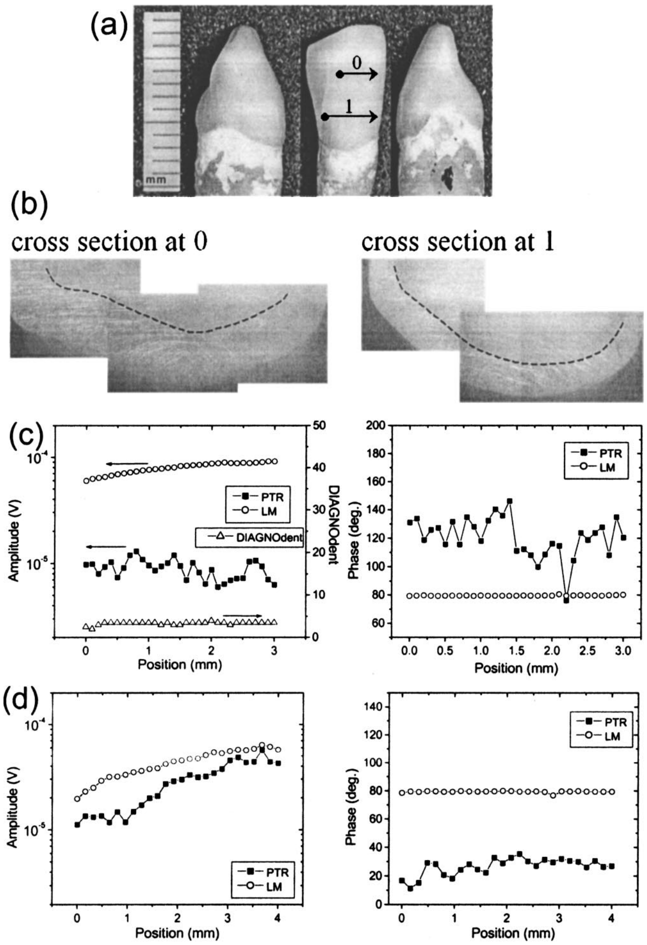

FIG. 4. Photographs and experimental results of sample tooth C. (a) left, front, and right views of the tooth; (b) cross sections at the scan lines 0 and 1, respectively; (c) PTR and LM amplitude and phase signals across the scanned line 0 at 5 Hz and DIAGNOdent readings (amplitude curves); and (d) PTR and LM amplitude and phase across the scanned line 1 at 5 Hz.

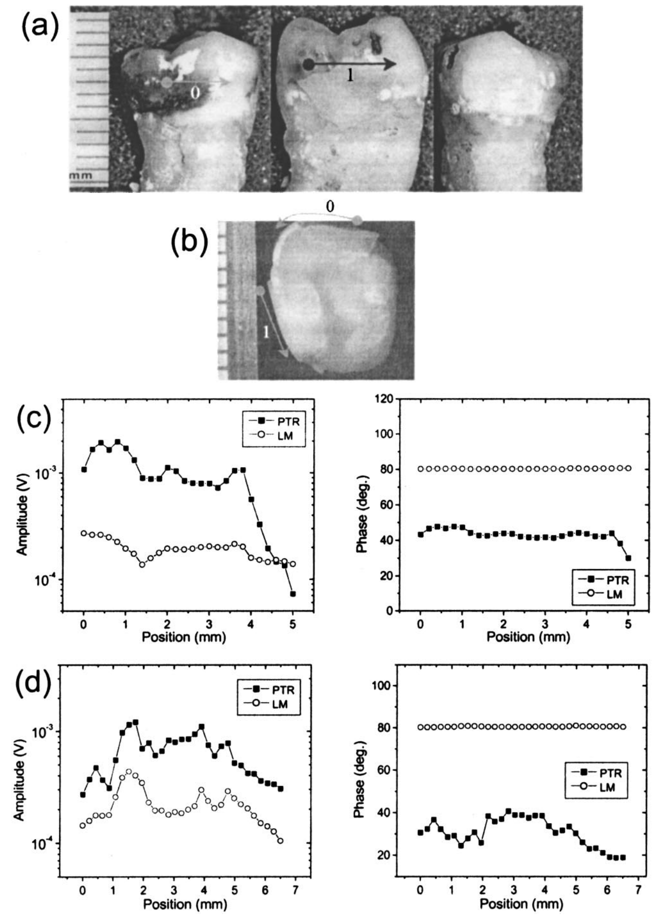

FIG. 5. Photographs and experimental results of sample tooth D. (a) left, front, and right views of the tooth; (b) cross section at the scan lines 0 and 1; (c) PTR and LM amplitude and phase across the scan line 0 at 5 Hz; and (d) PTR and LM amplitude and phase across the scan line 1 at 5 Hz.

sensitivity to the deep lesion than to surface cracks, compared with the high-frequency signals. The PTR dependence can be understood by the deeper penetration of the thermal wave. At the higher frequency only surface cracks or caries could be detected photothermally due to the decreased thermal probe (diffusion) length. The two surface cracks near the edge [dotted shapes at the bottom of Fig. 2(b)] are responsible for the PTR amplitude, Fig. 2(d). Here, the broad peaks correspond to the location of the cracks at 0.5 and 2.2 mm, respectively. The apparent loss of LM sensitivity to the deep-subsurface lesion at the higher frequency is due to the more prominent role of the near-surface cracks in the LM signal. The LM amplitude further shows sudden changes at those points, which is typical of the presence of cracks. Our results with modulated LM with several types of teeth have shown that there is some depth profilometric capability of this method (not as pronounced as PTR), mostly confined to subsurface layered structures with sharp boundaries, such as the enamel–dentin junction. The DIAGNOdent readings are consistently low, less than ten calibration units, which means according to the manufacturer[5] that the tooth is healthy all across the spatial scan. Both the PTR and LM phases show almost no variation at 700 Hz, signifying that the very-near-surface PTR results are mainly optical in nature rather than thermal, with the thermal centroid phase shift being too small to be measured.

Another sample in this case is tooth "B" shown in Fig. 3(a). This tooth is healthy but there is a crack in the thick enamel as shown in Fig. 3(b). In Fig. 3(b) each segment of the graduated scale (broken line at bottom) is equivalent to 1 mm. Dashes have been added at the enamel–dentin junction to aid the eye. Peaks in the PTR and the LM amplitude curves caused by the crack are shown in Fig. 3(c) around 2.8 mm. There are no significant changes in either phase curve, again signifying that the PTR signal contrast in the cracked region is mostly optical in nature rather than thermal. The apparent structure in the PTR phase of Fig. 3(c) is mostly noise, as the overall healthy tooth generates PTR signals less than 10^{-4} V. As a rule, healthy and thick enamel generates small PTR and LM amplitudes (<0.1 mV).

C. Case 3: Sensitivity to enamel morphology

Figure 4 shows an example of a changing signal amplitude base line. Tooth "C" is a healthy tooth (DIAGNOdent readings are below 5 at all points). Two different locations are examined; in Fig. 4(b) there are overlapped extended photographs shown of each cross section at locations 0 and 1. The dotted lines have been inserted to aid the eye at the enamel–dentin junction. Figures 4(c) and 4(d) are the results of scanning lines 0 and 1, respectively. At location 0, the PTR amplitude is very low $\sim 1\times 10^{-5}$ V, which also results in very noisy phase scans. The thick healthy enamel is the cause of the low PTR signal. The different enamel thicknesses of cross sections 0 and 1 can be clearly seen. The PTR amplitude for location 1 is greater than that for location 0 because the enamel is substantially thinner at location 1. However, the LM amplitudes exhibit an opposite trend: greater amplitude for the thicker enamel. Both the PTR and LM amplitudes gradually increase along the scanned line, especially at location 1, due to a slight decrease in the enamel thickness observed under the microscope. The PTR phases do not offer much useful information in this case, owing to the noise that accompanies the low PTR signals. As usual, the LM phases are essentially insensitive to tooth structure at low frequencies.

D. Case 4: Filling and stain diagnosis

As shown in Fig. 5(a), tooth ''D'' has a large dark stain on the left side (scan 0) and a filling on the front surface (scan 1). Scan line 0 starts from the stain and ends at a relatively healthy looking region. Scan line 1 was chosen for comparing signals from dental enamel, a filling (around 2–4 mm), and their interface. Figure 5(c) shows the experimental results for scan 0. The PTR amplitude is very high ($>10^{-3}$ V) within the stain region and exhibits some structure. The PTR phase also shows a similar structure, indicating that the stain is not a purely surface feature and may be accompanied by thermophysical material property changes (thermal diffusivity), and/or optical changes below the surface. Figure 5(b) corroborates the optical feature variations at some depth below the stained surface across scan 0. The stain–enamel border is visible in both the PTR and LM amplitudes, as well as in the PTR phase. The signals decrease rapidly beyond the border of the stain, as expected from healthy enamel. In Fig. 5(d), the PTR and LM amplitudes and the PTR phase clearly show the effect of the interface between the filling and tooth through the peaks around 1.5 and 4.3 mm.

IV. CONCLUSIONS

Modulated laser photothermal radiometry and luminescence were presented as diagnostic techniques of several defects and features of human teeth. PTR amplitude signals from a tooth can be used as a useful tool for detecting deep demineralized lesions and near-surface cracks, for monitoring enamel thickness in healthy teeth, and for diagnosing the presence of stains. A high PTR amplitude and sudden changes in the LM amplitude are caused by the presence of cracks in our tooth samples. By selecting proper modulation frequencies of the laser intensity, combined measurements of PTR and LM signals could be used as a dental diagnostic technique to differentiate deep-lying carious regions from surface cracks.

ACKNOWLEDGMENTS

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[1] D. McComb and L. E. Tam, J. Can. Dent. Assoc. **67**, 454 (2001).
[2] R. Hibst and K. Konig, U.S. Patent No. 5,306,144 (1994).
[3] R. Hibst, R. Gall, and M. Klafke, U.S. Patent No. 6,024,562 (2000).
[4] L. Nicolaides, A. Mandelis, and S. H. Abrams, J. Biomed. Opt. **5**, 31 (2000).
[5] DIAGNOdent Instruction Manual, KaVo, Biberach, Germany (2001).