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Thermophotonic lock-in imaging: An active thermography system for detecting early carious lesions in human teeth

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Lock-in thermography is an active thermographic method that incorporates quadrature demodulation to retrieve the amplitude and phase of the thermal waves generated inside the sample either optically, acoustically or mechanically. The role of subsurface defects, in this case, is then to shift the thermal-wave centroid and therefore produce dynamic contrast, both in amplitude and phase images, with respect to the intact areas. Thanks to recent advances in infrared camera technology, lock-in thermography has been successfully applied to various industrial fields as a powerful non-destructive evaluation technique but less work has been carried out in medical applications of this technology. The case of biological samples is challenging as these samples are usually translucent and do not effectively absorb the applied optical excitation. Even if they do, the medical codes prevent researchers from applying high power excitation to these samples. As a result, the photothermal signals obtained from biological samples are generally poor in terms of signal-to-noise ratio and this makes signal enhancement methods an inevitable part of lock-in thermography systems used in the medical field. The other significant difference of biological samples is that due to their translucency the infrared radiation emanating from them is governed by a coupled diffuse-photon-density and thermal-wave field, as opposed to purely thermal-wave field in opaque samples, which makes the interpretation of the results even more complicated.

Mandelis et al. [1] were the first to apply photothermal science to detect early carious lesions in human tooth. There are many benefits in detecting carious lesions in their early stages of progression. These include: 1) increased potential to remineralize the demineralized, noncavitated tooth surfaces; 2) decreased risk of progression to the cavitated stage; 3) reduced probability of tooth sensitivity associated with deeper lesions; 4) maintenance of the natural occlusion; 5) preservation of the natural esthetic appearance of tooth enamel; 6) reduced treatment cost associated with premature and unnecessary surgical interventions. However, these benefits will only be realized if dentists can find a diagnostic method that can effectively detect the carious lesions in their early stages of progression. An X-ray radiograph has poor sensitivity and therefore is incapable of detecting early carious lesions. So far, the most powerful inspection method is visual inspection which depends strongly on the visual capability and experience of the dentist. The experimental results of our research team [1] show that photothermal radiometry is a reliable and sensitive tool in detecting tooth decay in its early stages of progression and this paper is basically an imaging extension of our laser photothermal radiometry using an infrared camera.

When light enters the tooth it scatters specially at the carious areas where the pore volume is larger [2]. In general, more light scattering in a location results in higher probability of optical absorption, thermal conversion and Planck radiation emission (thermophotonics). As a result, the thermal waves that are generated in porous regions will have greater amplitude than those generated at intact enamel [2]. Moreover, as the carious porous areas are close to the surface they shift the thermal-wave centroid closer to the front surface and therefore decrease the phase lag between the applied optical excitation and the surface temperature oscillation. In both cases (amplitude and phase), a pronounced contrast can be observed between intact and carious locations.

To verify the capabilities of our thermophotonic lock-in imaging system in detecting early carious lesions in dental samples, extracted human (molars or wisdom) teeth with healthy surfaces were selected. In order to apply controlled demineralization on the tooth samples, a demineralizing solution was prepared. Since our goal was to study the contrast between demineralized and healthy spots in a whole tooth, the tooth was covered with two coats of transparent nail polish except for a rectangular window of size 1mm (W) x 4mm (H), referred to as the treatment window. The demineralization on the window was carried out by submerging the sample upside down in a polypropylene test tube containing 30 ml of demineralizing solution. After the treatment period the sample was removed from the gel, rinsed under running tap water and dried in air. Then, the nail polish was removed from the interrogated surface using acetone and the sample was again rinsed and dried before running thermophotonic lock-in imaging on the sample. After each measurement, the sample was covered again with the transparent nail polish (except for the treatment window) and demineralized for additional days in order to investigate the progression of caries with time.

Our infrared camera (CEDIP Titanium 520M, maximum frame rate at full window = 160 Hz) captured the infrared radiation (3.6-5.1 μm) emanating from the sample while it was illuminated by a 808 *nm* laser with a beam size of 25 *mm*. The

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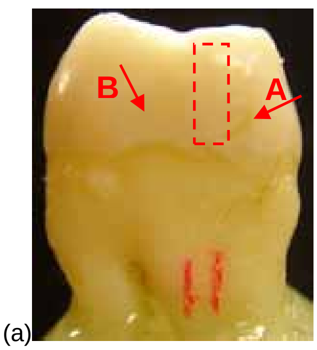
data acquisition program was designed in LabView platform and was able to perform signal averaging to suppress the stochastic noise. Furthermore, a synchronous undersampling algorithm [3] was added to the program so that the system could run lock-in imaging up to 150 Hz.

Figure 1(a) shows the optical image taken from the sample after the treatment window was demineralized for 2 days. As expected, due to the short demineralization time it is impossible to visually differentiate between the treated and untreated areas. However, a crack can be observed at the rightmost side of the crown (highlighted as A in Fig. 1(a)). Figure 1(b) shows the phase image obtained at 10 Hz from the sample before applying the treatment. This image not only confirms the presence of crack A, but also reveals the presence of a hairline crack at position B which was not visible in the optical image. The dark line extending horizontally at the bottom of this image is the cementum-enamel junction which can also be observed in the optical image. Despite the incapability of visual inspection to detect early carious lesions in teeth, Figure 1(c) shows that the phase image obtained at 10Hz after only 2 days of treatment can clearly detect the treated area. Figure 1(d) shows the phase image at 10 Hz after 4 days of demineralization on the treatment window. It can be observed that the contrast between the intact and treated sections increases with treatment time.



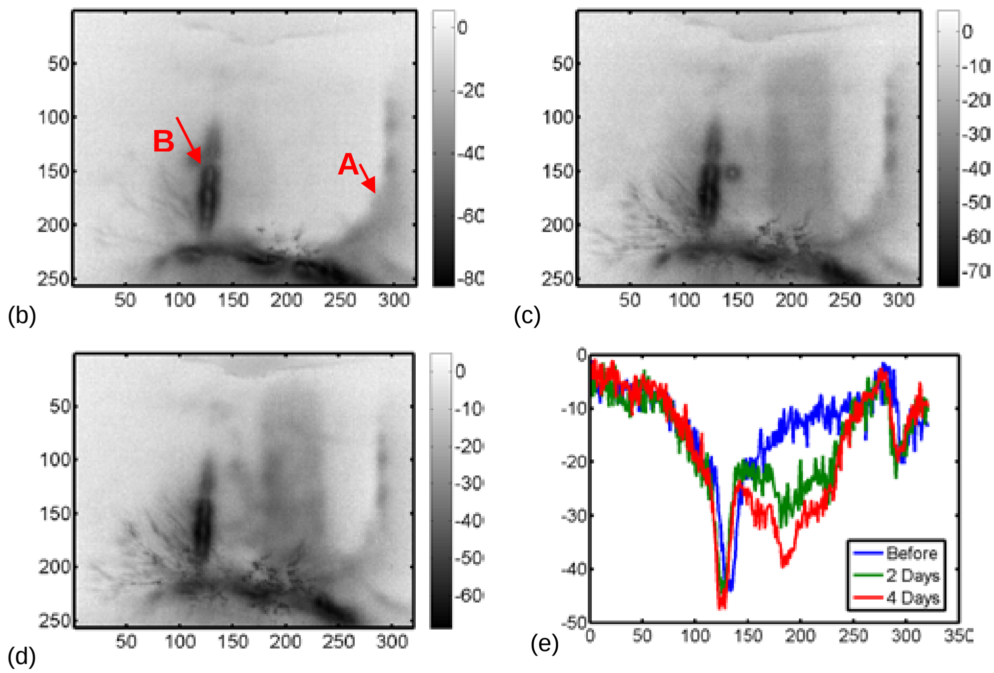


Fig. 1. (a) Optical image of the 2-day-demineralized sample,
(b) Phase image at 10 Hz of the untreated sample,
(c) and (d) Phase images at 10 Hz of the 2-day-demineralized and 4-day-demineralized samples, respectively.
e) Phase profile along row 120 of Figs. 1(b), (c), and (d).

Figure 1(e) is the phase profile along row 120 of Figs. 1(b) – (d). It can be observed that by increasing the treatment time the phase value of pixels within the treatment window decreases while that of pixels outside the treatment window remains the same.

These preliminarily results of our thermophotonic lock-in imaging system show that this method is capable of detecting invisible early carious lesions and cracks in dental samples. To the best of our knowledge, no other imaging modality can provide 2D maps of tooth decay in the very early stages of their formation.

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