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Photothermal Radiometry and Modulated Luminescence: Applications for Dental Caries Detection

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71.1
Introduction

The traditional methods for dental caries detection, visual examination and radiography, are not effective in detecting early caries lesions [1]. If dental caries is detected early, before a substantial amount of the tooth is destroyed, the area can be remineralized [2], which can prevent invasive procedures, radiation exposure, and create a sound surface devoid of restorations. Recently, a new group of light-based dental diagnostic techniques has been proposed [3]. The group includes techniques such as light-induced fluorescence, digital imaging fiber-optic transillumination (DIFOTI), electrical caries monitoring (ECM), optical coherence tomography (OCT), alternating current impedance spectroscopy, and photothermal radiometry (PTR) with modulated luminescence (LUM).

PTR–LUM combines PTR and LUM for detection and monitoring of carious lesions. In PTR, a beam of energy (typically a laser), intensity modulated at a certain frequency, is focused on the sample surface. The resulting periodic heat flow due to the absorbed optical energy in the material is a diffusive process, producing a periodic temperature rise (spatial distribution) which is called a "thermal wave." This temperature distribution, in turn, causes a modulated thermal infrared (IR) (black-body or Planck radiation) emission which is used to monitor the material under examination. PTR has the ability to penetrate, and yield information about, an opaque medium well beyond the range of optical imaging. Specifically, the frequency dependence of the penetration depth of thermal waves makes it possible to perform depth profiling of materials [4]. 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 controlled by the thermal diffusivity of enamel (50–500 μm); and radiatively, through blackbody IR emissions from considerably deeper regions commensurate with optical penetration of the diffusely scattered laser-induced optical field (several millimeters) and with the existence of IR spectral "windows" for IR photon transmission.

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The term luminescence is used to describe a process in which light is produced when an energy source causes a transition of electrons or other energetic particles from their lowest ("ground") energy state to a higher ("excited") state; subsequent return to the ground state releases the excess energy in the form of light photons of longer wavelength than the optical source (Stokes shift). There are several types of luminescence, each named according to the source of energy, or the trigger for the luminescence, for example, photoluminescence (caused by electromagnetic radiation), or fluorescence (caused by ultraviolet or visible excitation). However, these terms are often used interchangeably in the literature. Many important biological objects containing fluorescing components (fluorophores) exhibit intrinsic fluorescence (or autofluorescence). The reduction in fluorescence when enamel demineralizes has been attributed to the increase in porosity of carious lesions when compared with sound enamel. There is an associated uptake of water and decrease in the refractive index of the lesion resulting in increased scattering and a decrease in light-path length, absorption, and autofluorescence [5]. Additional sources of luminescence decrease are associated with the destruction of the enamel crystalline structure as a result of demineralization. In summary, a combination of PTR and LUM provides valuable complementary information about the conversion pathways of optical energy in a sample.

It has been a decade since the first publications on PTR–LUM for examining hard dental tissue appeared. In this chapter, we review the development of and future outlook for this novel dental diagnostic technology, including the clinical PTR-LUM device (The Canary System).

71.2
Theoretical Modeling

To appreciate better the capabilities of PTR–LUM, it is important to understand how the laser light interacts with turbid media generating two energy fields: optical and thermal. A coupled diffuse photon density and thermal wave model was developed for theoretical analysis of the photothermal field in demineralized teeth [6, 7]. The solution of the radiative transport equation in the limit of diffuse photon density field is considered as a source term in the thermal wave field equation. The chromophore (hydroxyapatite) relaxation lifetimes, optical absorption, scattering, and spectrally averaged IR emission coefficients were determined by fitting the model to the measured PTR–LUM data [6]. The influence of the foregoing optical and thermal parameters (thermal diffusivity and conductivity) of each layer of a demineralized tooth on the diffuse photon density and therma wave depth profiles has recently been analyzed using computer simulations that allow the optimized simultaneous measurement of these major optical and thermal properties of teeth from experimental PTR scans [7].

71.3
Depth Profilometry

One of the main advantages of PTR–LUM, intrinsic to diffusion wave methods, is the ability to perform depth profiling through scanning of the excitation source modulation frequency. By selecting several modulation frequencies, PTR measurements at different depths in the enamel can be obtained. Studies on the depth profilometric capability of PTR–LUM in dental applications [8] showed that the radiometric amplitude exhibited a superior dynamic range (two orders of magnitude signal resolution) to luminescence (a factor of two only) in distinguishing between intact and cracked subsurface structures in the enamel. Further studies [9] assessed the feasibility of PTR–LUM to detect deep lesions. PTR frequency scans over the surface of a fissure into demineralized enamel and dentin exhibited higher amplitude than those for healthy teeth, and also a pronounced curvature in both amplitude and phase signal channels. These can be excellent markers for the diagnosis of subsurface carious lesions. In addition, PTR exhibited superior sensitivity to the presence of sharp boundaries, and also to changes in natural demineralized regions of the tooth.

71.4 Pits and Fissures Caries Detection

Jeon *et al.* [10] examined pit and fissure caries in 52 extracted human teeth with simultaneous measurements of PTR and LUM. These measurements were compared with conventional diagnostic methods including continuous (DC) luminescence (DIAGNOdent), visual inspection, and radiographs. Sensitivities and specificities were calculated by using histologic observations as the gold standard to compare all examined methods. With the combined criteria of four PTR and LUM signals (two amplitudes and two phases), it was found that the sensitivity of this method was much higher than those of any of the other methods used in this study, whereas the specificity was comparable to that of the DC luminescence. Therefore, the combination of PTR and LUM has the potential to be a reliable tool to diagnose pit and fissure caries and could provide detailed information about deep lesions.

71.5 Interproximal Caries Detection

The interproximal contact area of teeth is a common location for dental caries. Here plaque (containing bacteria in a biofilm) and food particles can become trapped, leading to the creation of carious lesions. Jeon *et al.* used PTR–LUM to examine interproximal caries in extracted human teeth [11]. Three types of lesions were created: with dental burs in a high-speed handpiece, with 37% phosphoric acid, and with demineralization in artificial caries media. Each sample pair was examined before and after bur application, or sequential treatment with acid (etched for 20 s) and gel (time periods spanning from 6 h to 30 days). The results showed distinct differences in the signal for these types of lesions. Dental bitewing radiographs showed no sign of demineralized lesions even for the samples treated for 30 days. Only scanning electron microscopy and micro-computed tomographic imaging, which are destructive, showed visible signs of treatment. PTR further exhibited excellent reproducibility and consistent signal changes in the presence of interproximal demineralized lesions. The results suggested that PTR can be a reliable probe to detect early interproximal lesions. The LUM channel was also measured simultaneously, but it showed a lower ability than PTR to detect these lesions.

71.6 Early Lesion Detection

There is a great deal of value in detecting carious lesions early. PTR–LUM research in the laboratory setting [12] and observations from an early investigational trial [13] using the clinical version (Canary System), indicated that lesions can remineralize or stabilize if exposed to remineralizing agents such as fluoride and casein phosphopeptide–amorphous calcium phosphate (CCP–ACP). In laboratory studies, PTR–LUM was used to monitor early stages of tooth demineralization and remineralization [12]. Extracted teeth were treated with an artificial demineralization gel to simulate controlled mineral loss on the enamel surface and then exposed to a remineralizing agent. The treated region of the tooth was monitored with PTR–LUM before and after treatment. The results showed that PTR–LUM has very high sensitivity to incipient changes in the enamel structure. The PTR and LUM amplitudes and phases showed gradual and consistent changes with treatment time. There was good correlation of PTR–LUM results with the mineral loss or the lesion depth measured with transverse microradiography (TMR). This indicated that PTR–LUM is capable of monitoring artificially created carious lesions, their evolution during demineralization, and the reversal of the lesions during remineralization.

71.7 Recent Developments

In 2009, The Canary System developed by Quantum Dental Technologies (Toronto, ON, Canada) was used in a Health Canada-approved human investigational trial [13]. In that study, amplitude (A) and phase (P) responses at various modulation frequencies from healthy and carious dental enamel (ICDAS 0–6) were measured. Over 500 regions on healthy tooth surfaces of 50 subjects were used to construct a healthy baseline for each output channel (1-PTR-A, 2-PTR-P, 3-LUM-A, and 4-LUM-P). PTR-A and PTR-P were used to detect near-surface and subsurface lesions, whereas LUM-A and LUM-P were used to detect near-surface lesions. The results indicated that The Canary System did not cause any adverse events or soft or hard tissue trauma. There was no difference in signal from anterior and posterior healthy tooth surfaces, and the presence of surface stain and biofilm did not affect the signal from healthy tooth surfaces. A clear shift from the baseline in both PTR and LUM in carious enamel was observed depending on the type, depth, and nature of the lesion. The results showed that The Canary System is safe and discriminates between healthy and carious enamel. In 2010, a second Health Canada-approved investigational trial has shown the ability of The Canary System to detect carious lesions on smooth surfaces, occlusal surfaces and around restoration margins [14]. Preliminary results show that the system is safe and provided repeatable measurements that allowed it to monitor lesion growth and response to various remineralization therapies [14].

71.8 Conclusion

This review of the principles of PTR–LUM and its applications to dentistry has highlighted the significant progress in bringing this novel technology to clinical applications. PTR–LUM offers features beyond what is currently available in traditional dental detection methods. These features include the ability to perform depth profilometry and very early caries detection and monitoring on various tooth surfaces. It was also shown that The Canary System, a portable PTR–LUM instrument for clinical applications, is safe and can discriminate healthy and carious tooth tissue.

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