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Quantitative analysis of dental tissue properties using photothermal radiometry

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Abstract

Photothermal Radiometry was applied as a safe and highly sensitive tool for the detection of early tooth enamel demineralization. An extracted human tooth was treated sequentially with an artificial demineralization gel to simulate controlled mineral loss in the enamel. A semiconductor laser was a source of infrared blackbody radiation from teeth upon absorption and non-radiative energy conversion. A coupled diffuse-photon-density-wave and thermal-wave theoretical model was developed to describe the biothermophotonic phenomena in multi-layered hard tissue structures. As a result of the data analysis, thermal and optical properties of sound and demineralized enamel were obtained.

1. Introduction

Frequency-domain photothermal radiometry has shown the potential to provide simultaneous quantitative analysis of optical and thermal fields in multi-layered dental tissue structures [1]. This non-invasive and highly sensitive technique is superior to its pulsed version since it does not require high-fluence deposition of laser energy for time-resolved analysis. In this study, we used frequency-domain photothermal radiometry (PTR) to evaluate optical and thermal properties of tooth as a multi-layered structure [2]. We measured the amplitude and phase of the PTR signal and applied a Simplex Downhill algorithm [3] for the multi-parameter fits of the properties. The theoretical profiles were generated with a coupled diffuse-photon-density wave and thermal-wave model for the multi-layered turbid structures [1]. The fits were performed for healthy and the artificially demineralized tooth enamel. Separate sets of properties were fitted for different treatment times, allowing the analysis of the influence of demineralization on tissue property changes and the layer structure. The study showed the potential of PTR to quantitatively evaluate early tooth enamel demineralization in-vivo.

2. Theoretical model

The theoretical approach is described in detail in our previous study [1]. We assume that a three-layered one-dimensional turbid structure is irradiated with laser light (Fig. 1).

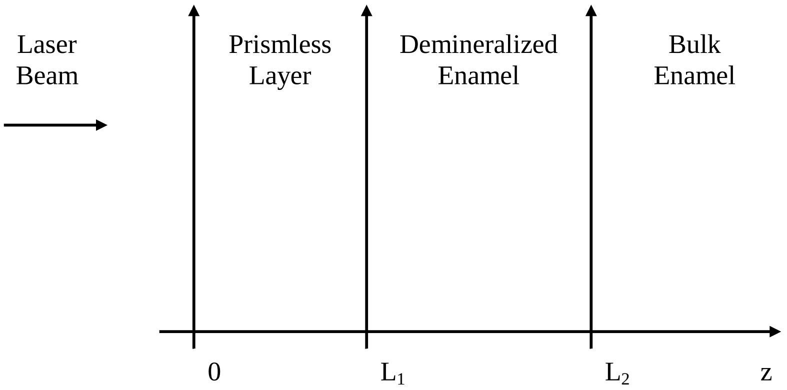

***Fig. 1.** Schematic tooth structure*

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As a result of the incident radiation, a one-dimensional photon field density arises in the medium. The detailed solutions for the optical fields for each layer, including coherent and diffuse components, as well as the thermal field are presented in our study [1]. The photothermal radiometric (PTR) signal represents the overall Planck radiation emission integrated over the depth of the sample:

$$V_{PTR}(\omega) = C(\omega)\,\mu_{IR}\left[\int_0^{L_1} T(z,\omega)e^{-\mu_{IR}z}dz + \int_{L_1}^{L_2} T(z,\omega)e^{-\mu_{IR}z}dz + \int_{L_2}^{\infty} T(z,\omega)e^{-\mu_{IR}z}dz\right] \qquad (1)$$

Here, μ_{IR} is the spectrally averaged effective infrared absorption of the medium, T(z, ω) is oscillating temperature field, C(ω) is instrumental function, which was normalized out during calculations [2].

3. Experimental setup

The PTR experimental setup [2] consisted of a semiconductor laser diode emitting at 659 nm as the source of the PTR signal. The diameter of the laser beam was approx. 3 mm to ensure the one-dimensionality of the photothermal field. A diode laser driver (Thorlab, LDC 210) was triggered by the built-in function generator of the lock-in amplifier (EG&G 7265) to modulate the laser current harmonically. The modulated infrared PTR signal from the tooth was collected and focused by two off-axis paraboloidal mirrors (Melles Griot 02POA017, Rhodium coated) onto a Mercury Cadmium Telluride (HgCdTe or MCT) detector (Judson Technologies J15D12). Before being sent to the lock-in amplifier, the PTR signal was amplified by a preamplifier (Judson Technologies PA-300).

4. Results

Our experimental PTR data were fitted using a Simplex Downhill algorithm for the multi-parameter minimization [3]. The amplitude and phase of the PTR signal were both fitted to the theory, and the combined residual represented the criterion for the best fits. The simultaneous use of two signals, the salient feature of the frequency-domain methods, doubles the amount of information gathered in a single set of scans compared to the time-domain techniques, increasing the validity of the fits. The resulting curves calculated with the fitted values of the optical and thermal properties [4] are presented in Fig. 2.

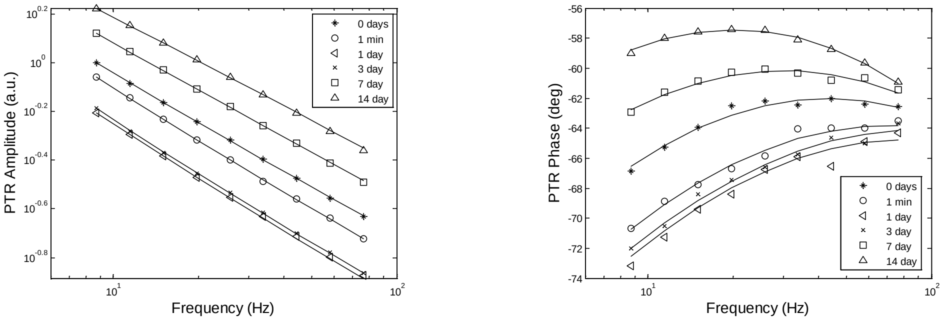

Fig. 2. *Amplitude and phase frequency scans for sequential treatment times with corresponding theoretical fits (solid lines)*

In conclusion, the presented methodology cannot only evaluate the properties of a multi-layered tissue structure, but can also be used for the in-vivo detection and monitoring of early enamel caries.

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