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Detection of Photoacoustic Signals from Blood in Dental Pulp

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Abstract

Photoacoustic waves from hemoglobin solutions in dental roots are detected by using a 1064-nm laser and an ultrasonic soft probe based on a composite transducer on the tooth surface. The high-frequency ultrasonic waves are detected from a tooth with a hemoglobin solution in the pulp cavity due to the large heat transfer coefficient and absorption coefficient of hemoglobin. The spectral intensities of frequency components higher than 1 MHz show good correlation with the hemoglobin solution concentrations, and maps of frequency spectra calculated by taking short-time Fourier transforms clearly exhibit the effect of absorbance in dental pulp.

Keywords

Photoacoustic Sensing, Dental Root, Hemoglobin Detection, Near Infrared Laser

1. Introduction

Dental pulp includes nerves, blood vessels, and lymphatic vessels, and it plays crucial roles in the delivery of nutrition to dental tissues. When infection and inflammation of dental pulp (caused by external injuries or the formation of dental caries) are found, diagnosis of dental pulp vitality becomes necessary. Direct diagnosis is difficult because the pulp is surrounded by hard tissues such as dentin and enamels, so vitality tests based on sensory nerve response to thermal or electrical stimulation have conventionally been used [1] [2].

These tests, however, can cause severe pain, and objective diagnosis is especially difficult in children, who sometimes show exaggerated responses to the tests. In addition, juvenile permanent teeth whose sensory nerves are still growing up sometimes show no response to the stimulation and this can cause a fatal error. Therefore a quantitative and noninvasive diagnosis of dental pulp vitality that replaces conventional test methods is strongly desired. Several groups have proposed a noninvasive diagnosis method based on optical pulse oximetry [3]-[9], and we have recently shown its feasibility for pulp vitality tests [10].

This method detects arterial pulses from dental pulp and the oxygen saturation of the dental pulp blood has inferred from the absorption spectra of those pulses. However, intensity of light transmitted through the tooth is usually very low because of the high scattering and absorption coefficients of dental hard tissues and this limits signal-to-noise ratio of detected signals. Here we propose to use a photoacoustic method to solve this problem because the photoacoustic analysis that detects acoustic waves generated by the absorption of incident light obtains signals from tissues deeper than those from which signals are obtained by methods based only on optical analyses.

Many types of photoacoustic imaging methods have proposed and developed as new diagnostic methods for a variety of organs [11]-[13]. Photoacoustic methods have had some dental applications. There have been some reports on the use of photoacoustic imaging for detecting dental caries [14]-[16], and the use of photoacoustic tomography for imaging early caries has recently been proposed [17]. The photoacoustic method is also expected to be used for diagnosing the vitality of dental pulp in the dental tissue because of its ability to reach deeper tissues. In this report, results of photoacoustic analyses of the dental pulp of extracted teeth are shown.

2. Experiment and Results

As shown in **Figure 1(a)**, an incisor tooth to be used as a sample in this test was split in half to expose the root cavity. Our research protocol was approved by the ethical committee of Tohoku University on the Use of Humans as Experimental Subjects. Without identifiers, the teeth samples donated from various individuals were washed in distilled water and stored in saline. In conventional photoacoustic systems, samples are usually dipped in water for acoustic impedance matching between the sample surface and the acoustic transducer. In our system, considering uses in clinical applications, an ultrasonic probe based on a composite transducer covered with a soft polymer was attached to the tooth surface. The diameter of the probe is 3 mm and the bandwidth and the central frequency are 6 MHz and 4.6 MHz, respectively. As shown in **Figure 1(b)**, a laser beam irradiated the outside surface of the tooth sample, and the polymer probe was attached to the inside surface of the tooth. The root canal was filled with water and a 3% hemoglobin solution based on the results of our previous estimation of pulp chamber hematocrit [18].

We first used a Q-switched YAG laser (Hamamatsu L11038) emitting light with a wavelength of 532 nm as the light source exciting photoacoustic waves because hemoglobin exhibits high absorption for this visible wavelength, resulting in photoacoustic signals with high intensities. The pulse width of the laser was 1.2 ns and the pulse repetition rate was 100 Hz. We set the pulse energy to 1 mJ to avoid damaging the tooth surface or the root cavities. **Figure 2** shows waveforms of acoustic signals obtained

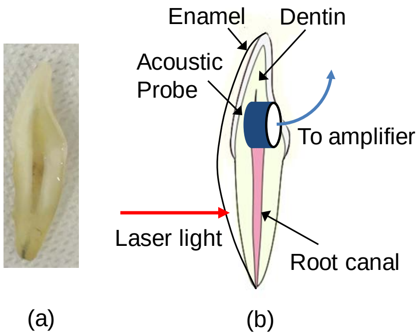


Figure 1. (a) Photograph of tooth sample split in half. (b) Sketch of measurement setup.

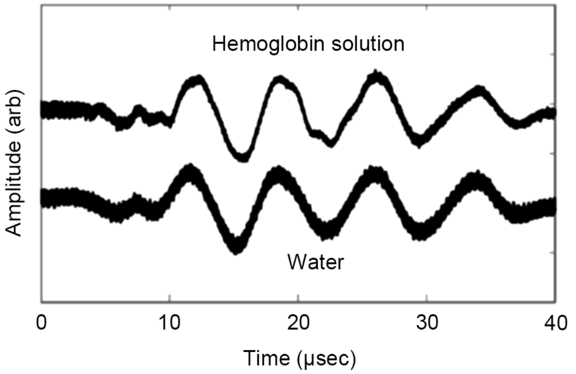


Figure 2. Waveforms of acoustic signals from split-tooth samples having water or a 3% hemoglobin solution in the root canals. The samples were excited by light with a wavelength 532 nm.

from a split-tooth sample with a cavity filled with water and from a sample filled with a hemoglobin solution having a concentration of 3%. One sees that there was no clear difference between the two waveforms. This is mainly because strong scattering in the enamel and dentin keeps light in the visible wavelength range from reaching the dental pulp. We therefore next used a laser with a wavelength of 1064 nm in the near infrared, expecting less scattering to results in greater penetration depths. The amplitudes of the signals detected were expected to be lower with the near-infrared excitation because of hemoglobin's small absorption in the near-infrared, but by using a detection system with a high signal-to-noise ratio we were able to detect photoacoustic waves whenever the excitation laser beam reached the dental root.

Figure 3 shows the waveforms of acoustic signals detected when split-tooth samples whose root cavities were filled with water or a 3% hemoglobin solution were excited with 1064-nm light. The waveform from the sample with the hemoglobin solution shows high-frequency vibrations in addition to the low-frequency vibrations that are also seen in the sample with only water. We also found that the intensity of the high-frequency vibration increases with the hemoglobin concentration.

By calculating the Fourier transforms of the acoustic signals based on signals in

Figure 3 from 0 to 80 μs, we obtained the frequency spectra of the detected acoustic signals as shown in **Figure 4**. It was found that many high-frequency components appear in the spectra of the hemoglobin-filled sample. These high-frequency vibrations seemed to be caused by photoacoustic waves excited in the hemoglobin solution. The heat transfer coefficient and absorption coefficient of hemoglobin are much larger than those of dental hard tissues.

To investigate the correlation between the concentration of the hemoglobin solution and the intensities of high-frequency components in the measured spectra, we integrated the detected spectra from 1 to 3 MHz where the differences between the spectra of teeth with hemoglobin and with water were large even in small hemoglobin concentrations, and the results are shown in **Figure 5** as a function of hemoglobin concentration. Although there was measurement deviation of around 20% in the result, it is seen that the integrated intensity linearly correlates with the solution concentration, and this

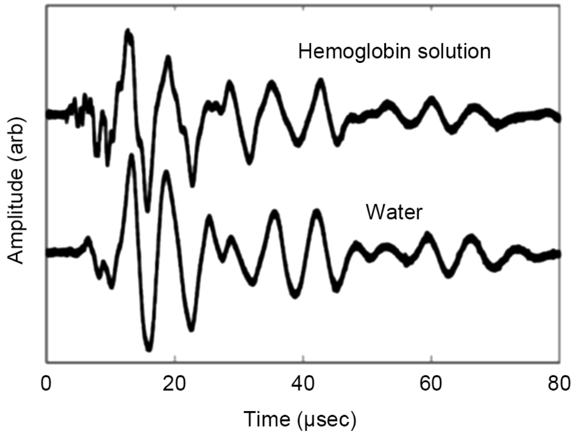


Figure 3. Waveforms of acoustic signals from split-tooth samples having water or a 3% hemoglobin solution in the root canals. The samples were excited by light with a wavelength of 1064 nm.

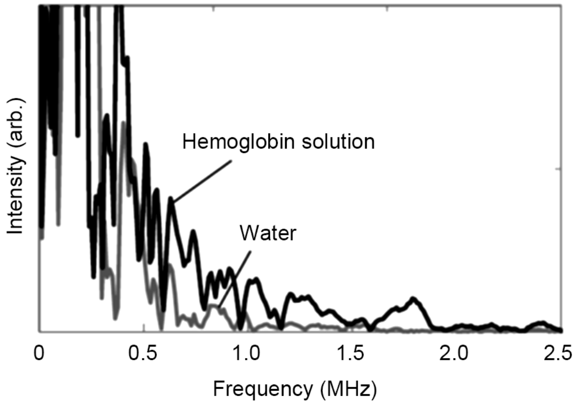


Figure 4. Frequency spectra of photoacoustic waves from a split-tooth sample with water and a split-tooth sample with a 3% hemoglobin solution.

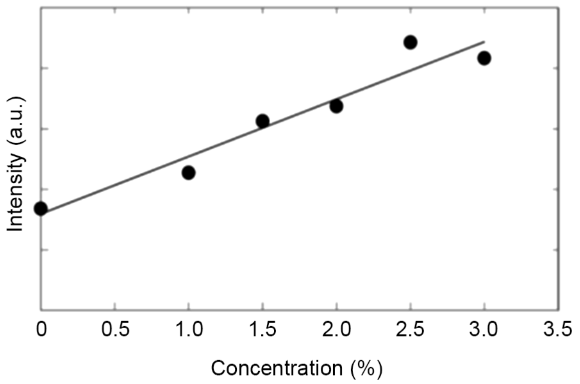
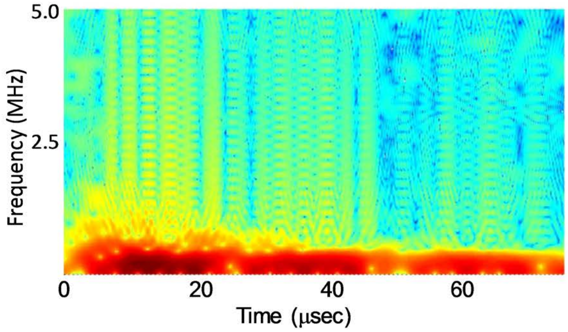


Figure 5. Relation between hemoglobin concentration and the spectral intensities integrated from 1 to 3 MHz for split-tooth samples with water and hemoglobin solutions.

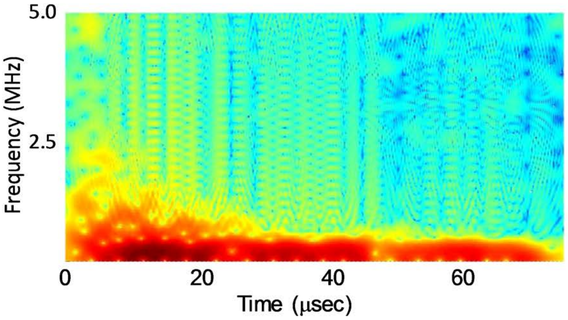
suggests that the proposed method can be used to diagnosis of dental pulp vitality since dental pulsative wave is observed as a change of hemoglobin concentration. A pulse wave with a frequency close to that of an animal's heartbeat could be detected by using a system combining a high-speed signal processing system with a laser source having a high repetition rate.

We next calculated short-time Fourier transforms of the detected signals in order to see the high-frequency components in the photoacoustic wave from dental pulp more clearly. In the short-time Fourier-transform calculation, a Hamming window with a width of 6 μs was moved in 0.2-μs steps from 0 to 80 μs. These calculation conditions were chosen to minimize noises resulting from short-time Fourier transform. Figure 6 shows maps of frequency spectra after laser radiation (at t = 0) for samples with water and with hemoglobin solutions with concentrations of 1% and 3%. It is seen in the sample without hemoglobin that only low-frequency components stayed appearing for a long time. In the samples with hemoglobin solutions, in contrast, high-frequency vibrations appeared soon after laser irradiation and gradually decreased. It was shown that the photoacoustic wave from dental pulp was observed more clearly at the time of 0 to around 30 μs after laser radiation in the frequency range higher than 1 MHz.

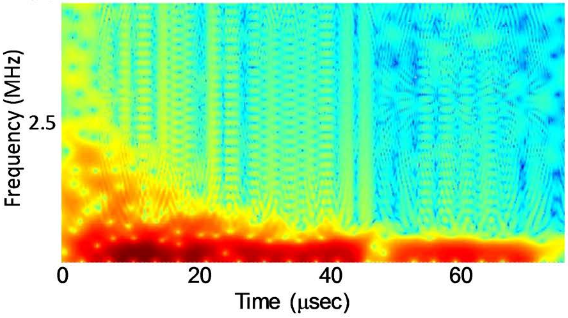
Then we changed the sample from the split-tooth type used in the previous experiments to a whole-tooth type and tried to detect photoacoustic signals from the dental root. We cut off the distal end of root canal and injected either water or a hemoglobin solution into the cavity. The ultrasonic probe, which was the same one used in the previous experiments, was attached to the tooth surface opposite the one irradiated by laser light. Measured frequency spectra of photoacoustic signals from the whole tooth sample that was filled with water and 3% hemoglobin solution are shown in Figure 7. An effect of hemoglobin absorption was seen at frequencies around 500 kHz, although the differences between the spectra were not distinct. Spectral maps calculated by taking the short-time Fourier transform are shown in Figure 8. The differences in the intensities of frequencies from 0.2 to 0.5 MHz are more clearly seen in the range of 20 to 60 μs after laser radiation. The frequencies that originate from absorption in the



(a) water



(b) 1% Hemoglobin solution



(c) 3% Hemoglobin solution

Figure 6. Changes of frequency spectra after laser radiation calculated by taking short-time Fourier transforms of signals from split-tooth samples with (a) water, (b) 1% hemoglobin solution, and (c) 3% hemoglobin solution in the root canals.

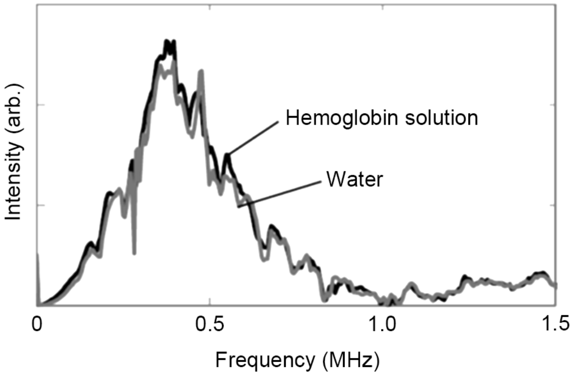
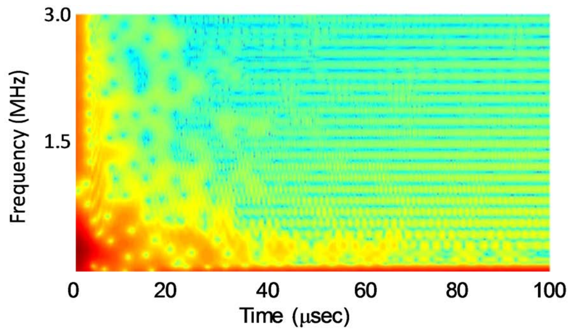
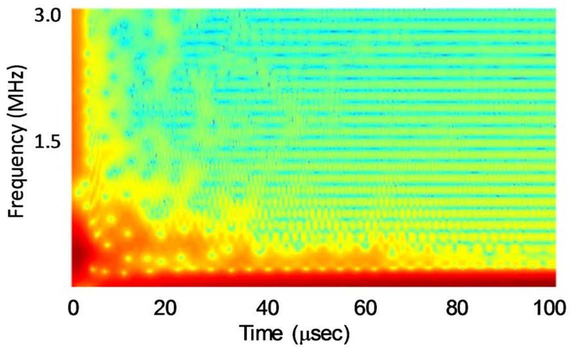


Figure 7. Frequency spectra of photoacoustic waves from whole-tooth samples with water and 3% hemoglobin solutions.



(a) water



(b) 3% Hemoglobin solution

Figure 8. Changes of frequency spectra after laser radiation calculated by taking short-time Fourier transforms of signals from whole-tooth samples with (a) water or (b) 3% hemoglobin solution in the root canals.

hemoglobin solution are lower than they were in the previous experiments because the hard tissue in the whole-tooth samples is much thicker than that in the split-tooth samples.

3. Conclusion

We investigated feasibility of a photoacoustic method for measurement of hemoglobin concentration in root canals. We detected photoacoustic waves from hemoglobin solution in dental root by using a 1064-nm near-infrared laser and an ultrasonic soft probe based on a composite transducer that is attached to the tooth surface. We showed that the high-frequency ultrasonic waves are detected from teeth with a hemoglobin solution in the pulp cavity. This seems to be mainly due to the large heat transfer coefficient and absorption coefficient of hemoglobin. The spectral intensities of frequency components higher than 1 MHz show good correlation with the concentration of the hemoglobin solution, and maps of frequency spectra calculated by taking short-time Fourier transforms clearly exhibit the effect of absorbance in dental pulp.

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