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Photoacoustic Imaging System based on Diode Laser and Condenser Microphone for Characterization of Dental Anatomy

Astrid Alifkalaila [a], Mitrayana [a], Rini Widyaningrum [b,*]

[a] Department of Physics, Universitas Gadjah Mada, Yogyakarta, 55281, Indonesia
[b] Department of Dentomaxillofacial Radiology, Faculty of Dentistry, Universitas Gadjah Mada, Yogyakarta, 55281, Indonesia
Corresponding author: *rinihapsara@ugm.ac.id

Abstract— **The feasibility of a diode laser and condenser microphone-based photoacoustic imaging system for dental anatomy characterization has been investigated. The sample of this study was human teeth illuminated by a diode laser with a wavelength of 532 nm. The laser and detector were fixed in a static position while the sample was moved in the X-Y direction. A laser diode illuminated the sample at 17-20 kHz frequencies combined with 30%, 35%, 40%, 45%, 50%, and 55% of the duty cycles to investigate optimal laser irradiation for dental anatomy imaging. The acoustic intensity was measured ten times to investigate the characterization of dental anatomical structure, *i.e.,* enamel, dentin, and pulp. The sample was then scanned using the system to determine the characterization of the dental structure in the photoacoustic image. The results of this study reveal that the optimal frequency and duty cycle of laser exposure to produce the photoacoustic image of the sample are 19 kHz and 50%, respectively. The maximum acoustic intensities of enamel, dentin and pulp are -71,8 dB, -70,8 dB, -70,5 dB, respectively. Whereas the minimum acoustic intensities of enamel, dentin and pulp are -72,0 dB, -70,9 dB, -70,6 dB respectively. In this study, a photoacoustic imaging system based on a diode laser and a condenser microphone can generate photoacoustic images of dental anatomical structures. The optical absorption of pulp is stronger than the dentin and enamel layer. Hence the pulp area emits the highest acoustic intensity and emerges as a red area in the photoacoustic image.**

Keywords— **Photoacoustic; imaging; tooth; anatomy; acoustic; intensity.**

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I. INTRODUCTION

Photoacoustic imaging has been used as a new method for non-invasive medical diagnosis and visualization. The photoacoustic imaging system uses effective imaging techniques that depend on the photoacoustic effect produced when the light is absorbed by the contrast media [1]. The basic principle of this imaging technique is based on the absorption of light by the photo-absorber in the tissue or material, resulting in temperature changes due to vibration relaxation, which subsequently induce photoacoustic effects followed by (photo)-acoustic signal emission from the sample [2]. This technique uses the optical contrast and penetration depth of ultrasonic imaging to overcome the low contrast limitations of common ultrasonic imaging and the translucency of pure optical imaging [3].

Photoacoustic imaging has shown great potential for imaging the subsurface physiological or biological transformation in ex vivo, in vitro, and in vivo experiments [4]–[6]. The acoustic observation in this imaging technique also has advantages since it reduces the scattering effect that often occurs in optical imaging and, therefore, improves the image's quality [7].

Previous studies have developed the application of photoacoustic technology to investigate oral tissues, including human teeth [8], dental restorations, caries [9], teeth ablation [10], dental materials, and tissue in dentistry [11]. However, no studies have yet been published on the feasibility of photoacoustic imaging for investigating dental anatomical structure characterization.

The imaging technique is commonly needed for tooth extraction procedures and preventing complications in root canal treatment [8]. The main structures of human teeth, generally known as dental anatomy, are enamel, dentin, and pulp. Enamel is the most mineralized tissue in the body, forming a very hard, thin, and translucent layer of calcified tissue covering the entire anatomical crown of the tooth. Dentin is the thickest part of a tooth and has bone-like properties but is softer than enamel. The dental pulp is a soft tissue containing nerves and blood vessels. This study imaged a tooth sample using a photoacoustic imaging system to obtain a subsurface characterization of the tooth structure.

The photoacoustic imaging (PAI) system usually comprises a pulsed laser combined with an ultrasound detector to record photoacoustic signals generated by materials or tissues illuminated by a laser beam. However, pulsed lasers and ultrasound transducers are very costly and difficult to be duplicated, as they employ complicated signal acquisition systems. The previous study reveals that a simple PAI system can be built by utilizing an intensity-modulation continues-wave diode laser combined with a condenser microphone [12] [13][14]. The transferred light energy reacts with a target tissue by transmission, reflection, scattering, and absorption [15]. The tooth samples in this study were cut in the sagittal plane and exposed to the diode laser in the photoacoustic imaging system so that all layers of the natural tooth structure could be imaged. This study aims to test the hypothesis that a simple PAI system based on a diode laser and a condenser microphone built in this study can characterize dental anatomy.

II. Materials and Methods

A. Materials

The samples in this study were molar teeth. To make it possible to observe in every layer of its anatomical structure, the tooth was cut vertically on the sagittal plane using a disk bur. The sample was then placed in a 5 x 4.5 cm box with an open-top surface, then the dental wax was poured into the sample until it was dense and the area around the teeth was filled (Fig. 1).

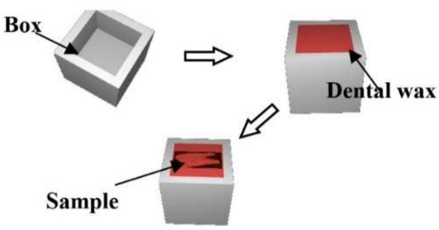

Fig. 1 The sample preparation using dental wax

In order to obtain an accurate photoacoustic signal detected from the sample, the surface of the sample was prepared to be flat, and the dental wax covering the teeth was as thin as possible. For this reason, the photoacoustic signals generated by the sample were not affected by the surface height of the sample so that the photoacoustic image could reveal the subsurface characterization of the sample. Fig. 2 shows the flowchart of the study.

B. Characterization of the PAI System for Tooth Imaging

The photoacoustic imaging system used in the study is shown in Fig. 3. As described in our previous study, a condenser microphone was used as a detector in the photoacoustic imaging system [13]. The characterization of the detector was performed by running the LabView program on the computer.

In order to obtain the characterization of the condenser microphone used in the PAI system of this study, it was used to record the sound generated in different frequencies. The frequency of the sound generator was set at 1,000-20,000 Hz, and the acoustic signals detected by the microphone were observed in the LabView program. Characterization of the X-Y stage was also carried out to determine whether the table shift in the X and Y direction was working concisely. The LabView program also controlled the sliding function for the X-Y stage operation.

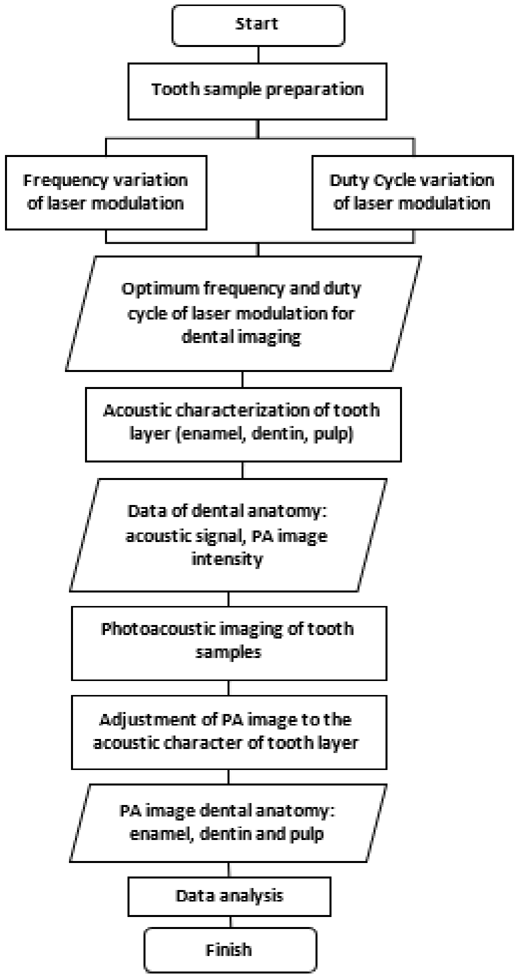

Fig. 2 Flowchart of the study design

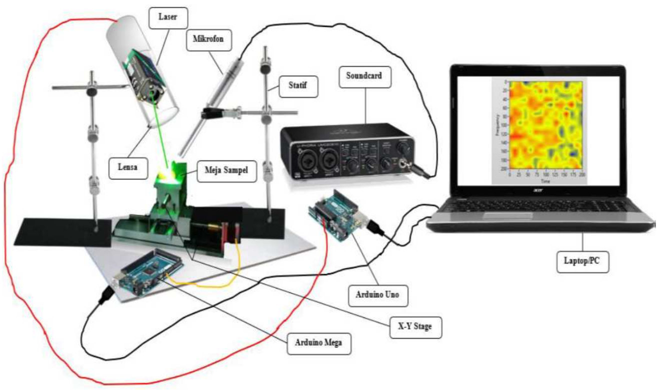

Fig. 3 Photoacoustic imaging system based on a diode laser and a condenser microphone.

C. The Diode Laser Intensity Modulation for Tooth Sample Imaging

The optimal frequency for laser modulation and optimal duty cycle of laser exposure was investigated to ensure that the sound intensity level generated by the sample was optimal, so the photoacoustic image produced by the system was also of good quality. Hence the laser frequency was modulated at 17,000 Hz, 18,000 Hz, 19,000 Hz, and 20,000 Hz, respectively. In comparison, the duty cycles of laser intensity modulation were set at 30%, 35%, 40%, 50%, and 55%, respectively.

D. The Acoustic Characterization of Dental Anatomy

In order to obtain the acoustic intensity generated by each layer of dental anatomical structure, the sample was placed on the scanning table. The laser point was set up precisely on the areas of the enamel, dentin, and pulp. Detection of acoustic peak intensity was confirmed in the LabView program (Fig. 4). This measurement was taken ten times for each anatomical layer of the tooth sample.

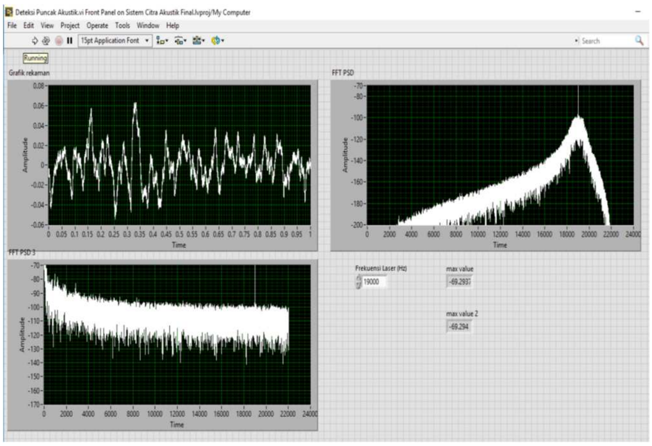

Fig. 4 Acoustic peak intensity detection in LabView program

E. The Photoacoustic Imaging of Dental Anatomy

The scanning process was performed to attain the photoacoustic image. This process was carried out by setting up the sample at the X-Y stage once the laser was exposed, as shown in Fig. 5. The microphone was placed close to the sample. The condenser microphone detected the acoustic signal generated by the sample, and thereafter the acoustic signals were reconstructed to form a photoacoustic image. This process was conducted with the LabView program on the computer.

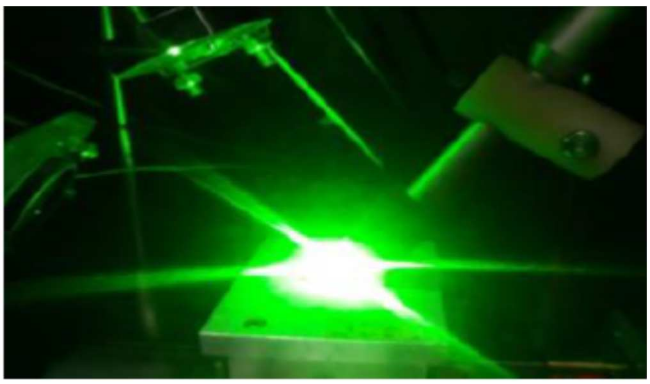

Fig. 5 The sample-laser-detector position during the scanning process in the photoacoustic imaging system.

In order to obtain the characterization of the enamel, dentin, and pulp structures in the photoacoustic image, we utilize the image reconstruction interface in LabView program (Fig. 6). The maximum and minimum acoustic intensity data collected from the previous experiment (The Acoustic Characterization of Dental Anatomy) were entered into the program (Fig. 6) to produces the photoacoustic image that visualizes the characterization of each structure of dental anatomy.

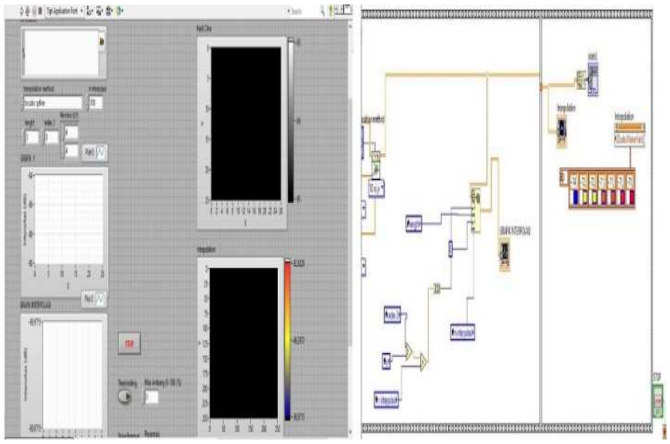

Fig. 6 (a) The image reconstruction interface and (b) block diagram of image reconstruction in LabView program.

III. RESULTS AND DISCUSSION

A. Characterization of the PAI System for Tooth Imaging

Based on Fig. 7, the acoustic signal detected by the condenser microphone in the photoacoustic system is linear with the acoustic frequency produced by the sound generator ($R^2 = 1{,}000$). In this study, the detector has an almost perfect accuracy in detecting acoustic signal frequencies.

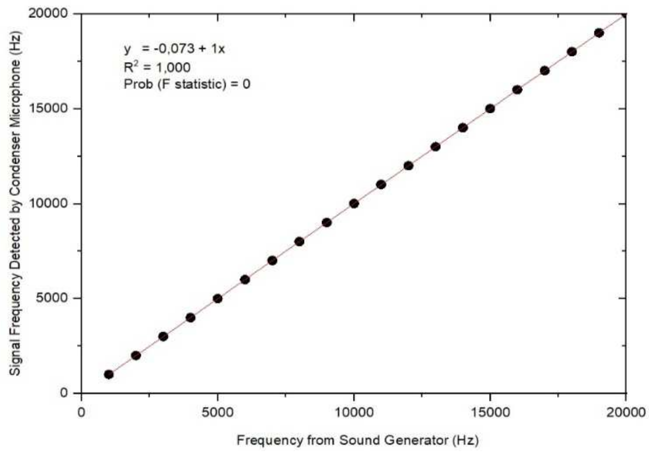

Fig. 7 The acoustic signal frequencies detected by the microphone (f_m) compared with those produced by the sound generator (f_g)

The $f_m = -0.073 + 1f_g$ Hz equation in Fig. 7 indicated that if the sound generator generates no acoustic signal, the acoustic frequency detected by the microphone is -0,073. The acoustic frequency also depends on the size of the tissue constituent [16].

The equation $y = -0.018 + 0.2x$ for the X-stage and the equation $y = -0.009 + 0.2x$ for the Y-stage are shown in Fig. 8. The regression coefficient indicates that for every 1 step increase, the measured X-stage and Y-stage step shift is 0.2 mm with an error of ± 0.1. After the regression test for the X-Y stage was carried out, the R^2 is 0.999, as shown in Fig. 8. The result indicates that the precision of the stepper motor to move the table on the X-Y stage is almost perfect.

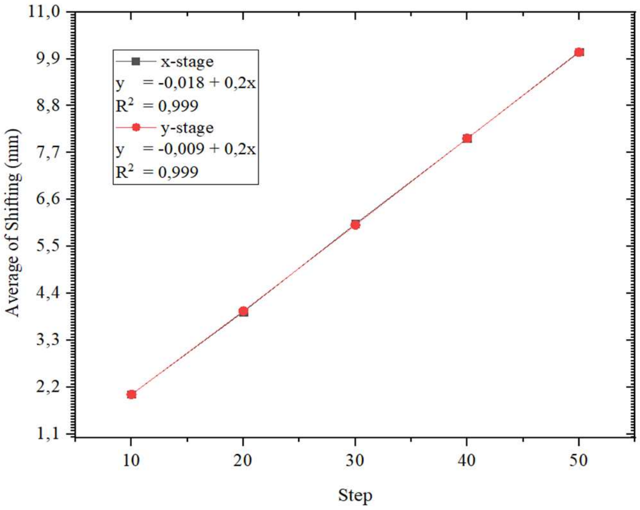

Fig. 8 The calibration factor of the stepper motor to shift the X-Y stage

B. The Diode Laser Intensity Modulation for Tooth Sample Imaging

The results in Fig. 9 demonstrates that the acoustic frequency is linear to the laser modulation frequency and is directly proportional to the energy absorbed by the sample. Whereas the duty cycle (DC) of laser modulation is related to the laser intensity that subsequently induces thermal expansion in the sample [17].

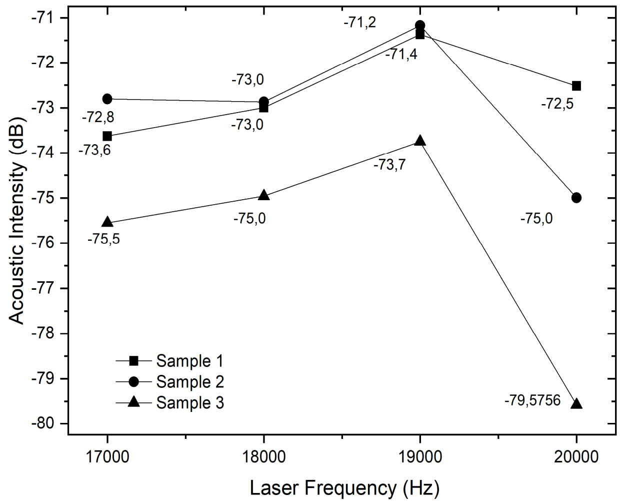

Fig. 9 The optimal frequency of laser modulation to the induced acoustic signal intensity from tooth samples

Based on Fig. 9, the optimum frequency setting for imaging the tooth sample in this study was 19 kHz. The maximum acoustic intensity generated by the sample illuminated by laser modulated on the frequency of 19 kHz were -71,4 dB, -71,2 dB, and -73,7 dB, respectively. Investigating the frequency helps to separate the photoacoustic signal from the unwanted interference [6]. The duty cycle under 30% is insufficient to generate acoustic signals from hard tissue, while the laser exposure with a duty cycle of 55% or more may produce an unfavorable effect on the sample [13]. According to the study results in Fig. 9, the photoacoustic system can detect the maximum acoustic intensity generated by the tooth sample exposed by the diode laser in the 50% duty cycle. At the 50% duty cycle, the acoustic intensities were -69.7 dB, -71.4 dB, and -72.9 dB.

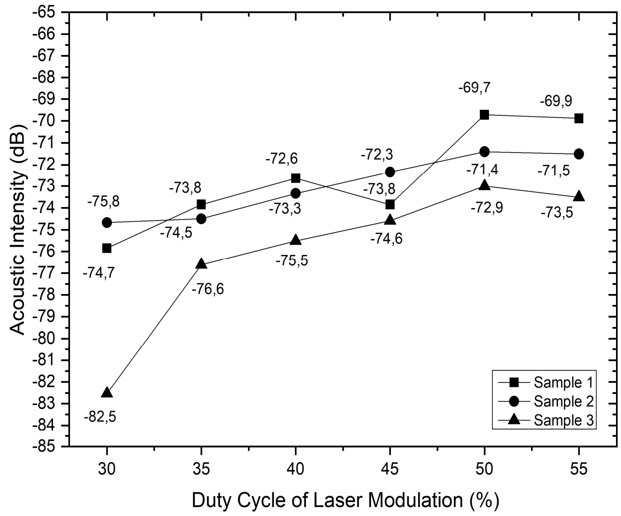

Fig. 10 The optimal duty cycle of laser intensity modulation for dental anatomy imaging

Based on the study results (Figs. 9 and 10), it is observed that the frequency and duty cycle of laser exposure could impact the production of acoustic signals from the sample. Otherwise, this study also indicates that the acoustic intensity is not linear with diode laser modulation's frequency and duty cycle. The higher the duty cycle of laser intensity modulation, the higher the acoustic intensity generated from the tooth sample (Fig. 10). Although the acoustic peak tends to increase in line with the laser duty cycle, it also tends to decrease slightly when the duty cycle is set at 55%. Based on the result of the experiment in Figs. 9 and 10, the laser exposure on the human teeth in this study was therefore set at 19 kHz with a duty cycle of 45%-50%.

C. The Acoustic Characterization of Dental Anatomy

The acoustic characterization of dental anatomy can be observed in Fig. 11, while each dental anatomical structure's maximum and minimum acoustic intensity has been summarized in Table I.

TABLE I
MAXIMUM AND MINIMUM ACOUSTIC INTENSITY OF ENAMEL, DENTIN AND PULP

Dental Anatomy	**Maximum Acoustic Intensity**	**Minimum Acoustic Intensity**
Enamel	-71,8 dB	-72,0 dB
Dentin	-70,8 dB	-70,9 dB
Pulp	-70,5 dB	-70,6 dB

The tooth sample surface was made as flat as possible to avoid the distance between the sample surface and detector to the photoacoustic signals [14]. In order to acquire acoustic characterization of dental anatomy, the acoustic signals were taken ten times from each area of enamel, dentin, and pulp layer on the sample.

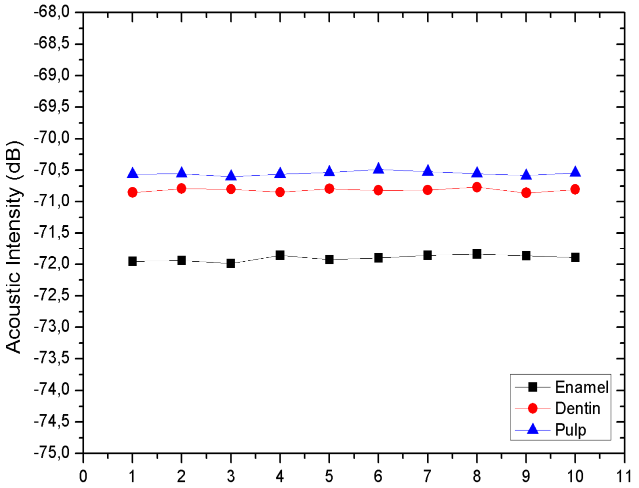

Fig. 11 Mean acoustic intensity of the dental anatomical structure

The maximum and minimum acoustic intensity within each dental anatomical structure was used to determine the pixel intensity of the photoacoustic image reconstruction (Fig. 6). The average intensity of the photoacoustic signal that varies in each tooth structure may also be due to differences in the physical properties of the particular tooth structure [18].

D. The Photoacoustic Imaging of Dental Anatomy

Photoacoustic images of dental anatomy, including enamel, dentin, and pulp, are shown in Fig. 12. Linear interpolation was used for photoacoustic image reconstruction by inserting new data according to the linear function of two adjacent data. Interpolation could further sharpen the photoacoustic image and gain a smooth image [17]. The system's ability to perform scanning sampling has a speed of 1 second/pixel. In that case, the sample with an average resolution of 54x38 pixels and a step of 0.2 mm will take ± 34.2 minutes of scanning time.

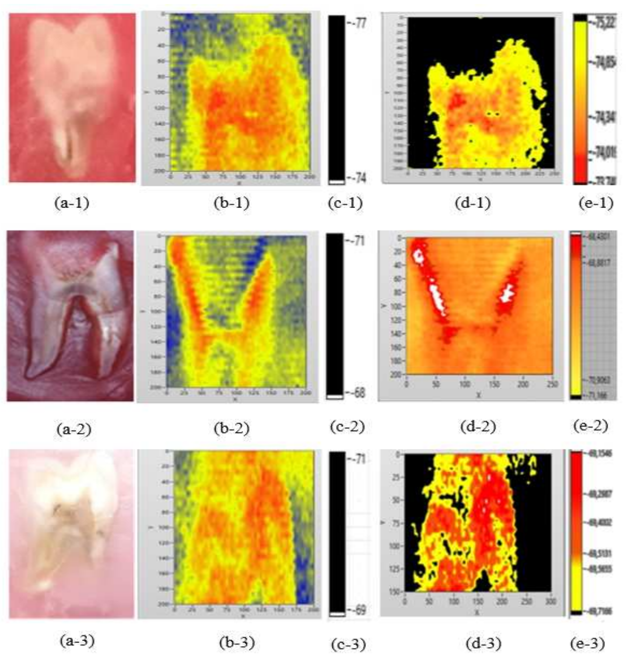

Fig. 12 (a) Tooth samples, (b) interpolated photoacoustic images, (c) acoustic intensity range of interpolated images, (d) photoacoustic images of dental anatomy adapted to the acoustic intensity of enamel, dentin, and pulp, and (e) acoustic intensity range of enamel, dentin and pulp.

Based on the photoacoustic images in Fig. 12, the area of dental wax in the sample shows the lowest intensity so that it appears blue in the photoacoustic image. The tooth appears as yellow to red in the photoacoustic image and demonstrates that the biological tissue may emit a higher acoustic intensity than the non-biological material around it. It can be seen in Fig. 12 that the enamel was visible in the yellow area around the outer layer of the tooth crown. The dentin indicates a moderate intensity marked with an orange color, while the pulp displays the highest intensity, marked with a reddish color in the photoacoustic image. Optical tissue imaging employs the spectroscopic characteristics of light-tissue interactions, such as absorption. Photoacoustic absorption also depends on the density of certain tissues or materials that are illuminated by a laser. This interaction is quite powerful in the characterization of tissue in photoacoustic imaging [19].

The biological molecules in the tissue capable of absorbing light energy from the laser are known as chromophores. Biological tissue in the oral cavity contains many chromophores. Teeth consist of several substances, including hydroxyapatite, protein, and blood vessels. Some of these chromophores are found in the layers of enamel, dentin, and pulp [20]. In order to develop better diagnostic techniques, it is necessary to know the optical properties of dental tissue. Dental enamel is the hardest tissue density substance, followed by dentin and dental pulp [21].

The results of this study indicate that the optical absorption of dentin is stronger than the enamel layer. The dentin layer appears as an orange area in the photoacoustic image (Fig. 12). The pulp could have the best optical properties as it emits the highest acoustic signals and exists as a red area in the photoacoustic image (Fig. 12). Meanwhile, the reddish-colored pulp area is a soft tissue that differs from the other hard tissue layers of enamel and dentin.

The mechanism in the photoacoustic imaging process is very beneficial for diverting the reflected light back to the tissue to increase the density of the photons, thus increasing the signal intensity [22]. The coefficient of heat transfer and absorption coefficient in the pulp tissue tend to be much higher than that of hard tooth tissue (enamel and dentin). Signal attenuation through dentin and pulp is greater than enamel, as dentin and pulp contain more than 50% of organic structures and fluids, which may scatter and absorb better laser light than those in enamel [23]. Thus, the higher the energy absorption value in the tissues, the higher the acoustic intensity produced.

However, the image of the sample (Fig. 12 (b-2)) is still unable to distinguish between the areas of enamel, dentin, and pulp within clear boundaries. The area of the yellow enamel is not very clear because there is a dental crown cavity known as dental caries in one of the samples (Fig. 12(a-2)) in this study. In normal conditions, the enamel is the outer layer covering the entire crown of the tooth. However, the edge of the outer enamel layer in the photoacoustic image of this study has not yet been properly depicted.

In Fig. 12 (a), the tooth samples do not differentiate between each dental structure area, *i.e.,* enamel, dentin, and pulp. However, after the photoacoustic imaging process is conducted on the sample, it can be seen that the intensity and the color contrast between each anatomical tooth layer are different. Yet, there is still noise in the form of dots on the photoacoustic image (Fig. 12). The noise in the photoacoustic image could be triggered by an unstable laser or by noise from the environmental condition around the device.

IV. Conclusion

This study confirmed that a photoacoustic imaging system based on a diode laser and a condenser microphone can generate a photoacoustic image of a dental anatomical structure characterized by enamel, dentin, and pulp. A diode laser combined with a condenser microphone can construct a photoacoustic system controlled by the LabView program and the Arduino IDE via a computer. Further study needs to be developed to investigate the application of photoacoustic imaging for other dental problems.

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