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System Design of a Non-invasive Photoacoustic Imaging System for Imaging Teeth

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ABSTRACT

Dental and oral health can impact overall health. Teeth can be damaged by inflammation of the soft tissue around them. Photoacoustic imaging was developed in the medical field to image biological materials. The aim of this study is to utilize a photoacoustic imaging system to image healthy and inflamed teeth. The radiation required is from an 808 nm diode laser. A condenser microphone serves as a detector. Samples are scanned using a mechanical XY-stage system. The research samples were extracted from teeth from Sprague-Dawley rats. Experimental animals were divided into two groups: healthy (R1) and inflammatory (R2). LabView on the computer reconstructs the acoustic signal into a grey level image. The results showed that the laser modulation frequency and duty cycle for imaging teeth were 13 kHz and 50%, respectively. Inflamed teeth have a higher grey level value (87.2±0.5) than healthy teeth (60.2±0.9). The

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normality test and statistical test of grey level values show significant differences between healthy and inflamed teeth. Based on the results, the photoacoustic imaging system was able to image healthy teeth as well as teeth affected by inflammation.

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1. Introduction

Teeth are one of the most important organs in the body, so maintaining dental health is critical to ensuring proper dental function [1]. Poor oral hygiene can contribute to a variety of diseases, including gingivitis and periodontitis [2]. Both diseases begin with gum inflammation caused by bacteria buildup in the oral cavity [3]. Dental and oral diseases are diagnosed with x-ray radiography [4]. Radiographic imaging employs ionizing radiation, which has the potential to harm nearby healthy cells [5]. As a result, an imaging technique that can image the tooth area without using ionizing radiation is required.

Photoacoustic imaging combines optical and ultrasonic imaging. Photoacoustic imaging is an imaging technique that utilizes the photoacoustic effect [6]. The photoacoustic effect is the phenomenon in which sound signals emerge from solid, liquid, or gaseous materials in response to modulated electromagnetic energy [7]. In previous studies, a Nd:YAG laser was used as the electromagnetic energy source for photoacoustic imaging [8,9]. This laser can generate high-energy laser pulses, resulting in detailed image resolution for objects. However, this laser source has several drawbacks, including its large size, high cost, and the requirement for complex cooling, limiting its portability for clinical applications. The use of a diode laser as the electromagnetic energy source resulted in a breakthrough in subsequent research [10].

Several recent studies have shown the use of diode lasers as a radiation source for photoacoustic imaging of biological tissues [11]. Detecting periodontal disease, imaging oral soft tissues, identifying tooth layers, and investigating hidden caries are all examples of photoacoustic imaging studies that use diode lasers. These studies employed diode lasers with a 532 nm wavelength (visible light).

The safety and health risks connected with laser radiation are strongly dependent on wavelength, output power, exposure duration, and interaction with biological tissue[12]. Nd:YAG lasers have wavelengths of 532 nm and 1064 nm, however their output power exceeds that of diode lasers of the same wavelength. As a result, diode lasers are considered safer than Nd:YAG lasers in terms of health safety

Molecular vibrations caused by the photoacoustic effect from visible light laser radiation (400-750 nm) are less significant. Lasers with near-infrared wavelengths (750-2500 nm) have higher molecular vibrations, resulting in a larger photoacoustic effect [13]. This study employed an 808 nm laser wavelength. The wavelength was chosen based on the absorption of chromophore molecules found in teeth. At 808 nm, all molecules in the sample can absorb laser energy effectively [14].

The use of acoustic signals to detect teeth caused by gum inflammation is novel in this study. Previous study focused solely on identifying gum inflammation [10]. Several prior photoacoustic imaging technologies [11] made use of the Nd:YAG laser modality, which is bulky and requires complicated cooling. Previous research used a laser wavelength of visible light with low molecular vibrations, resulting in a less substantial photoacoustic effect [11]. In contrast, this study uses a near-infrared wavelength, where many molecule vibrations occur, resulting in a better acoustic signal.

This study used Sprague-Dawley rats as an inflammatory model. Rats were chosen for a variety of reasons, including their similar characteristics, which made it easier to understand anatomical, physiological, and genetic changes during the experiment. Rats are mammals that share genetic and biological similarities with humans. They are very adaptable to new environments [15]. Rats were used as experimental animals in this study to model inflammation, which mimicked human inflammatory conditions.

2. Materials and Methods

Photoacoustic imaging system can be shown in the Figure 1. The acoustic signals are generated by an 808 nm laser diode and a maximum power of 500 mW (M5-808-0500-0XX, Sunshine-Electronics, China). The laser diode is modulated by an Arduino Uno (ATmega328P, Arduino.cc, Italy). The acoustic signal is detected by a condenser microphone (ECM8000, Behringer, Germany), which is linked to a sound card (UCM220HD, Behringer, Germany) and sent to the computer.

The present study used a condenser microphone as the detector. Condenser microphones are simple microphones that can detect frequencies up to 20 kHz, are inexpensive, and produce low self-noise levels. Condenser microphone testing ensures that the microphone can receive a frequency that is equal to the generated PA frequency. The current study, however, used a simple detector, a condenser microphone.

The research sample is scanned with a mechanical XY-stage system that has a minimum displacement of 0.2 mm. The XY stage scans at 0.2 mm/0.8 seconds or 0.16 mm/second, with a maximum scannable area of 50x50 mm^2. The mechanical system is managed using computer numerical control (CNC). Using LabView, the detected acoustic signal is converted into a grey level image. After obtaining the grey level image values, image analysis was carried out, which included normality tests and image statistics. This was done to see if there were any significant differences in the grey level values of healthy teeth versus those with inflammation.

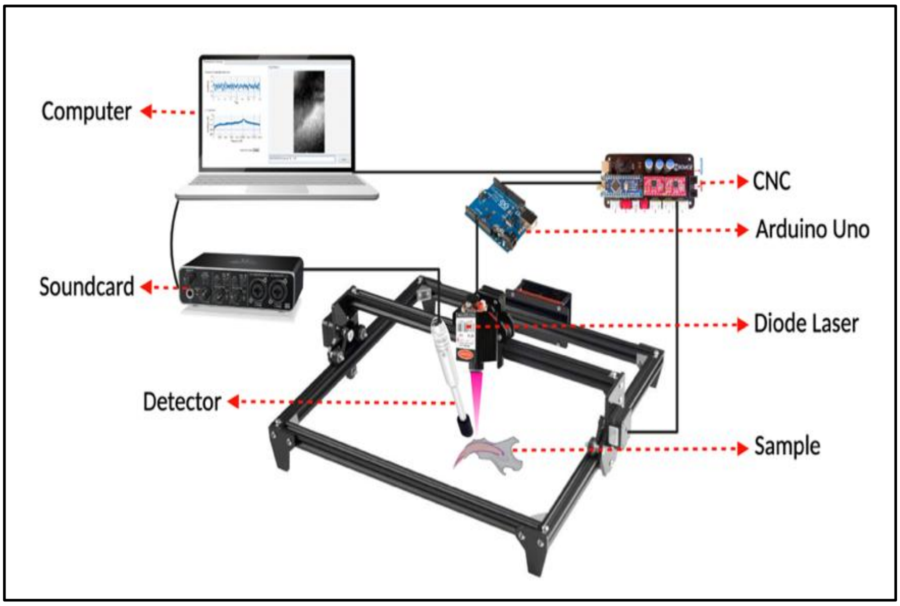

Figure 1. System design of photoacoustic imaging.

The research ethics commission of the Faculty of Dentistry, Prof. Soedomo Dental and Oral Hospital, Universitas Gadjah Mada, Yogyakarta, Indonesia, approved this study. This study used Sprague-Dawley rats, which were divided into two groups: healthy (R1) and inflamed (R2). Each treatment group contained seven rats. In the treatment group, inflammation was induced through a ligation technique that involved tying the rats' incisors for seven days. The study samples were teeth extracted from rats in each group. Figure 2 depicts the animals from each treatment group.

(a) (b)

Figure 2. Sprague-Dawley rats. (a) Healthy group (R1). (b) Inflammatory group (R2).

Before scanning the entire sample, the optimal laser frequency and duty cycle were determined. This was done to get the strongest acoustic signal for imaging the sample. The laser modulation frequency settings included 10 kHz, 11 kHz, 12 kHz, 13 kHz, 14 kHz, and 15 kHz. The laser duty cycle settings included 10%, 20%, 30%, 40%, and 50%.

3. Results and Discussion

3.1. Results of setting the laser modulation frequency and duty cycle

One method for producing an acoustic signal is to modulate a radiation source with an acoustic frequency. The resulting acoustic frequency is the same as the modulation frequency and is proportional to the energy absorbed by the sample. The duty cycle is the fraction of a period that the signal is active. Figure 3 shows the results of frequency settings in the photoacoustic imaging system. The x axis represents the frequency variation. The y axis represents the grey level value produced by the acoustic signal in a photoacoustic image. The best frequency for imaging teeth is 13 kHz, with a grey level of 62.1 for the healthy group (R1) and 90.2 for the inflamed group (R2).

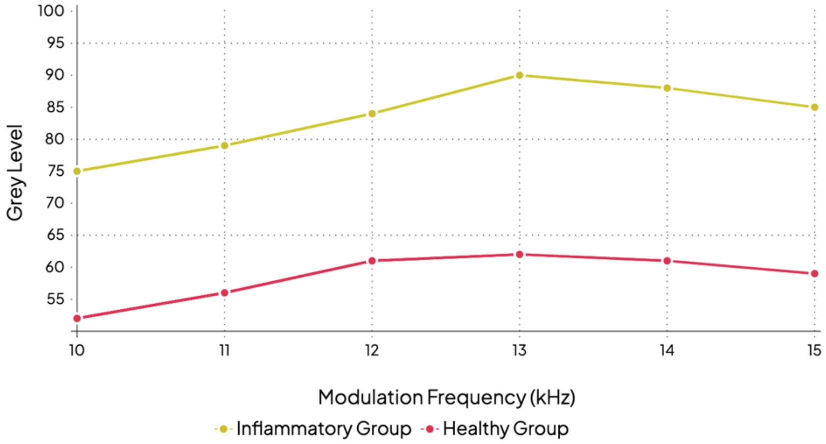

Figure 3. The results of optimal frequency settings on samples.

According to Figure 3, the acoustic signal from the sample can be generated and detected correctly using laser modulation at a frequency of 13 kHz. This frequency has a higher grey level value than other frequencies. The high grey level value at 13 kHz can be used to compare healthy and inflamed teeth. Figure 4 shows the optimal duty cycle variation settings.

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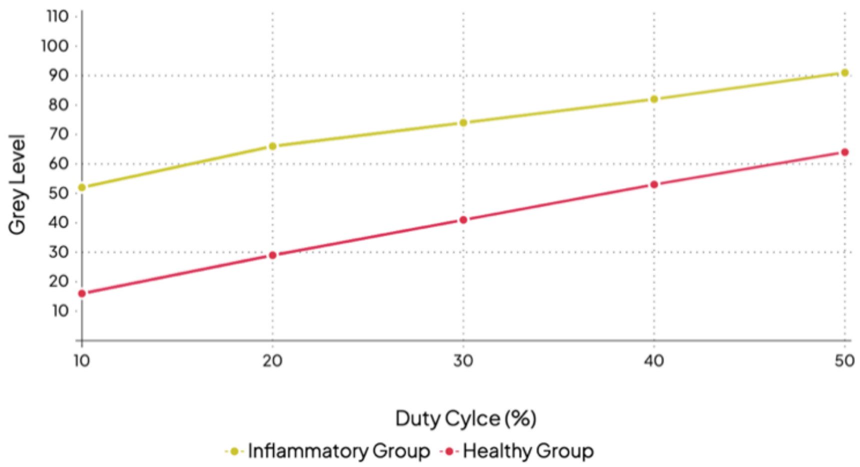


Figure 4. The results of optimal duty cycle settings on samples.

Figure 4 depicts the grey level value of the sample in relation to duty cycle variation based on the measurements taken. The photoacoustic imaging system can represent the sample at 50% duty cycle, with a grey level k value of 64.3 for the healthy group (R1) and 91.6 for the inflammation group (R2).

3.2. Acoustic signal of teeth

The optimal frequency and duty cycle for producing a strong acoustic signal and representing the sample are 13 kHz and 50% duty cycle, respectively. Based on the research data, a significant difference was found between the grey level values in the photoacoustic images of the healthy and inflammation groups, as shown in Figure 5.

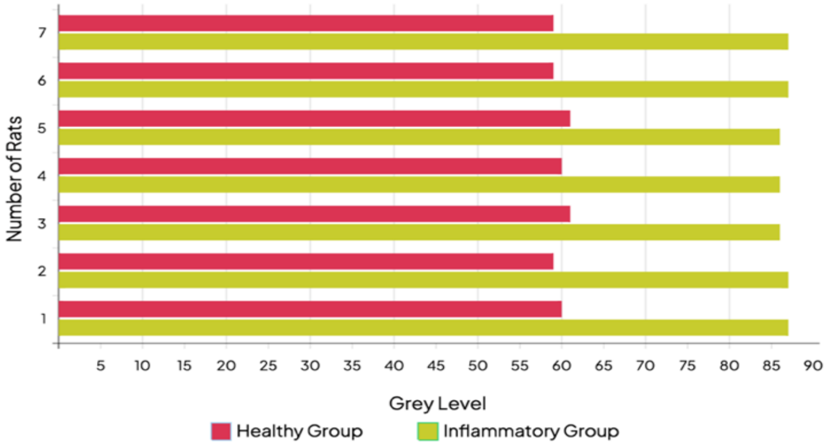
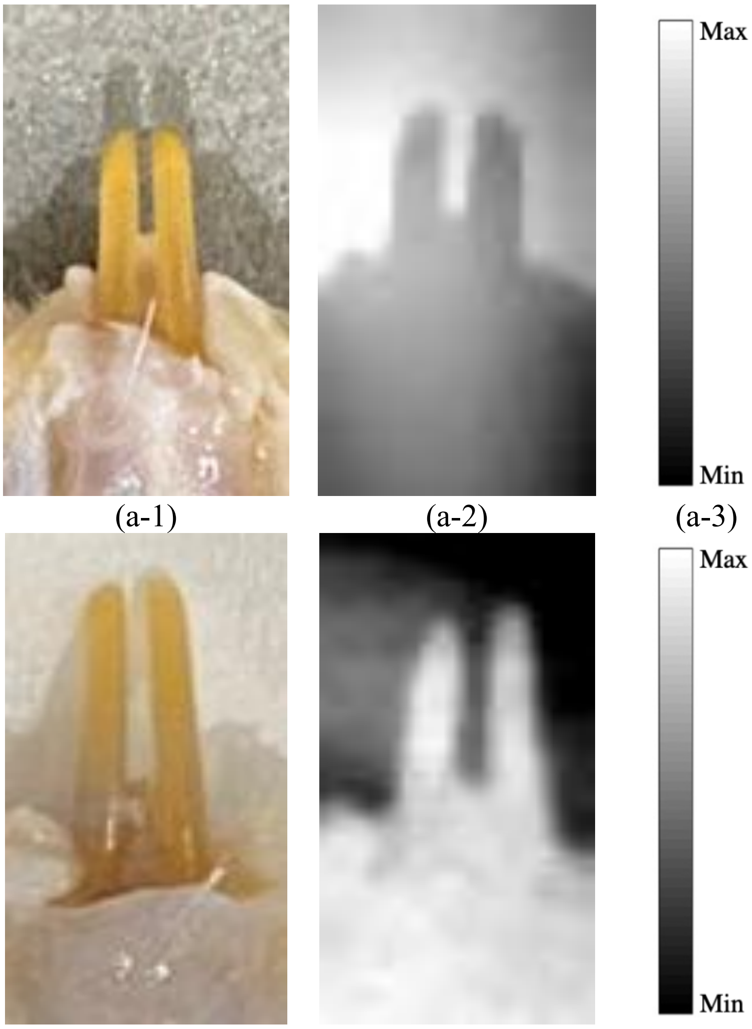


Figure 5. The average grey level values in samples.

Figure 5 shows that the inflammation group has a higher grey level than the healthy group. The average grey level value for the healthy group is 60.2 ± 0.9, while the inflammation group is 87.2 ± 0.5. Figure 6 depicts the photoacoustic imaging results for each group.



(a-1) (a-2) (a-3)

(b-1) (b-2) (b-3)

Figure 6. Dental imaging results. (a-1) Samples of healthy teeth. (a-2) Photoacoustic images of healthy teeth. (a-3) Grey level range. (b-1) Samples of inflamed teeth. (b-2) Photoacoustic images of inflamed teeth. (b-3) Grey level range.

3.3. Normality Test and Statistical Test of Acoustic Signals

Because the sample size was less than 50, the Shapiro-Wilk test was used to determine the normality of grey level data in this study. The Shapiro-Wilk test results indicated that the data in this study were normally distributed. This is demonstrated by a p-value in the treatment group greater than 0.05. Table 1 displays the results of the Shapiro-Wilk normality test.

Table 1. Shapiro-Wilk test

Groups	Statistic	P value
Healthy	0.939	0.629*

Inflammatory	0.952	0.707*

The sign * indicates data on the variable is normally distributed ($p \geq 0.05$).

A parametric statistical analysis approach was used to test the research hypothesis, with the independent t-test. The independent t-test statistical test was used to compare grey levels across all treatment groups. The results yielded a p-value (Asymp. Sig.) of less than 0.05. This indicates that the grey level values of all samples varied significantly. Figure 7 displays the results of the independent t-test statistical test.

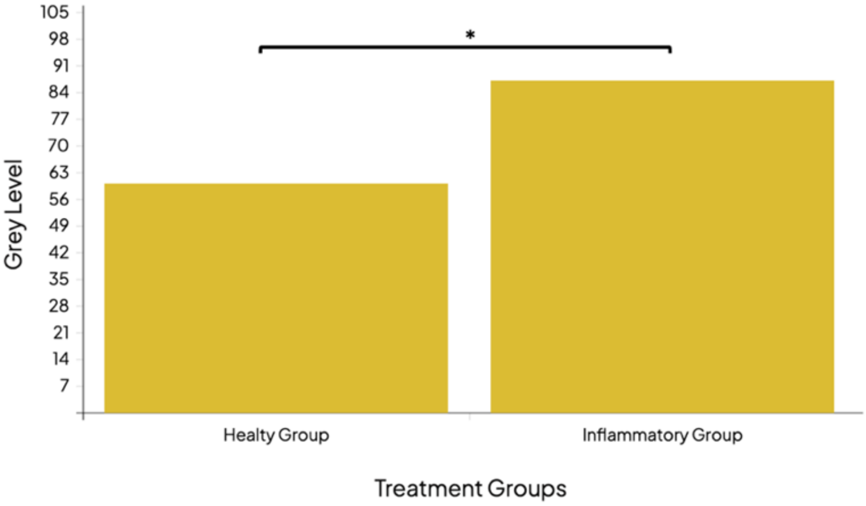


Figure 7. Independent t-test analysis was used to compare the results of the various tests between treatment groups. The * sign indicates a significant difference ($p<0.05$) based on independent t-test results.

Photoacoustic imaging systems can produce photoacoustic images from biological materials. Photoacoustic images are produced by the photoacoustic effect caused by the absorption of modulated laser energy. Energy absorption is determined by the composition of the photo absorber in the tissue. Every biological tissue has a unique absorption coefficient [11]. Biological tissues contain a variety of chromophores, including hemoglobin, melanin, lipids, and water. These chromophores can absorb laser energy and produce acoustic waves[10].

The study's outcomes, which identified teeth impacted by gum inflammation, were consistent with earlier research. In the previous study, the grey level of inflammatory gum tissue was higher than that of healthy tissue (104.37 versus 64.37) [10]. Gum inflammation alters the composition of tooth structure, resulting in more acoustic signals in inflamed teeth than in healthy teeth.

Previous research found significant differences between grey level values for gums and teeth. The grey level in gums was higher than in teeth. This is because gums have a higher concentration of chromophores than teeth, resulting in a stronger acoustic signal from them.

Gingival inflammation is the inflammation of the gingiva caused by bacterial infection[16]. The inflammation induction process, which uses a ligation technique (silk ligature), causes gingival inflammation that lasts about 7 days. This induction technique causes bacteria to accumulate around the silk ligature, resulting in gingival inflammation[17]. Inflamed tissue has a higher acoustic signal than normal tissue because of an increase in chromophores, which allow them to absorb more laser energy, resulting in an increased acoustic signal. Inflammation of the gingiva raises the acoustic signal in the surrounding teeth above that of healthy teeth.

Photoacoustic imaging systems have potential for clinical use. Some of these potential applications include the detection of an acoustic signal in the tooth area, which reveals differences in grey level values

between healthy teeth and teeth with inflammation. The grey level values are derived from an acoustic signal that has been reconstructed into an image. Inflamed tissue generates a strong acoustic signal, resulting in higher grey level values.

The developed photoacoustic imaging system can distinguish between healthy and inflamed teeth. This is demonstrated by the results of normality and statistical tests on teeth in each treatment group. Photoacoustic imaging has the potential to detect tooth changes caused by gingival inflammation.

4. Summary

Based on the obtained photoacoustic images, the developed photoacoustic imaging system can distinguish between healthy teeth and teeth with gingival inflammation. The inflammation group generated photoacoustic images with higher grey level values than the healthy group. Normality and statistical tests on photoacoustic images revealed significant differences between the healthy and inflammation groups. More research is expected to yield a more portable photoacoustic imaging system for scanning the inside of the mouth

5. Acknowledgement

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