Analysis of Reflectance Photoplethysmograph Sensors

Fu-Hsuan Huang, Po-Jung Yuan, Kang-Ping Lin, Hen-Hong Chang, and Cheng-Lun Tsai

Abstract—Photoplethysmography is a simple measurement of the variation in blood volume in tissue. It detects the pulse signal of heart beat as well as the low frequency signal of vasoconstriction and vasodilation. The transmission type measurement is limited to only a few specific positions for example the index finger that have a short path length for light. The reflectance type measurement can be conveniently applied on most parts of the body surface. This study analyzed the factors that determine the quality of reflectance photoplethysmograph signal including the emitter-detector distance, wavelength, light intensity, and optical properties of skin tissue.

Light emitting diodes (LEDs) with four different visible wavelengths were used as the light emitters. A phototransistor was used as the light detector. A micro translation stage adjusts the emitter-detector distance from 2 mm to 15 mm.

The reflective photoplethysmograph signals were measured on different sites. The optimal emitter-detector distance was chosen to have a large dynamic range for low frequency drifting without signal saturation and a high perfusion index. Among these four wavelengths, a yellowish green (571nm) light with a proper emitter-detection distance of 2mm is the most suitable for obtaining a steady and reliable reflectance photoplethysmograph signal

Keywords—Reflectance photoplethysmograph, Perfusion index, Signal-to-noise ratio

I. INTRODUCTION

PHOTOPLETHYAMOGRAPH is a physiological signal of blood perfusion in tissue. Since the change in blood volume in tissue is synchronous with heart beat, it also can be used to calculate the heart rate. The noninvasive detection of photoplethysmograph does not require a disposable sensor like the electrodes of electrocardiograph. This makes it a preferable method for measuring heart rate for more than one occasion.

Transmittance and reflectance are two basic types of photoplethysmograph sensors. The strong light scattering property of biological tissue greatly limits the penetration depth

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of light. Therefore, the transmittance sensor is generally designed to clip on finger tip or ear lobe where light can easily shine through the tissue [1][2]. On the other hand, the reflectance does not have to penetrate the body. Theoretically, the reflectance measurement can be taken at any skin surface. Moreover, the path length of reflectance in tissue is much shorter than that of transmittance. Less power intensity of light is needed as the light source for reflectance measurement.

Penetration depth is defined as the depth where light intensity drops to 37% of the intensity on the incident surface [3]. Penetration depth of light in tissue depends mainly on the light extinction coefficient of tissue. The extinction coefficient combines both absorption and scattering coefficients. The scattering coefficient only gradually decreases as wavelength increases.

However, the absorption coefficient greatly varies for different wavelengths. Hemoglobin in red blood cells is generally the most abundant chromophore in skin tissue. It has two major absorption peaks in the visible region. The first Soret band at 415nm has a very strong absorption of blue light. The second has twin peaks at around 550nm, and the absorption property is much less than the Soret band. The wavelength is shorter than the blue light and is generally believed to affect the biochemical reactions in the cell [4].

Photoplethysmograph signal is generated by the very small portion of change in blood volume with heart beat. As the volume of blood in tissue changes, the absorption of light by blood also changes. This results in the change in transmission or reflectance light intensity.

Most biological tissue has lower scattering and absorption coefficients for red and near-infrared light. This makes them very useful for measuring the transmission of light in tissue. Their low scattering property also means less backscattering for taking reflectance measurement. In order to acquire a good reflectance photoplethysmograph signal, blue and green light are more preferable [5][6]. The major purpose of this study is to analyze the factors that influence the signal quality of reflectance photoplethysmograph. These factors include the wavelength of light, the distance between the light source and the detector, and the optical properties of tissue[7].

II. MATERIALS AND METHODS

The experimental set up for light reflectance measurement is shown in Figure 1. Surface mount light-emitting diodes (LEDs) with a size of 1.4mm×1.25mm were used as the light source. Four different wavelengths (463nm, 543nm, 571nm, and 634nm) of light were tested in the experiment. The penetration depth is approximately 0.2mm for blue light (463nm), 0.4mm
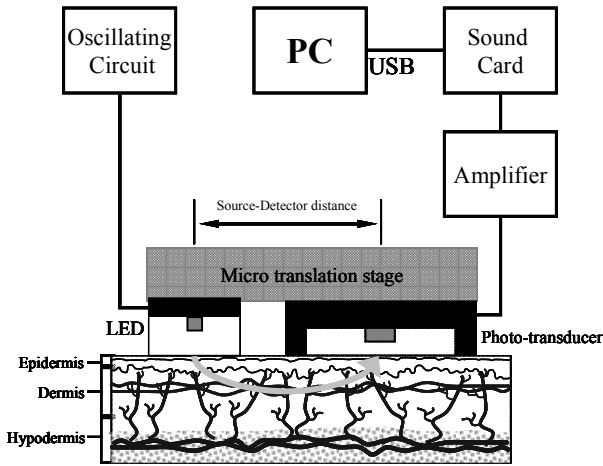
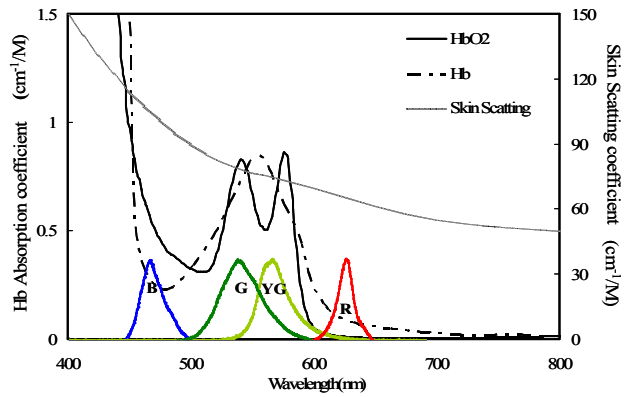Fig. 1 Measurement setup of reflectance photoplethysmograph

Fig. 2 Emission spectra of LEDs and the absorption spectra of oxyhemoglobin and hemoglobin. The dash line shows the scattering coefficient of skin tissue

for green light (543nm), 0.5mm for yellowish green light (571nm), and 0.62mm for red light (634nm). The light detector used was a phototransistor (SFH 3410, OSRAM) with a size of 2.5mm×2mm. The sensitivity of this phototransistor covers a spectral range from 400nm to 1100nm and peaks at 550nm. Both a light source and a sensor were mounted on a micro translation stage for accurately adjusting the distance between them. The adjustable range is from 2mm to 15mm. The experiment was carried out in an air conditioned dark room by setting the temperature to 20°C. The reflectance signal was continuously measured for 20 seconds at each position. The LED light source was driven by a 30Hz current source. Only a small portion of light reached the detector after it traveled inside the skin tissue. The reflectance intensity of the flashing light varied with changes in blood volume of tissue. The detected reflectance was amplified and sent to the line-in port of a sound card (Jazz-UB80, INTOPIC). This amplitude modulated signal was digitized by the sound card and finally transferred to computer through the USB port.

A computer program in MATLAB demodulated the recorded signal in order to extract the envelope signal. The plethysmograph signal was further divided into three parts (AC_{High}, AC_{Low}, and DC) based on their frequency regions. The AC_{High} signal covers the frequency region from 0.5Hz to 4Hz. The AC_{Low} signal is the portion below 0.5Hz. The DC is the steady portion of the signal of reflectance intensity.

In order to compare the signal quality of different LEDs, plethysmograph signal was expressed as the perfusion index (PI) and the signal-to-noise ratio (SNR). The perfusion indexes are defined as the ratio of variable amplitude to the steady reflectance intensity, formulated as equation (1). The signal-to-noise ratio is defined as the logarithm of the ratio of AC_{High} to the background noise (2) which is the average of dark current signal continuously measured in a dark room for 30 seconds. The signal-effect-index (3) is used to check the signal effect.

$$PI_H = \frac{AC_{High}}{DC} . \tag{1}$$

$$SNR_H = 20\log\frac{AC_{High}}{N} . \tag{2}$$

$$SEI_H = NPI_H \times SNR_H ; \tag{3}$$

$$NPI_H = 100 \times \frac{PI_H(n)}{PI_H(\max)} .$$

III. RESULTS

The emission spectra of LEDs were measured by using a fiber optic spectrometer (USB4000, Ocean Optics). Figure 2 shows the LEDs' emission spectra together with the absorption spectra of hemoglobin and oxyhemoglobin as well as the scattering coefficient spectrum of skin tissue. The central wavelengths of LEDs are 463nm for blue light, 543nm for green light, 571nm for yellowish green light, and 634nm for red light.
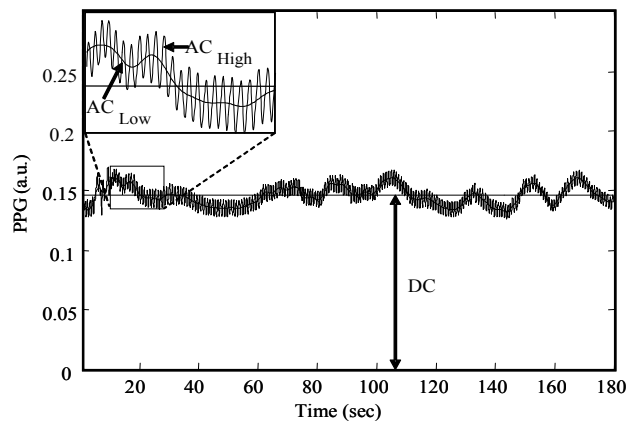

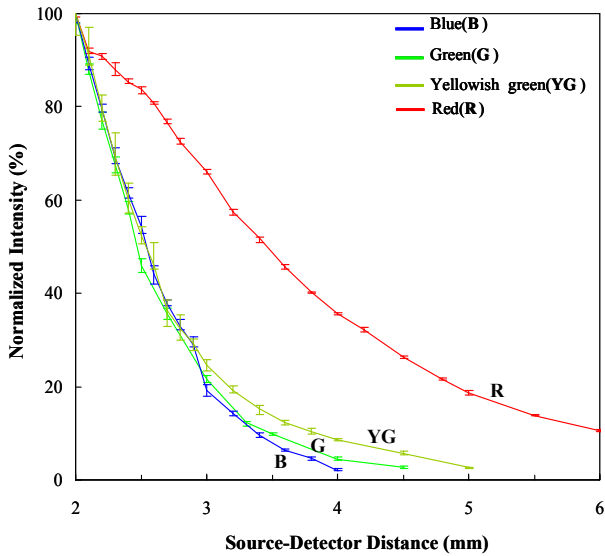Fig. 3 A typical reflectance photoplethysmograph signal.

Fig. 4 Reflectance intensity at different emitter-detector distance. Error bar in the figure shows the varying range of low frequency signal

A typical measurement of reflectance plethysmograph signal while sitting still is shown in Figure 3. The intensity of DC signal is obviously much larger than the AC portions. The low frequency drift does not show a regular periodic change as the high frequency variation shown in the inset. This high frequency signal is synchronous with the heart beat.

Similar to the inverse-square law found in many physical phenomena, the reflectance intensity decayed exponentially as the source-detector distance increases. The intensity profiles of all four wavelengths show the same tendency, as seen in Figure 4. Red light travels a longer distance in tissue than other wavelengths. This is because red light has much smaller absorption and scattering properties than other wavelengths.
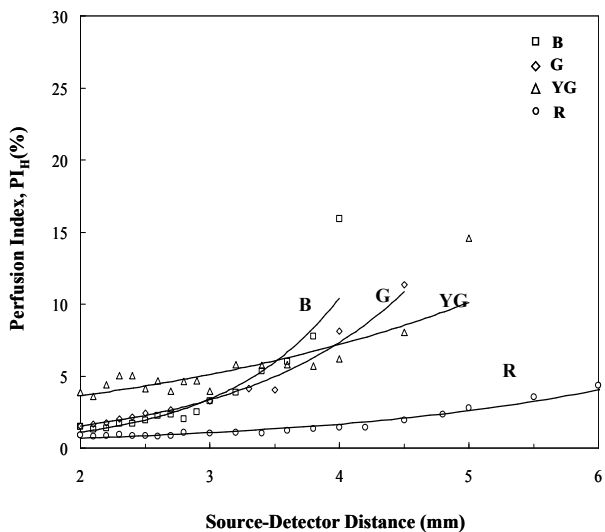

Fig. 5 The high frequency perfusion index (PI_H) at different emitter-detector distance.

Figure 5 show that PI_H increase as the emitter-detector distance increases. The indexes of each wavelength fit to an exponential function to show the nonlinear rising tendency. When light travels for a longer distance, more light is absorbed by blood and results in a larger plethysmograph signal. It is preferable to have large signal amplitude to acquire the heart rate signal. However, the signal-to-noise ratio drops when the light intensity signal decreases, as shown in Figure 6. Figure 7. show that SEI_H curves for analysis the probe design.
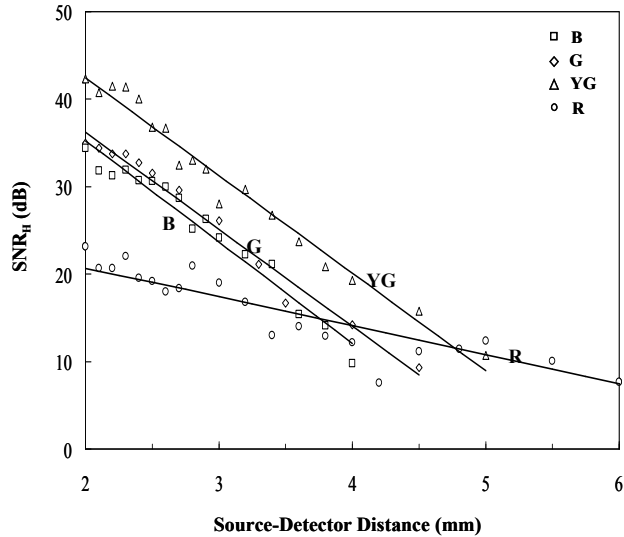

Fig. 6 The high frequency signal-to-noise ratio (SNR_H) at different emitter-detector distance
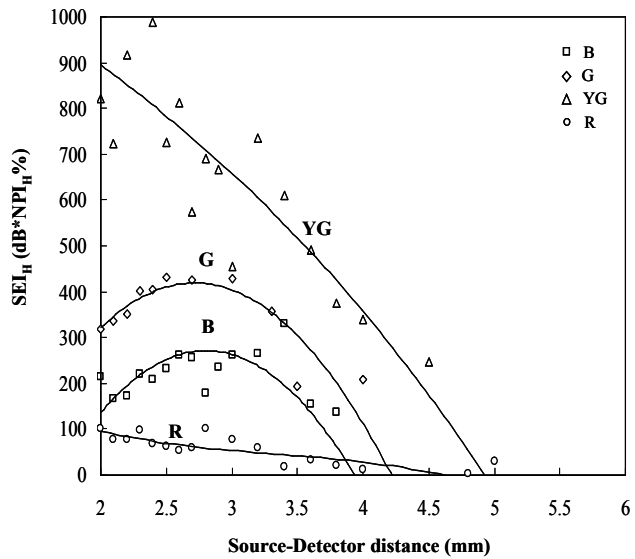

Fig. 7 The signal-effect-index (SEI_H) at different emitter-detector distance

IV. DISCUSSION

Transmission type of photoplethysmograph is generally used in pulse oximeter to evaluate the oxygen saturation in the blood. To carry out the measurement on an earlobe or finger tip, probe

light has to penetrate the thick tissue to acquire information in the perfusion blood. Since the scattered path length of light could be over 10 mm, red and near-infrared light are used as the light sources because of their low absorption and scattering properties.

The reflective photoplethysmograph is more convenient to apply when only the heart rate measurement is interested. The measurement can be taken at any site of skin surface other than earlobe and fingertips. The light intensity distribution of diffusive reflectance on skin surface is also determined by the absorption and scattering properties of skin tissue. These two factors are both wavelength dependent. In general, the scattering coefficient decreases monotonically with the increasing of wavelength, however, the absorption coefficient greatly varies near the absorption peaks.

In the short wavelength region of visible light, the scattering of light is stronger than those at the red end. This results in a strong backscattering of light from skin surface which can be detected using less power of light.

The diffusive reflectance of light signal includes three major components: the static component (DC), the low frequency of drifting (AC_{Low}), and the high frequency of pulsatile signal (AC_{High}). The static portion of reflectance is mostly determined by the light scattering property of tissue, whereas the variable portion is determined by the light absorption property of blood. The purpose of this study is to find the optimal wavelength and source-detector distance for measuring the reflective photoplethysmograph.

In this study, three indexes are used to quantify the quality of photoplethysmograph signal. The perfusion indexes, PI_H, represent the magnitude ratio of AC to DC. The larger value of perfusion index, the easier to abstract plethysmograph from the reflectance signal. The perfusion indexes of four wavelengths used in this study all show the up rise tendency with larger source-detector distance. This means the contribution of absorption gradually surpasses that of scattering in light attenuation when the separation is increased. However, the signal-to-noise of the high frequency reflectance signal shows a decaying tendency as the separation increased. This is because the signal level greatly drops with increasing distance while the background noise remains the same.

The difference between the perfusion index and signal-to-noise ratio indicates that there exists an optimal source-detector distance in the design of a reflectance photoplethysmograph probe. According to the results in Figure 5, the yellowish green does not only has a larger perfusion index than blue and green. Also, when the emitter-detector distance is shorter than 3.5mm, there is a higher signal-to-noise ratio in the small distance region.

By setting an upper limit of SEI_H must upper limit of 600(dB%) only the yellowish green light satisfies both conditions. The good sensing distance range for the yellowish green light (571nm) is between 2 to 3.2mm.

V. CONCLUSION

A micro translation stage setup was used to study the distance factor of perfusion index and the signal-to-noise ratio of reflectance photoplethysmograph signal.

Even thought red light is generally used as the light source in transmission measurement, it has relatively small absorption and scattering properties. In reflectance measurement, received light only travels a short distance in tissue. Therefore, the reflectance signal of red light is generally not very observable compared with those of other wavelengths. Among the four wavelengths of light tested in this study, the yellowish green light with peak wavelength at 571nm has the best reflectance signal quality. The optimal emitter-detector distance for the yellowish green is at about 2mm.

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