Theoretical Base of Alcoholic-Intake Detection Using Blood-Pulse Signals and New Findings

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Abstract—**We spectroscopically investigate the impact of alcohol intake on the blood-pulse waveform and confirm that alcohol intake can be discerned by opto-electronic sensors. This paper focuses on specific spectra in the blood-pulse waveform and demonstrates the importance of observing the harmonics ratio of the blood-pulse waveform. In contrast to past studies, it is strongly suggested that the best light source for detecting alcohol intake is a green-LED. An analysis of the time evolution of the harmonic ratio shows that it includes important information from which the intake of alcohol can be discerned despite the complexity involved. This analysis is verified by mathematical modeling.**

I. INTRODUCTION

Fatal traffic accidents caused by alcohol-impaired driving continue to attract wide social attention in Japan because their number has not significantly decreased in spite of the tough revisions made to the Road Traffic Law in 2002. Accordingly, various sensors, some of which are portable, have been proposed to prevent drivers from driving while alcohol-impaired, and thus reducing the number of fatal traffic accidents [1-3]. However, no current device can meet the two key requirements of accurate detection and low running cost. This omission must be overcome through technological innovation.

In trying to noninvasively detect alcohol intake, the most commonly applied approaches are to analyze the breath or blood of drivers. Pulse oximetry is a famous noninvasive technique that can detect respiratory signals, pulsation signals, and chemicals in the blood [4, 5-11]. It is an electro-optical method and detects blood volume changes in the finger arterial tree. The changes in the optical properties of blood due to changes in its chemistry, i. e., oxyhemoglobin and reduced hemoglobin, are already known [4, 5]; red-LEDs and infrared (IR)-LEDs are often used as compound light sources [6-10].

Many studies have focused on optical capture of the blood-pulse waveform [6-11]. This approach is attracting more attention from the viewpoint of its many medical applications [7, 12]. The studies referenced attempted to suppress the uncertainty inherent in the raw data representing the blood-pulse waveform, which is due to diverse factors including body posture and age [13, 14].

This paper investigates the difference in specific spectra of the blood-pulse waveform between pre-alcohol and post-alcohol-intake states in order to examine the feasibility of various sensors in detecting alcohol in the blood. An important target of this study is to propose an advanced method to prevent alcohol-impaired driving. Our approach is to convert the blood-pulse wave signal into the frequency-domain by fast-Fourier-transformation (FFT) [13-15]. This paper demonstrates the importance of observing the harmonics ratio of the blood-pulse waveform. It also shows that specific spectra can be effective in the detection of alcohol intake. This paper also verifies the experimental study by a mathematical procedure; new findings are supported by theoretical considerations.

II. EXPERINTAL METHOD AND SETUP

Pulse oximetry captures the pulsations of arteries to evaluate heart rate and blood oxygen concentration. It is medically known that the concentration of oxygenated hemoglobin is reduced after alcohol is consumed, because the alcohol-related chemicals hinder the oxygenation of hemoglobin. It is anticipated that the use of IR- and red-LEDs is appropriate for detection of alcohol intake.

The procedure used in the experiments described in this paper is as follows [16]. The blood-pulse wave signal is converted into the frequency domain by FFT processing after the source signal is linearly amplified by an operational amplifier (see Fig. 1). The light-source LEDs are used in the continuously dc-biased state. The subject's finger is held about 7 mm from the combined light source and photo-detector (photo-transistor); the lights emitted from the source are partially absorbed, reflected from around the bone, and captured by the photo-transistor. The measurements are performed in a dark room to avoid the noise generated by room lights and/or natural light. FFT processing is performed at the sampling frequency of 1000 Hz. Since the magnitude of the original spectral component is so large, its square-root value is used in the analysis in Fig. 2, but the original values are used in the other figures.

Though various studies that perform waveform analysis have been published [13-15], none considered the harmonics ratios of the blood-pulse waveform. Since our preliminary experiments discovered that the blood-pulse waveforms of post-alcohol-intake subjects demonstrate some unique behaviors, we analyzed the harmonics in detail. We note that the harmonics of the blood-pulse waveform depend on the wavelength of the primary light source which supports the finding of article [5]. In preliminary experiments shown in a later section (see Fig. 3), the colors of the light-source LEDs used were 'infrared' with primary wavelength of 935 nm and 'red' with wavelength of 660 nm. In some experiments, as demonstrated later (see Fig. 2), we use 'blue' (470 nm) and 'green' (525 nm) LEDs as an extension of the study.

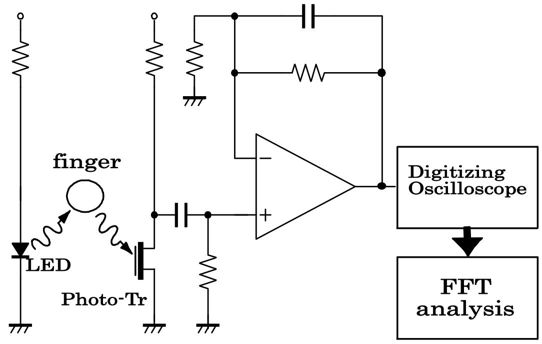


Fig. 1. Experimental setup.

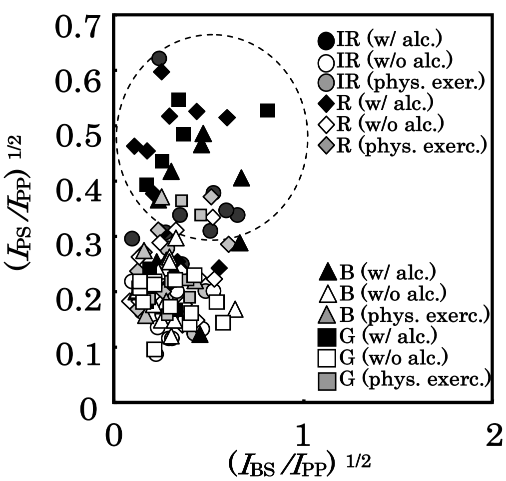


Figure 2. Correlation between spectral intensity ratios. All data are averaged over three repeated measurements. (IR: infrared, R: red, B: blue, G: green)

In the experiment, we selected 12 healthy volunteers (22-to-23-year-old males and one female) working in the laboratory. They consumed 350 cm^3 of 7-%-alcohol beer within 15 minutes. This experimental setting (small volume of beer) was determined to confirm the feasibility and the sensitivity of the method proposed here. Their blood-pulse waveforms were repeatedly measured at 15 min intervals over a 2 hour period after consuming the beer by the system shown in Fig. 1.

III. Results and Discussion

A. Fandamental aspects of blood-pulse signals

From the results shown in our previous work [16], we could extract the following features from all volunteers despite their variation. The mathematical basis of the following consideration is described in the *Appendix*.

(1) Ratio (I_{BS}/I_{PP}), the spectral intensity of the respiratory signal ($\cong$ 0.4 Hz) (I_{BS}) over that of the primary pulsation signal ($\cong$1.8 Hz) (I_{PP}), is raised by the intake of alcohol.

(2) Harmonic ratio (I_{PS}/I_{PP}), the spectral intensity of the second harmonic ($\cong$3.6 Hz) of the pulsation signal (I_{PS}) over that of the primary one ($\cong$1.8 Hz) (I_{PP}), is raised by the intake of alcohol.

(3) The above-mentioned features appear regardless of the central wavelength of the four different light sources used in the study.

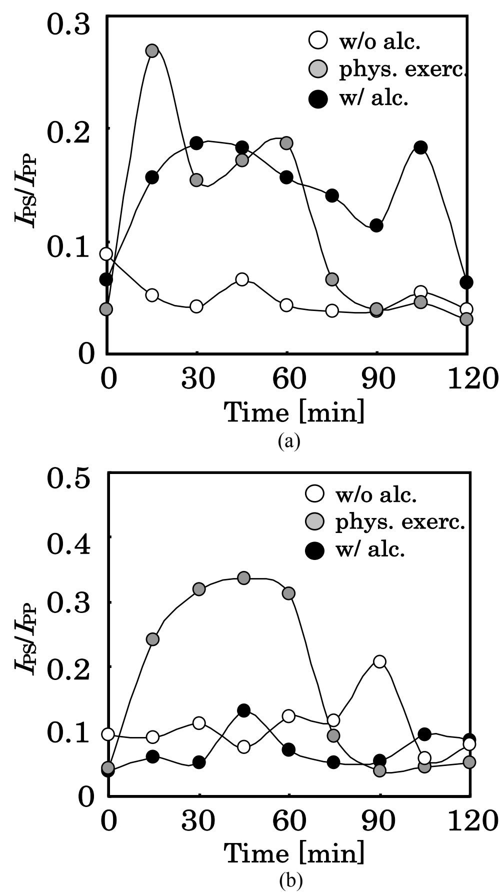


Figure 3. Time evolution of harmonic ratio extracted from the PPG signal. All data are averaged over three repeated measurements. (a) IR-LED, (b) red LED.

The correlation between I_{BS}/I_{PP} values and I_{PS}/I_{PP} values extracted from the data of the 12 volunteers is plotted in Fig. 2. These data were acquired in the 90 minute period after the volunteers consumed the beer. For comparison, Fig. 2 also shows the data obtained from the same volunteers who physically exercised with no alcohol before the measurement; in this experiment, the volunteers spent 5 min running up and down a flight of stairs. It is revealed that I_{BS}/I_{PP} values and I_{PS}/I_{PP} values are raised significantly by the intake of alcohol (see the broken line circle); the increase in harmonic ratio (I_{PS}/I_{PP}) values is remarkable. On the other hand, physical exercise showed limited impact on the harmonic ratios. This suggests that FFT analysis of the blood-pulse waveform has great potential for the extraction of signals highly indicative of alcohol intake.

Fig. 2 plots the results obtained using a green-LED and a blue-LED as the light source. The impact of light source wavelength on the detection of alcohol intake is discussed in a latter section after the results obtained using the IR-LED and red-LED are described.

B. Response of harmonics ratio to physical exercise and alcohol intake

We have already shown that the harmonics ratios (I_{PS}/I_{PP}) of PPG signals rise after alcohol intake for various LED light sources; see Fig. 2. However, these results are not totally conclusive because the time evolution of such signals was not addressed. This paper rectifies this omission by evaluating the time evolution of the harmonic ratio (I_{PS}/I_{PP}) of PPG signals using the IR-LED and red-LED, see Figs. 3(a) and 3(b), respectively. For comparison, harmonic ratio (I_{PS}/I_{PP}) values after physical exercise are also shown.

It is seen in Fig. 3 that the harmonic ratio observed after physical exercise is initially high, comparable to that stemming from alcohol intake, but it decays within 80 min for both IR-LED and red-LED. The reason for the high initial harmonic ratio after physical exercise stems from the fact that physical exercise temporarily reduces the density of oxyhemoglobin in the blood; the harmonic ratio yielded by the red-LED is also high.

The harmonics ratio observed after alcohol intake, on the other hand, remains high for 2 hours (IR-LED source); this suggests that the alcohol intake alters the cardiac motion, and that the volume of oxyhemoglobin increases in order to decompose the alcohol. Note that using the red-LED yields a signal that is almost identical to that without alcohol intake; this suggests that the volume of reduced hemoglobin decreases. This suggests that the IR-LED is applicable to long-term observations, not short-term observations.

C. Impact of wavelength of LED light on detection of alcohol intake

The results of the previous section reveal that the harmonics ratio (I_{PS}/I_{PP}) of the PPG signal is basically sensitive to alcohol intake, and that its value remains high for long periods in contrast to the concentration of alcohol-related chemicals in the breath [16]. The use of IR-LED and/or red-LED for pulse oximetry [5] is predicated on Beer-Lambert's law [18]. Pulse oximetry utilizes the change in the optical absorbance (wavelength-dependent) of the medium (reduced hemoglobin and oxyhemoglobin).

In this study, on the other hand, we are not, for now, interested in the oxygen saturation level of the blood. The absorbance coefficients of reduced hemoglobin and oxyhemoglobin [5] take very large local maxima around the wavelengths of 400 nm and 550 nm. This suggests that blue-LED and green-LED may be better at realizing the highly sensitive detection of the local volume change of arterial blood stemming from pulsation. Accordingly, we examined the use of such LEDs in PPG signal detection. Preliminary studies on the application of green-LED to PPG signal detection have already been performed [11]. However, the target was limited to the analysis of electrocardiography (ECG) signals.

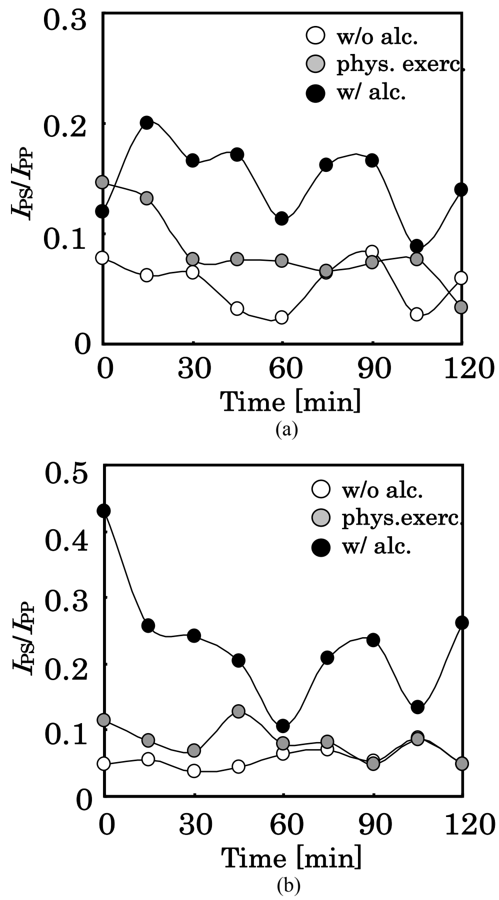


Figure 4. Time evolution of the harmonic ratio extracted from the PPG signal. All data are averaged over three repeated measurements. (a) blue LED, (b) green LED.

Various time evolutions of the harmonic ratio of the PPG signal are shown in Fig. 4. The harmonics ratios after alcohol intake hold relatively high values compared to those after physical exercise for both LED types, but the green-LED gave the superior results. This can be explained by the conventional prediction that alcohol intake reduces oxyhemoglobin levels. The alcohol intake probably raises the density of specific chemicals (for example, acetaldehyde, acetate, and other chemicals [19]) that absorb green and blue lights ranging from 470 nm to 530 nm. Anyway, this experimental result strongly suggests that green-LEDs can be used to achieve the sensitive detection of alcohol intake.

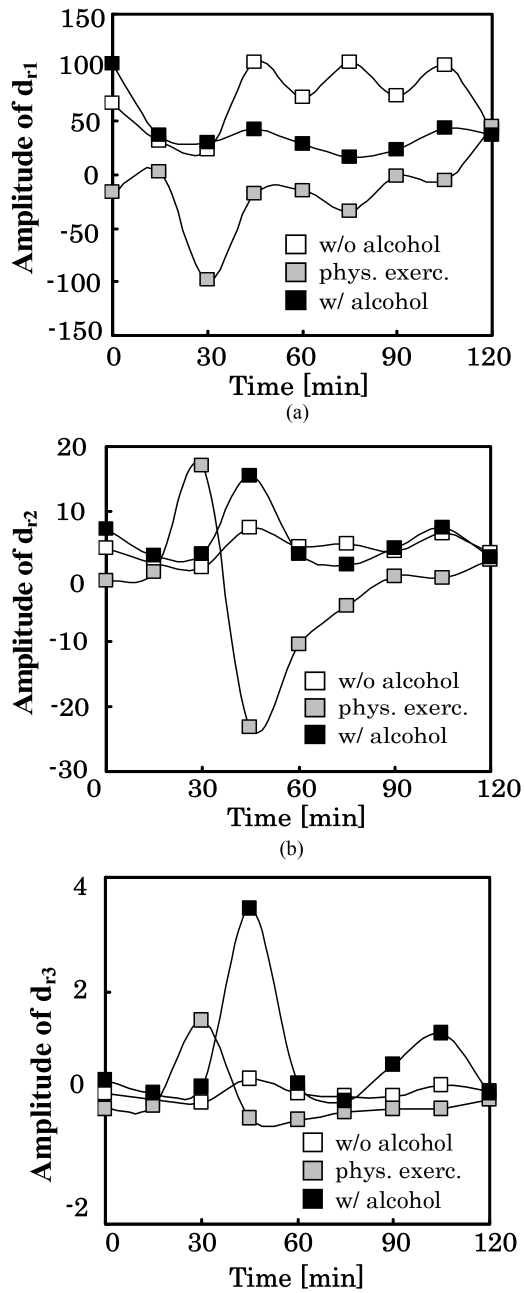


Figure 5. Time evolution of the amplitude of the primary harmonic, the 2[nd] harmonic, and the 3[rd] harmonic of the PPG signal. All data are averaged over three repeated measurements. (a) the primary harmonic of the PPG signal, (b) the 2[nd] harmonic of the PPG signal, (c) the 3[rd] harmonic of the PPG signal.

D. Relation between experimental results of harmonic ratio and mathematical model proposed

First, we briefly summarize the experimental results. Figure 3 reveals that the IR- and red-LEDs successfully catch the impact of physical exercise on the PPG signal. In contrast, Figure 4 shows that blue- and green-LEDs are less effective in catching the impact of physical exercise on the PPG signal, but are more effective on discerning alcohol intake. Since these data are obtained from the same subject, it can be concluded that the harmonic ratio is a function of the wavelength of light source. This suggests two possibilities: (1) Both I_{PS} and I_{PP} are intrinsic functions of the wavelength, and (2) I_{PS} or I_{PP} is an intrinsic function of the wavelength. We need to turn to mathematical modeling to acquire a deep understanding of this issue.

According to the mathematical modeling described in *Appendix*, we can extract the 'apparent' harmonic components from the FFT-analyzed data. The mathematical simplification described in *Appendix* yields an important insight in interpreting the PPG signal detected and the calculated harmonic ratio characteristics. We have the following results.

(1) The 1st-order approximation of the harmonic ratio extracted theoretically from the assumed PPG signal gives the harmonic ratio of the blood-pulse source signal itself. This probably shows that harmonics are approximately independent of the wavelength of the light source.

(2) The 1.5th-order approximation of the harmonic ratio yields additional information on the influence of the 2nd- and 3rd-harmonics of the blood-pulse wave; the harmonics are functions of the optical absorption coefficient of the arterial tree.

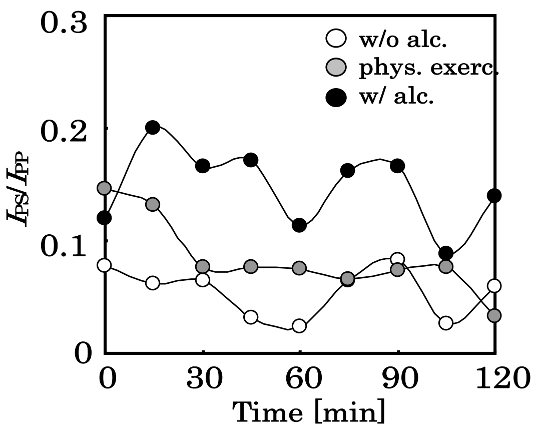
Experimental results of harmonic ratios definitely suggest that the 1.5th-order approximation is suitable for the present consideration because the alcohol intake raises the harmonic ratio (***I_{PS}/I_{PP}***) and the ratio depends on the wavelength of the light source. Therefore, the theoretical analysis suggests that the use of green- and blue-LEDs as the light source successfully enhances the 2nd harmonic because the increase in the optical absorption coefficient (α_2) of arterial tree reduces the dominator of eq. (A1). In addition, this mathematical basis allows us to extract the values of the 'true' harmonic components from the experimental results as shown in Fig. 5; the amplitude of the primary harmonic (d_{r1}), the 2nd harmonic (d_{r2}), and the 3rd harmonic (d_{r3}) of the PPG signal, that were extracted from the experimental results, are shown in Figs. 5(a)-5(c), respectively. As they characterize the behaviors of 'true' harmonic components, we think they should be useful in considering the impact of alcohol intake on cardiac motion.

E. Feasibility of Fourier transformation of derivative of PPG signals

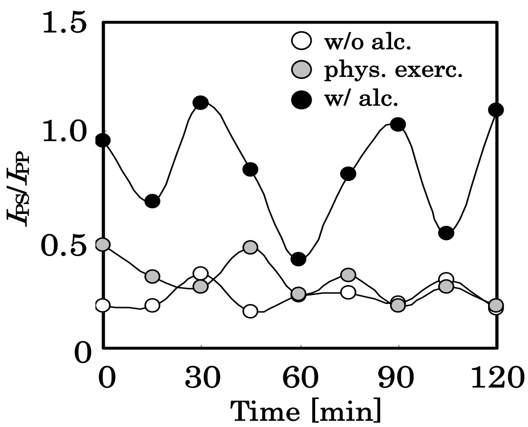
Finally, we challenge an advanced technique to detect alcohol intake. Considering technical applicability, the method must clearly differentiate the PPG signals between those who have consumed alcohol and those have not. To successfully capture these differences, we Fourier transform derivatives of the PPG signals. Time evolutions of harmonic ratio of the derivatives of the pulsation signal are shown in

Fig. 6; Figure 6(a) shows the results yielded by the IR-LED, and Figure 6(b) shows the results yielded by the green-LED.

Comparing Fig. 6 with Fig. 3, it is clearly seen that the analysis technique proposed here quadruples the harmonic ratio regardless of the subject's body conditions, which definitely improves the signal-to-noise ratio. According to the mathematical calculation using eqs. (A2) and (A3), the derivative of PPG signal does not yield such a large harmonic ratio. Therefore, this suggests that the pulsation wave has nonlinear nature [20], and that a more advanced study is requested to realize the successful and reliable detection of alcohol intake.



(a)



(b)

Figure 6. Time evolution of harmonic ratio extracted from derivative of the PPG signal. All points are averaged over three repeated raw data. (a) IR LED, (b) green LED

IV. Conclusion

This paper investigated the characteristic of specific spectra of the blood-pulse waveforms of adult subjects observed after consuming alcohol in order to examine the feasibility of using photoplethysmographic sensors to detect the intake of alcohol. The FFT spectra of captured blood-pulse waveforms were analyzed to determine their characteristics. This paper focused on the behaviors of specific spectra and demonstrated the importance of observing the harmonic ratio of the blood-pulse waveform. An analysis of the time evolution of the harmonic ratio discovered that the harmonic ratio includes important information that allows the intake of alcohol to be detected. We successfully demonstrated the desirability of using green-LEDs, proposed here, in realizing a very sensitive and practical alcohol-intake sensor for drivers. We also introduced a mathematical modeling approach and demonstrated that it supports the experimental results.

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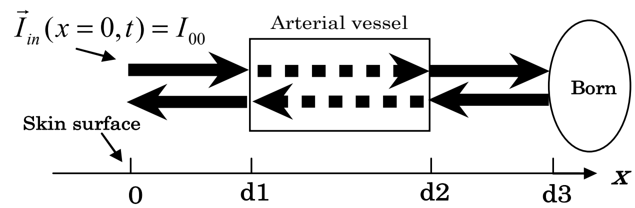

Figure 7. Physical model underlying the mathematical formulation of the harmonic ratio.

Appendix: Theoretical review of the use of the harmonics ratio

Here we advance the mathematical basis demanded by the paper. Assumed physical configuration is illustrated in Fig. 7. It is assumed that the incident light passes through the skin of the finger, the arterial vessel, and is reflected from the surface of the bone. In this process, the incident light is absorbed inside the finger. When the incident light intensity is given at the skin surface by I_{00}, the light intensity, I_{out}, that emerges from the skin surface is given by

$$\vec{I}_{out}(x=0,t) = I_{00}\exp\{-2\alpha_1(\lambda)(d_1+D_2)\} \times\exp\{-2\alpha_2(\lambda)D_{av}(t)\}\ , \tag{A1}$$

where $\alpha_1(\lambda)$ is the absorption coefficient of the hypodermis including the dermis, $\alpha_2(\lambda)$ denotes the absorption coefficient of the arterial vessel, D_2 denotes d_3-d_2, $D_{av}(t)$ denotes the instantaneous diameter of arterial vessel ($=d_2$-d_1) (this oscillates due to periodic pulsation). For simplicity, this paper assumes that the oscillation of the diameter of the arterial vessel can be expressed in Fourier series as follows.

$$D_{av}(t) = \sum_{n=0} d_{avn}\cos(\omega_n t)\ . \tag{A2}$$

The light emerging from the finger is captured by the photo-transistor. The electrical signal voltage coming from the photo-transistor, $V_{out}(t)$, is given by

$$V_{out}(t) = V_P\left[1-\exp\{-2\alpha_1(\lambda)(d_1+D_2)\} \times\exp\{-2\alpha_2(\lambda)D_{av}(t)\}\right], \tag{A3}$$

where V_P denotes a constant. The Fourier component ($V_o(\omega_n)$) of $V_{out}(t)$ is given by solving the following integration.

$$V_o(\omega_n) = K_1 \int_{-t_p}^{t_p} \exp\{-2\alpha_2(\lambda) \sum_{m=0} d_{avm} \cos(\omega_m t)\} \times \cos(\omega_n t) dt, \tag{A4}$$

$$K_1 = -V_P (1/t_p) \exp\{-2\alpha_1(\lambda)(d_1 + D_2)\}, \tag{A5}$$

where t_p denotes the periodic time.

Here, for simplicity, we assume that $d_{av1}<1$, $d_{av2}<1$, and $d_{av3}<1$, but $d_{av1} > d_{av2}, d_{av3}$. This enables the Taylor's expansion of the exponential function. Thus, we can apply the 1.5th-order approximation to eq. (A4). First, we calculate primary spectrum $V_0(\omega_1)$. We have

$$\begin{aligned} V_o(\omega_1) \cong 2K_1 \int_0^{t_p} &\{\exp\{-2\alpha_2 d_0\}\{1 - 2\alpha_2 d_{av1}\cos(\omega_1 t)\} \\ &\times [(1 + 2\alpha_2 d_{av2})\cos(\omega_1 t) + 6\alpha_2 d_{av3}\cos^2(\omega_1 t) \\ &- 4\alpha_2 d_{av2}\cos^3(\omega_1 t) - 8\alpha_2 d_{av3}\cos^4(\omega_1 t)]\} dt. \end{aligned} \tag{A6}$$

Performing the integration yields the following result.

$$V_0(\omega_1) = 2K_1 \{(\pi/\omega_1)(-\alpha_2 d_{av1} + \alpha_2^2 d_{av1} d_{av2})\} \exp\{-2\alpha_2 d_0\}. \tag{A7}$$

In a similar manner, we gain the secondary spectrum $V_0(2\omega_1)$ as

$$V_0(2\omega_1) = 2K_1 \{(\pi/\omega_1)(-\alpha_2 d_{av2} + \alpha_2^2 d_{av1} d_{av3})\} \exp\{-2\alpha_2 d_0\}. \tag{A8}$$

From eqs. (A7) and (A8), we have the harmonic ratio (I_{PS}/I_{PP}).

$$\begin{aligned} \frac{I_{PS}}{I_{PP}} &= \frac{2K_1 \{(\pi/\omega_1)(-\alpha_2 d_{av2} + \alpha_2^2 d_{av1} d_{av3})\} \exp\{-2\alpha_2 d_0\}}{2K_1 \{(\pi/\omega_1)(-\alpha_2 d_{av1} + \alpha_2^2 d_{av1} d_{av2})\} \exp\{-2\alpha_2 d_0\}} \\ &= \frac{d_{av2}(1 - \alpha_2 d_{av1} d_{av3} / d_{av2})}{d_{av1}(1 - \alpha_2 d_{av2})}. \end{aligned} \tag{A9}$$

When we apply the 1st-order approximation to eq. (A4), we have

$$\frac{I_{PS}}{I_{PP}} = \frac{d_{av2}}{d_{av1}}. \tag{A10}$$

Therefore, it is found that the present mathematical procedure is valid. On the other hand, the 1.5th-order approximation (eq. (A9)) eases the PPG signal analysis because I_{PS}/I_{PP} is given as a function of $\alpha_2(\lambda)$.

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