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Empirical Analysis Based on Light Attenuation Gradient of Wavelength Pairs for the Prediction of Skin Oxygen Status

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Abstract:
An empirical technique that allows noninvasive prediction of skin (transcutaneous) oxygen saturation (S_tO_2) using the absorption coefficients of the preprocessing stored wavelength pairs is proposed. The highest probable S_tO_2 value is decided by selecting the bin containing wavelength pairs that produce the smallest variation in the distribution of the calculated attenuation gradient value. The performance this technique was evaluated using Monte Carlo simulated data. The simulation results revealed that this technique worked reasonably well even at low S_tO_2 condition with an overall mean error of not more than 2 %. This shows that the proposed analytic technique can potentially be used for measurement of the blood oxygen level of individuals with respiratory disease or with oxygen deprivation conditions such as hypoxic-hypoxia.

Keywords: Skin blood oxygen saturation, Attenuation gradient, Wavelength pairs, Binning.

1. Introduction

Oximeter is an important diagnostic tool to monitor one's oxygen level. A normal and healthy person would have arterial blood oxygen saturation, S_aO_2, of at least 95 % and a decrease in this value to a critical level for several minutes can result in cell (neuron) death; this may later lead to paralysis and death. The working principle of the first oximetry system was based on the change in the colour of hemoglobin in response to the oxygen level. Following that the first prototype of ear oximetry, which involved heating of ear pinna to induce vasodilation, was introduced [1].

In year 1970, an eight wavelengths ear oximetry, which did not require pre-measurement calibration, was marketed by Hewlett-Packard and it was the gold standard of that time for S_aO_2 monitoring. Several years later, Aayogi [1] discovered the pulsatile based oximetry for continuous monitoring of blood oxygen saturation using the ratio of ratios equation, which is adopted in modern pulse oximeters [2]. Two wavelengths chosen from red and Near Infrared (NIR) region were selected to produce the time varying attenuation, $\partial A/\partial t$. The normalized ratio between the time varying signals of these wavelengths, R, removed the non-pulsatile components of the detected signals. This measurement technique required a reference data to translate the measured R into the related S_aO_2. However, it is the ethical issue that prevented manufacturers from introducing severe hypoxia on volunteers for calibration purposes. Therefore the limitation of modern pulse oximetry is its poor performance for measurement at low S_aO_2 condition.

In a light absorbing medium, the Lambert-Beer law relates the light absorbance with the medium absorption coefficient, μ_a. However, this law does not hold for measurements on a scattering medium as photons traveled multiple paths before reached the detector. Twersky [3] derived an attenuation expression for light scattering-absorbing medium which included losses in the signal level by both absorption and scattering processes. This expression was simplified by Duling and Pittman [4] and known as Modified Lambert Beer model. This linear approximation is known to estimate medium's μ_a with some errors; the latter can be minimized if appropriate wavelengths were carefully chosen [5,6]. Following that, other similar analytic models were proposed in the prediction of this health related parameter for clinical use [7, 8]. This work aims to explore the attenuation gradient characteristics of wavelength pairs for the prediction of skin blood oxygen saturation. The accuracy in the predicted S_tO_2 value is evaluated using Monte Carlo simulated data as the medium's optical properties are known.

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2. Method

2.1 Monte Carlo Modeling of Light Propagation in Skin Model

To demonstrate the validity of the technique discussed in section 2.2, this work modeled human skin as a single layer heterogeneous infinite slab with water, hemoglobin and melanin as its absorbers. The total medium's μ_a is given by

$$\mu_a = \mu_{a(water)} f_W + \mu_{a(Hb)} f_B + \mu_{a(melanin)} f_M \quad (1)$$

where the absorber to which each μ_a component is corresponded with is indicated by its subscript while f_W, f_B and f_M are the unit-less volume fraction of water, blood and melanocytes, respectively. Their value is listed in Table 1.

Table 1 The volume fraction of absorbers used in the modeled infinite slab. Data taken from [9].

Parameter	Value
f_W	0.50
f_B	0.04
f_M	0.01

This work assumed light absorption by Carboxyhemoglobin (COHb) and Methemoglobin (MetHb) are negligible, the absorption coefficient of blood, $\mu_{a(Hb)}$, at wavelength, λ, is given by the absorptivity of oxyhemoglobin (OxyHb), $\mu_{a(OxyHb)}$, and deoxyhemoglobin (dHb), $\mu_{a(dHb)}$, as followed [10]:

$$\mu_{a(Hb)}(\lambda) = \left(\Delta\mu_{a(\Delta Hb)}(\lambda) S_t O_2 + \mu_{a(dHb)}(\lambda)\right) T \quad (2)$$

where $\Delta\mu_{a(\Delta Hb)}$ denotes the difference in the value of $\mu_{a(OxyHb)}$ and $\mu_{a(dHb)}$, T represents total blood concentration and was taken to be 150 g/L. The S_tO_2 is given by the ratio of OxyHb concentration and T. The wavelength dependent μ_a for all the considered absorbers is shown in Fig. 1 (top).

The main source of light scattering in the modeled skin was by the adipose layer that comprised of intralipid tissue. The wavelength dependent reduced scattering coefficient, $\mu'_s(\lambda)$, for intralipid-10% in the units of cm^{-1} is given by [10]:

$$\mu'_s = 3.488\lambda^{-2.4}(1.1 - 0.58\lambda) \quad (3)$$

where λ is in the unit of micrometres. The wavelength dependent μ'_s is shown in Fig. 1 (bottom).

The propagation behavior of photons in the medium was simulated using a Monte Carlo model. For each simulation, 20 million photons were launched into the medium at normal incidence. The refractive index mismatch between the scatterer and its surrounding was given by 1.195. An annular detector with inner and outer detection rings of 4 mm and 6 mm, respectively, was placed in contact with the slab. It was assumed that with the medium thickness, d, of 150 mm none of the photons can escape from the medium without being scattered and absorbed. Further discussion of the Monte Carlo model can be found in [10].

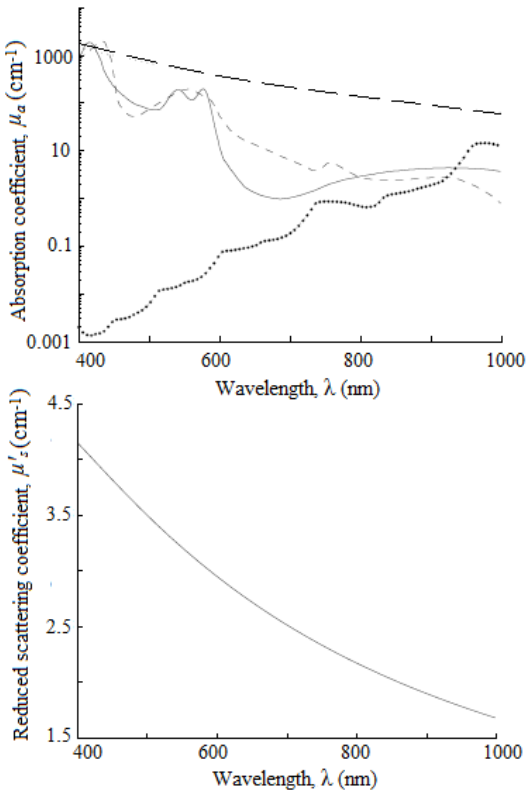

Fig 1 (Top) Absorption coefficients of oxyhemoglobin (solid line), deoxyhemoglobin (dashed line), water (closed circles), and melanin (long dashed line). (Bottom) Wavelength dependent reduced scattering coefficient.

2.2 Light Attenuation Characteristics of Wavelength Pairs

Consider a case where the absorption of light by absorbers other than hemoglobin is negligible, equation (1) can be simplified as:

$$\mu_a = \mu_{(Hb)} f_B \,. \quad (4)$$

Assuming under a certain S_tO_2 condition, a wavelength pair has their absorptivity shown in equation (2) related as followed:

$$\mu_{a(Hb)}(\lambda_1) = \mu_{a(Hb)}(\lambda_2) \quad (5)$$

where the subscript represents the wavelength index. These wavelengths may not necessarily be an isosbestic pair. Substituting equation (2) into equation (5) and solving for S_tO_2 gives

$$S_t O_2 = \frac{\mu_{a(dHb)}(\lambda_1) - \mu_{a(dHb)}(\lambda_2)}{\Delta\mu_{a(\Delta Hb)}(\lambda_2) - \Delta\mu_{a(\Delta Hb)}(\lambda_1)} \,. \quad (6)$$

Equation (6) shows that the S_tO_2 value can be predicted using the absorptivity data of a wavelength pair that satisfied the condition in equation (5). If the light attenuation is given from light absorbing medium where

the Lambert Beer law holds, the related wavelength pair can be determined by identifying wavelengths that produce the same light attenuation, $A(\lambda_1) = A(\lambda_1)$.

In practice the prediction of S_tO_2 value using equation (6) is not straightforward when wavelength-dependent scattering is introduced into the medium. This is because the effects of light scattering on light attenuation would intertwine with that of the absorption to give a nonlinear change in light attenuation with both absorption and scattering events. Since the wavelength dependent μ'_s varied relatively inversely linear with the wavelength as shown in Fig. 1 (bottom), it approximately modified wavelength dependent light attenuation in an inverse linear relationship manner. Therefore, it is reasonable to assume that under a certain S_tO_2 condition, all wavelength pairs that satisfied equation (5) would produce the same attenuation gradient value calculated from light attenuation versus wavelength plot. Further description of this technique can be found in [10].

2.2.1 Binning of wavelength pairs and the prediction of skin oxygen level

In the efforts to identify all wavelength pairs potentially used in the prediction of S_tO_2 value, different combinations of wavelength pairs were attempted in preprocessing stage in the calculation of the S_tO_2 based on the hemoglobin absorptivity value as given in equation (6). This study considered only wavelengths from the wavelength range of 510 nm- 590 nm owing to the significant differences in the hemoglobin absorption signatures. Wavelength pairs that give percent S_tO_2 in the range of 0 % to 100 % were stored and binned with the bin size of 0.5 %. The wavelength pairs that give invalid S_tO_2 value (i.e. not between 0 % and 100 %) were removed. This work considered hemoglobin absorption spectra in Fig. 1 (top) with sampling resolution of 0.4 nm and 0.2 nm. This is in agreement with that normally found in the market available light detection devices.

3. Results

An overall of 107,825 and 6,714 pairs of wavelength were found from the considered wavelength range of 510 nm – 590 nm. These wavelength pairs give the S_tO_2 value ranging in between 0 % and 100 % from equation (5) using hemoglobin absorption spectra with sampling resolution of 0.2 nm and 0.4 nm, respectively. An example of the wavelength pairs that satisfied the condition in equation (5), say for S_tO_2 of 80 %, are 551 nm and 582 nm, and 532 nm and 554 nm, respectively, using the spectra sampling intervals of 0.2 nm and 0.4 nm.

Shown in Fig. 2 is the absolute error in the predicted S_tO_2 when different sampling intervals were being used. The S_tO_2 value used in the generation of Monte Carlo simulated attenuation data is shown in the *x*-axis. The S_tO_2 values estimated using the attenuation spectra with the interval of 0.4 nm showed a mean absolute error of around 2 %, whereas a slight decrease in mean absolute error of 1.5 % were found for sampling interval of 0.2 nm.

4. Discussion

The results in Fig. 2 revealed reasonably accurate S_tO_2 value predicted based on the analysis of light attenuation gradient of preprocessing stored wavelength pairs. This study found no significant difference in the mean absolute error in the predicted value using the considered spectral sampling resolutions.

There are several reasons for the error in the predicted value in Fig. 2. First, by referring to Fig. 1 (top) the absorption of light by melanin is significant and it varied across the considered working range of wavelengths. Since the S_tO_2 in equation (6) is derived based on the assumption that the absorption of light by absorbers other than hemoglobin is negligible, this placed a significant impact on the overall performance of the predicted S_tO_2. The accuracy of the estimated values can, therefore, be improved if volume fraction of melanin, f_M is less than that listed in Table 1. This yielded the absorption induced changes in the light attenuation predominantly due to the variation in the S_tO_2 level.

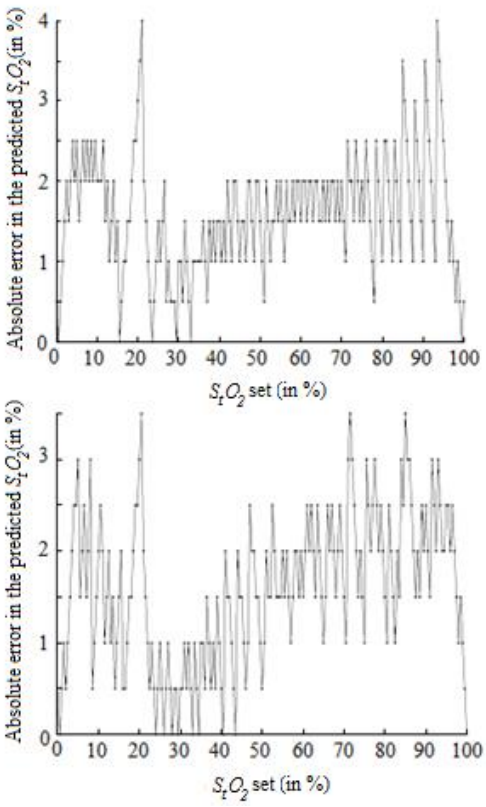

Fig. 2: The percent absolute error in the predicted value against the actual S_tO_2 value using spectral sampling intervals of (top) 0.2 nm and (bottom) 0.4 nm.

In addition, the assumption that wavelength pairs in a bin with the most probable S_tO_2 value would produce the same attenuation gradient value is not strictly true. This is because the light attenuation value is a complex function of light scattering and absorption; this rendered the gradient value influenced not only by μ_a but also the wavelength varying μ'_s. These discrepancies may be

minimized with the use of an increased spectral sampling point at the price of a longer computing time.

It must also be mentioned that other factors that may affect the accuracy of the predicted S_tO_2 is the presence of noise in the processed signals. A small noise-induced change in the light attenuation data of a wavelength pair, amongst all other wavelength pairs in the same bin, would affect the gradient distribution width of the corresponding bin, and hence introduced error in the predicted values. Therefore, it is important to have a large amount of stored wavelength pairs to reduce the effects of noise-affected outliers in the analysis. Practically, many ways are also available to minimize the effect of noise in the system such as with the use of a constant current light source and a cooled detector in the system or via signal averaging or with the use of a longer detection integration time.

The results shown in Fig. 2 revealed the ability of the proposed technique to produce a reasonably good performance in the prediction of S_tO_2 as compared to the modern pulse oximeters which good performance is limited to $S_aO_2 > 70\%$. Further work involved applying this technique on human subjects to predict their skin oxygen status.

5. Conclusion

This work established a new empirical method to determine one's S_tO_2 based on the analysis of the light attenuation gradient characteristics of the preprocessing stored wavelength pairs. The performance of this technique was evaluated for wavelengths in the range of 510 nm to 590 nm. The results showed relatively consistent and considerably good accuracy in the predicted S_tO_2 with the absolute mean error of 1.5 % and 2 % using the chosen spectral sampling intervals of 0.2 nm and 0.4 nm, respectively. This method did not require any calibration data and it may also be used for other applications and in industries such as food preparation and processing, and pharmaceutical industry to estimate the fractional concentration of a present absorber.

References

[1] Dutta, S. D., and Maria, R. Pulse Oximetry: A New Tool in Pulpal Vitality Testing. *People's Journal of Scientific Research*, volume 6 (2013), pp. 49 – 52.

[2] Huong, A., and Ngu, X. Quantitative analysis of spectroscopy data for skin oximetry. *Proceedings of the 3rd International Conference on Biomedical and Bioinformatics* Engineering, (2016), pp. 46-49.

[3] Twersky, V. Interface effects in multiple scattering by large, low-refracting, absorbing particles. *Journal of the Optical Society of America*, volume 60, (1970), pp. 908-914.

[4] Pittman R.N., and Duling B.R. A new method for the measurement of percent oxyhemoglobin. *Journal of Applied Physiology*, volume 38, (1975), pp. 315–320.

[5] Denstedt, M., Pukstad, B. S., Paluchowski, L. A., Hernandez-Palacios, J. E., and Randeberg, L. L. Hyperspectral imaging as a diagnostic tool for chronic skin ulcers. *SPIE BiOS International Society for Optics and Photonics*, volume 8565, (2013), pp. 85650N-1-85650N-14.

[6] Huong, A.K.C., Stockford, I.M., Crowe, J.A., and Morgan, S.P. Investigation of optimum wavelengths for oximetry. *Proceedings of SPIE-OSA Biomedical Optics*, volume 7368, (2009), pp. 736811.

[7] Kashani, A. H., Jaime, G. R. L., Saati, S., Martin, G., Varma, R., and Humayun, M. S. Non-invasive Assessment of Retinal Vascular Oxygen Content Among Normal and Diabetic Human Subjects: A Study Using Hyperspectral Computed Tomographic Imaging Spectroscopy. *Retina*, volume 34, (2014), pp. 1854-1860.

[8] Huong, A., Philimon, S., and Ngu, X. Multispectral Imaging of Acute Wound Tissue Oxygenation. *Journal of Innovative Optical Health Sciences*, volume 10, (2017), pp. 17500041-8.

[9] Zhang, R., Verkruysse, W., Choi, B., Viator, J. A., Jung, B., Svaasand, L. O., Aguilar, G., and Nelson. J. S. Determination of human skin optical properties from spectrophotometric measurements based on optimization by genetic algorithms. *Journal of biomedical optics*, volume 10, (2005), pp. 024030 – 02403011.

[10] Huong, A.K.C. Spectroscopy Analysis of Scattering Media via Different Quantification Techniques. University of Nottingham: Thesis, (2012).