Optical investigation of variability in body region dependent transcutaneous oxygen saturation

Sheena P Philimon, Audrey K C Huong, W M Hafizah, P E Ong, and Xavier T I Ngu

Faculty of Electrical and Electronic Engineering
Universiti Tun Hussein Onn Malaysia

E-mail: audrey@uthm.edu.my

Abstract. This paper presents the use of multispectral imaging system to investigate variability in transcutaneous oxygen saturation ($S_tO_2$) amongst different individuals and at different skin sites. Noncontact reflectance data are collected from central forehead, posterior forearm, thenar region of palm and proximal ankle of three healthy Asians. The prediction of the required $S_tO_2$ value is via fitting Extended Modified Lambert (EMLB) model to the measured attenuation data using extinction coefficient of hemoglobin components in the wavelength range of 520 - 600 nm as its priori knowledge. The obtained results revealed a relatively high mean $S_tO_2$ of 54 ± 1.9% at the palm of the hand site. This is followed by measurement at foot ankle and forehead with $S_tO_2$ of 52.3 ± 2.4% and 51.2 ± 7.7%, respectively. Meanwhile the lowest reading of $S_tO_2$ of 48.8 ± 5.1% is observed at the posterior forearm. Based on these findings, this work concluded that palm of the hand would provide considerably consistent measurement of $S_tO_2$ among individuals. This is largely owing to the higher density of circulatory anastomosis at this skin site. This implied viability of using the developed strategy in the studies of microcirculation mechanism especially on wound at this skin region.

1. Introduction

The in-vivo study of tissue oxygenation status has been a subject of interest in recent years especially in the biomedical field. The common method of obtaining the oxygen saturation level is by clinically available pulse oximeter. The use of this technique is limited to certain body parts such as fingertip or earlobe; therefore the application of this device is deemed unsuitable for wound assessment and skin graft. Furthermore, the accuracy of pulse oximeter is still a subject of dispute as false positive reading was reported in cases of blocked microcirculatory or patients diagnosed with carbon monoxide poisoning [1]. Although blood gas analyzer is well known for its accuracy, this device requires drawing of blood samples from radial artery. To this end, a noninvasive and accurate prediction of mean blood oxygen saturation is highly sought after. Optical reflectance spectroscopy has been widely used to provide reflected intensity signals required in the estimation of oxygen saturation using analytical models such as Modified Lambert Beer law (MLBL) [2], Extended Modified Lambert Beer (EMLB) model [3], cumulant based forward model (CM) [4], power law model [5] and cubic law model [6]. This is owing to the noninvasive and noncontact attributes of the corresponding technique that allows measurement of reflectance data to be taken from any parts of the body.

In the recent work by Philimon et al. [7], multispectral imaging system was used in the comparison work on $S_tO_2$ value predicted for fingertips of the recruited volunteers with that presented in the
literatures. There, however, remains a need for further research on differences in $S_tO_2$ at body parts with varying skin thickness, and variability of this parameter amongst individuals. This work is important in determining viability of the recruited strategy in the studies of tissue microcirculation system, wherein consistent $S_tO_2$ independent of individuals is desirable. The aim of this study is to investigate differences in $S_tO_2$ at different skin site using multispectral imaging system. This paper is arranged as followed: The employed system and strategy used in the prediction of $S_tO_2$ is presented in section 2. This is followed by results and discussion in section 3. The conclusion of the findings of this work is in section 4.

2. Materials and method

2.1. Experiment system and data pre-processing

Shown in figure 1 is the employed multispectral imaging system. Multispectral intensity data reflected from targeted skin sites are detected by a charge-coupled device (CCD) camera (Bestscope BUC4-500C Cooled CCD camera). The measurement is in the reflection mode. A high intensity light emitting diode (LED) (XLamp X-QE LED from Cree) is shone through a monochromator (Oriel Mini Monochromator model 78026 from Newport); the latter is tuned across the wavelength range of 520 - 600 nm with a sampling step of 10 nm to illuminate the selected skin region. The imager was placed at normal and 170 mm from skin sample. This device is located at an angle of approximately 45° from the source. This system is mounted on an optical breadboard for better portability and mobility.

![Multispectral imaging system](image)

**Figure 1.** Multispectral imaging system.

The attenuation data is used in the prediction of the required oxygen saturation parameter owing to the variability in the light intensity output of the monochromator at different wavelength. For this purpose, white reference data is taken, this is given by the reflected signals of spectralon (from Labsphere, Inc.) with 99% reflectance. Meanwhile correction of multispectral images for dark noise is by subtracting the corresponding data with dark reference. The latter was obtained by covering the CCD window with a shutter cap. The measured light attenuation at a specific wavelength, $\lambda$, is calculated as:
\[ A_{corr}(\lambda) = \frac{I_{\text{white}}(\lambda) - I_{\text{dark}}(\lambda)}{I_{\text{sample}}(\lambda) - I_{\text{dark}}(\lambda)} \]  

(1)

where \( I_{\text{sample}} \), \( I_{\text{white}} \) and \( I_{\text{dark}} \) are reflected light intensity from skin sample, white and dark standard, respectively. The measured intensity reflected from the skin sample, \( I_{\text{sample}} \), is presumed to carry information on mean transcutaneous oxygen saturation, \( S_{\text{tO}_2} \), across arteries, veins and capillaries.

2.2. Experimental subjects

This study recruited three Asian volunteers consisted of both male and female (age 25 - 27). Prior to the experiment, all volunteers gave their written informed consent. These volunteers declared to be healthy nonsmoking subjects with no underlying illnesses. Volunteers were first acclimatized to room temperature set at 24°C for at least 15 minutes before measurement is taken. They were instructed to position the selected body part in front of the CCD camera while multispectral data are acquired from the targeted skin region. This work selected central forehead, posterior forearm, thenar region of palm and proximal ankle as the measurement sites.

2.3. Extended Modified Lambert Beer model and iterative fitting procedure

In this work, the estimation of percent \( S_{\text{tO}_2} \) is via the EMLB model proposed by Huong and Ngu [3] shown in equation (2). This model was extended from the MLBL law and was complemented by the third and fourth term in the equation. This model offered a nonlinear approximation of light attenuation value, \( A \), versus absorption coefficient, \( \mu_a \), of a medium.

\[ A(\lambda) = G_0 + \mu_a d_0 + G_1 \lambda + \lambda \exp(-\mu_a d_1). \]  

(2)

Given that \( \text{HbO}_2 \) and \( \text{Hb} \) are the only absorbers present, \( \mu_a \), can be written as the sum of product of concentration, \( C \), and wavelength dependent extinction coefficient of present absorbers, \( \varepsilon_{\text{HbO}_2} \) and \( \varepsilon_{\text{Hb}} \), expressed as followed:

\[ \mu_a(\lambda) = \varepsilon_{\text{HbO}_2}(\lambda) C_{\text{HbO}_2} + \varepsilon_{\text{Hb}}(\lambda) C_{\text{Hb}}. \]  

(3)

The light absorption, \( \mu_a \), used in this work is given from the extinction coefficient of \( \text{HbO}_2 \) and \( \text{Hb} \) in the wavelength range of 520 – 600 nm taken from [8]. This is considering the distinctive differences in the absorption of hemoglobin derivatives within this wavelength range shown in figure 2.

Since \( \text{HbO}_2 \) and \( \text{Hb} \) are considered as light absorbers in dermis layer, the total hemoglobin concentration is expressed as \( T = C_{\text{HbO}_2} + C_{\text{Hb}} \). Meanwhile, \( S_{\text{tO}_2} \) is given by the ratio of oxyhemoglobin concentration to the total hemoglobin concentration as followed:

\[ S_{\text{tO}_2} = \frac{C_{\text{HbO}_2}}{T}. \]  

(4)
The estimation of \( S_tO_2 \) is via an iterative fitting routine developed in MATLAB. This fitting algorithm used \texttt{fminsearch} function to find the optimum value of the unknown parameters in equation 2 (i.e. \( S_tO_2, G_0, d_0T, G_1 \) and \( d_1T \)) based on the size of error, \( \Delta E \), between the value given from the EMLB model and the calculated attenuation described in section 2.1. This fitting process began by initializing all the unknowns with value ‘1’, the process was terminated when either the absolute mean \( \Delta E \) is less than \( 1 \times 10^{-20} \) or the number of iteration has reached 1000 when the optimum \( S_tO_2 \) value is assumed to have been obtained.

### 3. Results and discussion

The image of skin locations and the corresponding calculated \( S_tO_2 \) map for volunteer A shown in table 1 is used here as an example to illustrate the predicted oxygen saturation mapping at each selected site. Spectroscopic data were collected from four different parts of the body: central forehead, posterior forearm, thenar region of palm and proximal ankle. Based on the \( S_tO_2 \) map, the calculated mean \( S_tO_2 \) for the three volunteers, identified as Subjects A, B and C, are presented in table 2. Also shown in table 2 are the calculated mean, \( \mu \), and standard deviation, \( \sigma \), of these values among individuals at each skin site.

#### Table 1. The skin location images and the calculated \( S_tO_2 \) map of volunteer A.

| Skin location | \( S_tO_2 \) map |
|---------------|------------------|
| Central forehead | ![Image](image-url) |
Table 2. Mean and standard deviation (µ ± σ) of mean S\textsubscript{T}O\textsubscript{2} of different skin site for each individual (referred to as A, B and C).

| Subject | Central forehead | Posterior forearm | Thenar of palm | Proximal ankle |
|---------|------------------|-------------------|----------------|---------------|
| A       | 42.3%            | 43.9%             | 53.5%          | 51.2%         |
| B       | 55.7%            | 54.1%             | 56%            | 55.1%         |
| C       | 55.5%            | 48.4%             | 52.2%          | 50.7%         |
| µ ± σ   | 51.2 ± 7.7%      | 48.8 ± 5.1%       | 54 ± 1.9%      | 52.3 ± 2.4%   |

The results shown in table 1 and table 2 revealed variability in S\textsubscript{T}O\textsubscript{2} depending on individuals and skin sites. This work observed a considerably consistent and higher S\textsubscript{T}O\textsubscript{2} of 54 ± 1.9% at the palm area followed by proximal ankle with the calculated value given by 52.3 ± 2.4%. The S\textsubscript{T}O\textsubscript{2} readings for both central forehead and posterior forearm fluctuated with the recruited individuals, likely arises from differences in their skin thickness. Meanwhile the measurement on all these volunteers revealed the lowest S\textsubscript{T}O\textsubscript{2} with mean and standard deviation of 48.8 ± 5.1% at the posterior forearm. It must also be mentioned that an overall lower average mean and standard deviation of S\textsubscript{T}O\textsubscript{2} reading of 51.6 ± 4.3% is observed in this work compared to 75 ± 5% in Philimon et al. [7]. This previous related work was conducted on fingertips where arteriovenous anastomoses (AVAs) can be found in abundance. The AVAs system provides direct connection between arteries and vein, and serves to produce shunting of arterial blood into the venous compartment without passing through the capillaries [9]. This rendered significant changes in S\textsubscript{T}O\textsubscript{2} with external intervention and higher S\textsubscript{T}O\textsubscript{2} at rest condition compared to other skin sites.

This observation in the trend of S\textsubscript{T}O\textsubscript{2} in table 2 is supported by Caspary et. al [10] who also showed differences in oxygen saturation between proximal and distal skin sites. In addition, Thorn et. al [11]
suggested the variation in $S_tO_2$ at different skin sites could possibly be contributed by differences in cutaneous blood flow that affects the washout of deoxyhemoglobin. High cutaneous blood flow at the acral skin site such as palm of the hand would increase the washout of Hb and account for high $S_tO_2$. Otherwise is true for low $S_tO_2$. It must also be mentioned that there were also extensive studies on the correlation between skin oxygenation and blood flow, with body temperature and emotions being identified as influence factors [12].

This study demonstrated the feasibility of using the developed technique to detect differences in one's $S_tO_2$ with the varying skin site. The predicted value shown in table 2 is considerably consistent amongst the recruited individuals for measurement on palm of the hand. This is likely due to the denser circulatory anatomoses in this site. This implies that the employed strategy could potentially be adopted in the future research studies on one’s microcirculatory structure specifically at the hand palm. This can be useful in the research of wound healing mechanisms for injury inflicted on this skin site.

4. Conclusion
This paper concluded that the employed EMLB model and developed multispectral imaging system can be used to provide reliable information on tissue oxygenation status at palm of the hand. This is following the ability of the system to predict considerably consistent $S_tO_2$ at this skin site compared to other skin region of the recruited subjects. The preliminary findings from this work suggested the possible application of this system to monitor changes in tissue oxygenation of wound on acral sites.

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