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Research paper

A Handheld Technology for Optical Monitoring of Transcutaneous Blood Oxygen Saturation

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Abstract

This paper presents the use of a handheld technology for noninvasive prediction of one's transcutaneous blood oxygen saturation, S_tO_2, via an in-house developed skin oxygenation system. The quantification strategy involved the use of wavelength dependent Modified Lambert Beer law and is based on light signals of wavelengths 532 nm, 560 nm and 650 nm reflected from the selected skin site. This study performed at rest and arterial blood occlusion experiment on left palm of the hand of five healthy Asian volunteers to evaluate the performance of the system and to verify the validity of the predicted results. The preliminary results revealed a considerable decrease in the predicted mean percent S_tO_2 value from 63.7 ± 13.2 % for at rest condition to 52.2 ± 11.4 % after a pressure of 140 mmHg was applied on upper left arm of these recruits for 120 seconds. This work concluded that the developed optical system is able to provide comprehensive information on spatially dependent S_tO_2 and it has unlimited skin access, hence may be potentially used in field applications to assess the skin oxygen level of those in workforce whose job is at risk of exposure to poisonous gases.

Keywords: *Skin oxygen status, wavelength dependent Modified Lambert Beer, oxygen mapping.*

1. Introduction

Oxygen is one of the key parameters required for tissues metabolism to ensure life sustainability. Devices able to provide comprehensive information of tissue oxygen level are, thereof, highly sought after as this information is useful especially to aid in medical decision [2]. A single point sampling measurement of arterial blood oxygen saturation provided by commercially available pulse oximeter lacks information on spatially dependent variability in tissue oxygen level. In addition, the application of this diagnostic tool is limited to well-perfused areas, such as the fingertip, where a probe or clamp piece can be used.

The current state of art of the techniques able to provide information of spatially varying tissue oxygenation level includes the use of multispectral and hyperspectral imaging approach, which difference is in the number of wavelengths produced. The former approach produced tens of wavelengths while the latter produced hundreds. This strategy involved the collection of images of targeted skin area (limited to the field of view of the imager) illuminated by light emitter of different wavelength.

The prediction of skin tissue oxygen level is via either a library of data built up from light propagation simulation software or model, or a suitable analytic model. The selection of light beam of different wavelengths is viable with the use of either a diffraction grating or transmission filter system. These systems produce a large number of data, or known as a data cube. This placed a high demand on the system required for data acquisition and processing, hence a continuous measurement of the required blood oxygen level is not possible with these instruments. In addition, both of these imaging systems have drawbacks in terms of cost, mobility and size. Even so, these imaging systems have found its applications in a wide range of fields including noninvasive assessment of superficial wound healing progress [2] , in visualization of tumor progression [4], food quality investigation [8] and in agricultural industry [3]. It is, therefore, the objective of this work to develop a low cost and portable imaging system for measurement of transcutaneous blood oxygen saturation using light beam of three wavelengths.

2. Materials and Methods

Skin Oxygenation System and Technology. The schematic diagram of an in-house developed optical system for noninvasive and continuous measurement of one's transcutaneous blood oxygen saturation value is shown in Fig. 1. This system used light source of three wavelengths 532 nm, 560 nm, and 655 nm, respectively, for illumination. This is owing to the high variability in the light absorptivity of hemoglobin components namely oxygen-bound hemoglobin (oxyhemoglobin) and reduced hemoglobin (deoxyhemoglobin) at these
wavelengths as shown in Fig. 2. The availability of light source of wavelength 532 nm and 650 nm is limited to laser diode, therefore diffused beam from laser module is used. Meanwhile light emitting diode (part no. L560-01) is used to emit light of wavelength 560 nm. Light reflected from the selected skin region is detected by a Complementary Metal Oxide Semiconductor (CMOS) imager (part no. CW835) located at about 30 mm from the light sources. The field of view of the imager is given by 35 mm × 26 mm. Both light sources and the imager were positioned at a distance of 35 mm from the measurement sites.

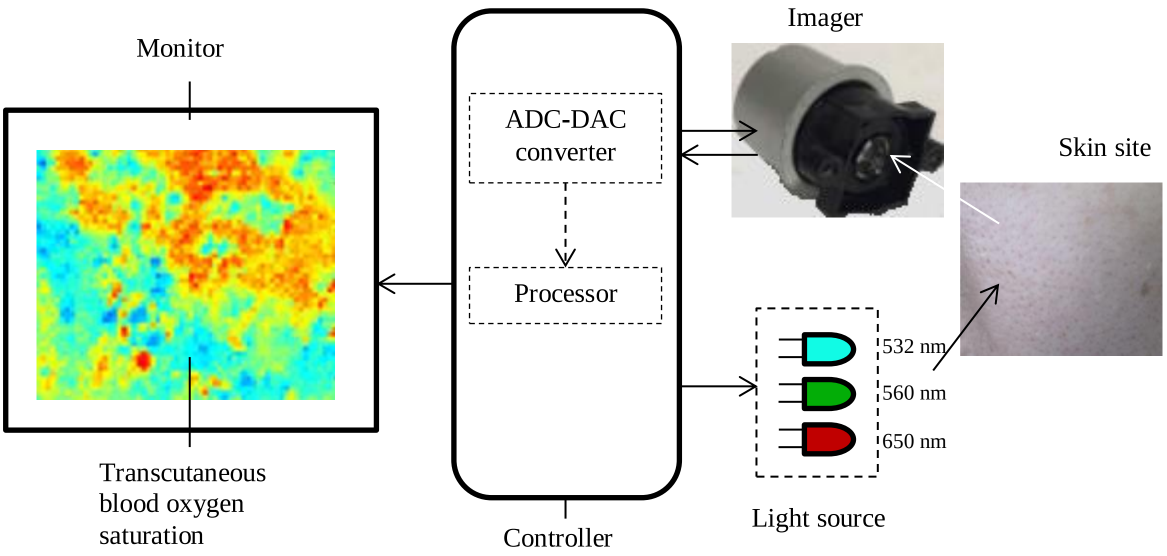


Fig.1: Schematic diagram of the developed optical system

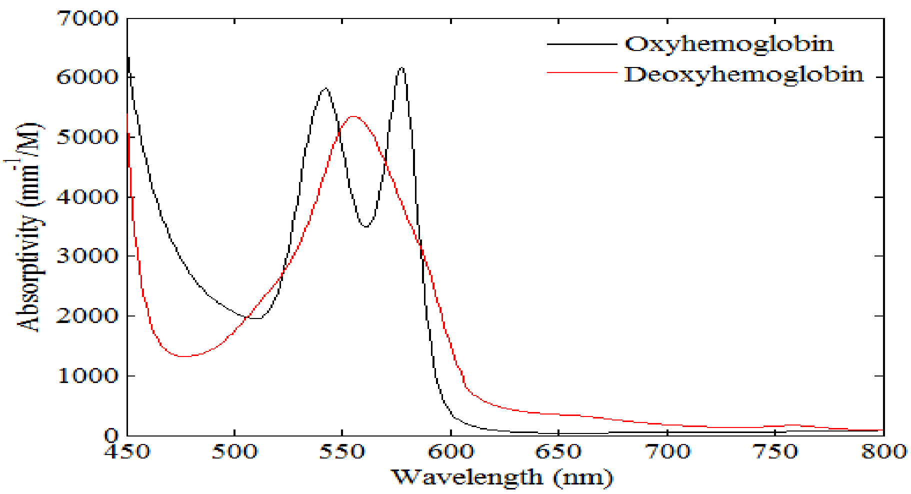


Fig. 2: Wavelength dependent absorptivity of oxyhemoglobin and deoxyhemoglobin. Data taken from Zijlstra [9]

The light sources of the selected three wavelengths shown in Fig. 1 were turned on simultaneously one at a time at a rate of 0.1 Hz to illuminate the selected skin site. The sampling and collection of the reflected signals was synchronized with the corresponding frequency, and signals detected by the imager were sent via a controller (Arduino Uno R3) to a personal computer for online processing of the acquired image using a simple coding written in MATLAB. This system does not require the use of a clamp piece or probe, so its application is not limited to a certain body part.

Experimental subjects and procedures. This study recruited five Asian volunteers (aged between 20 and 28 years) for the demonstration work. The volunteers were briefed on the experimental procedure and their written informed consent was collected prior to the experiment. This work measured light reflected from thenar region of left palm of the hand of these volunteers. Two modes of experiment were conducted to evaluate the performance of the developed system they are namely: at rest and arterial blood occlusion experiment. This is to investigate the feasibility of the system to detect changes in one's transcutaneous blood oxygen saturation following the external intervention. For the first experiment, the recruits were rested in a sitting position with the left arm rested on a table during data collection. Meanwhile for arterial blood occlusion experiment, the upper left arm of these recruits, who were still sitting in the same posture, was wrapped using a pressure cuff and a pressure of 140 mmHg was applied for 120 seconds prior to the measurement to prevent arterial blood from flowing into the lower arm.

Forward Model. This work used a wavelength dependent modified Lambert Beer model expressed in Eq. 1 in the prediction of the required skin oxygen saturation value. This model is an extended version of modified Lambert Beer model [6] to account for wavelength dependent variation in the scattering coefficient in skin. The relationship between wavelength dependent light absorption, $\mu_a(\lambda)$, and light attenuation, A, is as followed:

$$A(\lambda_x) = \mu_a(\lambda_x)d + K\lambda_x \quad (1)$$

where λ_x denotes wavelength index. While d is taken as light pathlength, $K\lambda$ presents linear change in the light attenuation with wavelength dependent medium's scattering coefficient in the presence of no absorber or when $\mu_a(\lambda) = 0$. In the case of an absorbing medium with only oxyhemoglobin, HbO_2, and deoxyhemoglobin, Hb, present, μ_a is related to the transcutaneous blood oxygen saturation, S_tO_2, as followed:

$$\mu_a(\lambda) = \left(\left(\varepsilon_{HbO_2}(\lambda) - \varepsilon_{Hb}(\lambda)\right) S_tO_2 + \varepsilon_{Hb}\right) T. \quad (2)$$

Here the symbol ε represents light absorptivity while its subscript denotes that of the associated absorbers. The wavelength dependent absorptivities of the considered absorbers are shown in Fig. 2. The parameter T in Eq. 2 is total blood concentration and is taken as 150 mg/L. Assuming that parameter d and K in Eq. 1 is a constant and does not vary with wavelength, solving the simultaneous equation in Eq. 1 for S_tO_2 in Eq. 2 using three wavelengths, λ_1, λ_2 and λ_3, yields:

$$S_tO_2 = \frac{A(\lambda_1)\left(\lambda_2\varepsilon_{Hb}(\lambda_3) - \lambda_3\varepsilon_{Hb}(\lambda_2)\right) + A(\lambda_2)\left(\lambda_3\varepsilon_{Hb}(\lambda_1) - \lambda_1\varepsilon_{Hb}(\lambda_3)\right) + A(\lambda_3)\left(\lambda_1\varepsilon_{Hb}(\lambda_2) - \lambda_2\varepsilon_{Hb}(\lambda_1)\right)}{A(\lambda_1)\left(\lambda_3\Delta\varepsilon(\lambda_2) - \lambda_2\Delta\varepsilon(\lambda_3)\right) + A(\lambda_2)\left(\lambda_1\Delta\varepsilon(\lambda_3) - \lambda_3\Delta\varepsilon(\lambda_1)\right) + A(\lambda_3)\left(\lambda_2\Delta\varepsilon(\lambda_1) - \lambda_1\Delta\varepsilon(\lambda_2)\right)} \quad (3)$$

where $\Delta\varepsilon(\lambda_x)$ represents the differences between $\varepsilon_{HbO2}(\lambda_x)$ and $\varepsilon_{Hb}(\lambda_x)$.

3. Results

The S_tO_2 map of the left palm of the recruited volunteers (indicated as subject index A – E) predicted using the wavelength dependent Modified Lambert Beer model for at rest and arterial blood occlusion experiment is shown in Table 1. Also shown in Table 1 is the image of the corresponding skin site and the S_tO_2 value averaged from the S_tO_2 map, $\langle S_tO_2 \rangle$. The colorbar shown in Table 1 indicated the S_tO_2 level in %. The overall mean and standard deviation of $\langle S_tO_2 \rangle$ for the recruits is calculated as 63.7 ± 13.2 % and 52.2 ± 11.4 % for at rest and blood occlusion, respectively.

4. Discussion

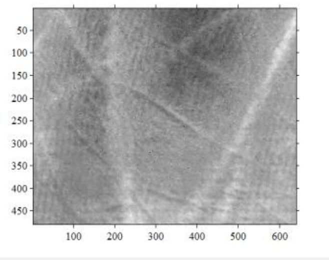
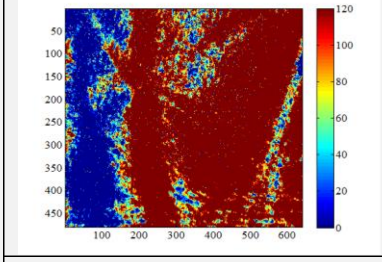
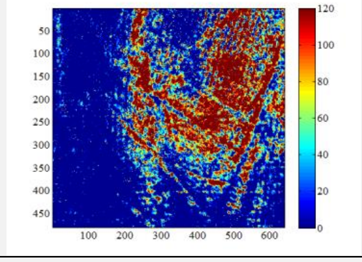
The results shown in Table 1 revealed changes in one's S_tO_2 following the external invention that modified the microcirculatory activities of the investigated skin site. Unlike the measurement of oxygen saturation of pulsatile arterial blood using clinically available pulse oximeter, non-pulsatile signals that carry useful information on transcutaneous blood oxygen saturation was measured in this study. Since the employed light of wavelengths 532 nm, 560 nm, and 655 nm probed at a depth of no more than 550 µm below skin surface [7], its light path encompassed networks of capillaries, arteries and veins, and the measured S_tO_2 was taken as the averaged of oxygen saturation of these blood vessels. Therefore the predicted S_tO_2 in the range of 60 - 80 % is agreeable with the results in [1] and [5], which works revealed the variation in this value depending on the selected skin site. This is in contrary to the arterial blood oxygen saturation value of 98 - 100% measured using pulse oximeter from fingertip of a healthy individual.

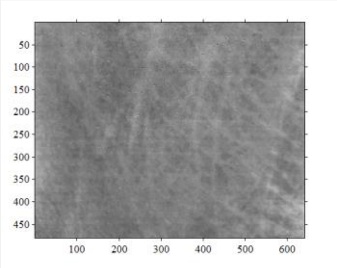
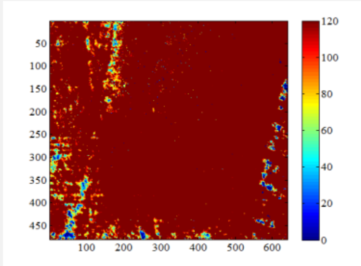
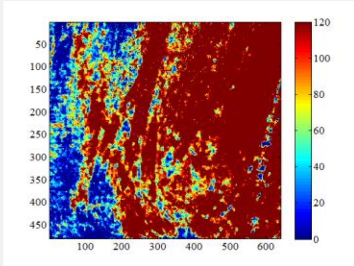
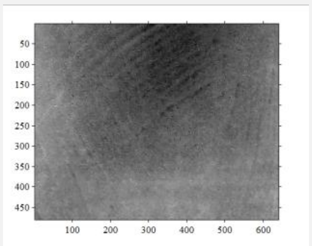
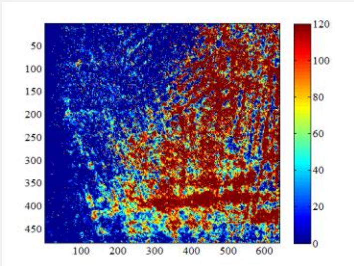
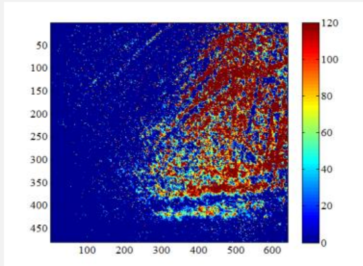
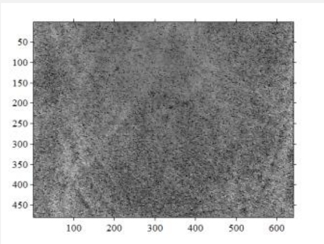
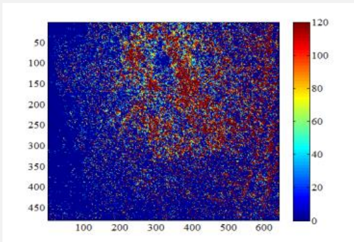
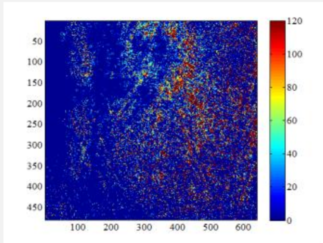
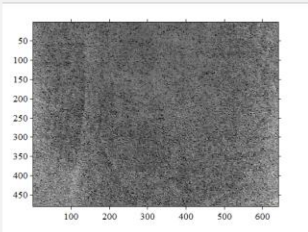
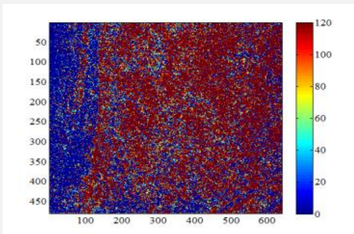
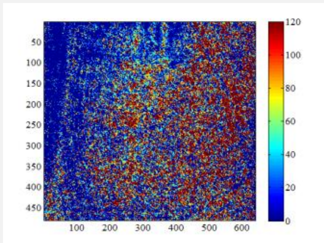
Table 1 showed an overall high S_tO_2 level, wherein most of the regions in S_tO_2 map in the hue of red color can be observed for all the five recruits for at rest condition. Most of these red colored regions were replaced by cool colors following the arterial blood occlusion procedure for 120 seconds. This suggested that the S_tO_2 of the local tissues revealed signs of oxygen deprivation under this condition. These changes in the S_tO_2 are evident in the calculated $\langle S_tO_2 \rangle$, wherein the overall mean of $\langle S_tO_2 \rangle$ showed a significant drop of 11.5 % in its value following the block of the arterial blood flow to the investigated site.

It must be mentioned that large variability of 13.2 % and 11.4 %, respectively, in the S_tO_2 value predicted for at rest and arterial blood occlusion experiment among the recruits is largely due to the differences in the skin thickness and skin melanin concentration of these individuals. In addition, the variation in health status, gender and nutritional level of each individual is among the other factors that would affect the S_tO_2 readings.

This work demonstrated the use of simultaneous solution of the model in Eq. 1 in the prediction of the required S_tO_2 parameter. This technique has comparatively fast computation time as compared to that of the fitting technique demonstrated in other related work [2]. The significant changes in the estimated S_tO_2 shown in Table 1 following interruption of local microcirculatory activities may imply that the proposed model can suitable be used to represent light propagation behavior in a scattering-absorbing medium.

Table 1: Skin image and S_tO_2 map predicted for at rest and arterial blood occlusion condition for the recruited individuals. The mean S_tO_2, $\langle S_tO_2 \rangle$, averaged from the associated S_tO_2 map.

Subject Index	Skin Image	At rest condition	Arterial blood occlusion
A			
		$\langle S_tO_2 \rangle$ = 66.3 %	$\langle S_tO_2 \rangle$ = 45.1 %

B			
		$\langle S_tO_2 \rangle$ = 85 %	$\langle S_tO_2 \rangle$ = 71.8 %
C			
		$\langle S_tO_2 \rangle$ = 53.1 %	$\langle S_tO_2 \rangle$ = 46.9 %
D			
		$\langle S_tO_2 \rangle$ = 52.6 %	$\langle S_tO_2 \rangle$ = 44.5 %
E			
		$\langle S_tO_2 \rangle$ = 61.5 %	$\langle S_tO_2 \rangle$ = 52.8 %

5. Conclusion

This study showed differences in the predicted mean S_tO_2 using the developed handheld optical system. This suggested the potential of the proposed technology and system to detect variation in one's S_tO_2 following local hemodynamic changes. In addition to the comprehensive information on spatially varying S_tO_2 of the imaged skin site, this system has noninvasive and high portability features; it can possibly be used in clinical settings or field applications to monitor one's transcutaneous oxygen saturation level. This is beneficial to groups in workforce such as firefighters and plant workers, whose work is at risk of exposure to poisonous gases such as carbon monoxide gas.

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