Investigating optical path in reflectance pulse oximetry using a multilayer Monte Carlo model

S. Chatterjee, J. P. Phillips, P. A. Kyriacou
Research Centre for Biomedical Engineering, City, University of London, Northampton Square, London EC1V0HB, UK
e-mail: subhasri.chatterjee.1@city.ac.uk

Abstract: Despite the wide clinical uses of pulse-oximetry, the precise nature of the light-tissue interaction underneath the technique is not clearly understood. A heterogeneous opto-anatomical model is presented to describe the optical path in pulse oximetry.

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1. Introduction

Pulse oximetry is a photometric method for measurement of blood oxygen saturation from photoplethysmographic (PPG) signals. Since past several decades, there has been a tremendous advancement in technology that has made pulse oximetry a standard of care in anesthesia and related medical specialties. Although a significant amount of work has been carried out in recent years [1] for improving the technicalities regarding pulse oximetry, no much research works can be found analyzing the basic light-tissue interactions underlying the measurement system. The limitations of the method with regard to its accuracy in low oxygen saturation is well documented but partly resolved. There is lack of detailed knowledge about the optical path in pulse oximetry, which is essential in order to optimize the positioning and geometry of pulse oximetry probes. To address such problems, a Monte Carlo technique based opto-anatomical was developed to investigate the optical path and its dependence on source-detector separations and blood oxygen saturations.

Monte Carlo is a well-known computational method to solve the problems regarding tissue-optics which are very difficult to solve analytically [2]. The efficiency of a single layer Monte Carlo model to describe the optical path and its dependence on blood volume and oxygen saturation is already shown in our previous work [3]. However, considering highly heterogeneous architecture of tissue, a monolayer model is not sufficient to describe the actual scenario, so a tissue model that resembles the multilayer skin tissue is presented in this work. Also, considering the difference in tissue blood volume during diastole and systole, a more rigorous model including the pulsatality was necessary. In present work, a multilayer pulsatile Monte was executed Carlo model in a reflectance mode pulse oximetry geometry at two most commonly used pulse oximetry wavelengths, 660 nm (red) and 940 nm (infrared).

2. Method

Monte Carlo is a stochastic method to simulate propagation of photons through absorbing and scattering medium. The propagation medium, i.e., biological tissue is characterized by its absorption coefficient μ_a, scattering coefficient μ_s and anisotropy factor g, which are specific to the operating optical wavelengths. The basic algorithm to simulate photon path through biological tissues have been explicitly described elsewhere [4]. The basic algorithm used in this work is presented in Fig. 1(a). The model was executed in a reflectance mode geometry as shown in Fig. 1(b), the details of which were described in our previous work [2].

Table 1 : Skin tissue sublayers

Sublayers	Thickness (mm)	Diastolic Blood volume (%)
Epidermis	0.1	0
Dermis	0.2	0.04
Papillary plexus	0.2	0.3
Dermis	0.9	0.04
Cutaneous plexus	0.6	0.2
Subdermal fat	1	0.05

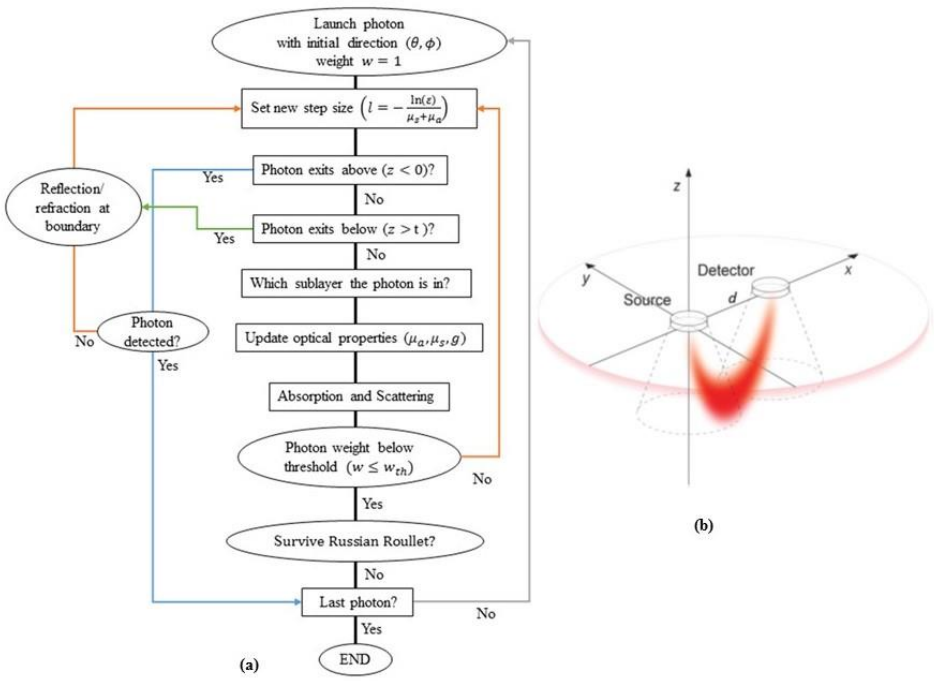

Fig.1. A basic flowchart for photon packet propagation in a biological tissue medium of thickness *t* is presented (a). A schematic is presented in (b) how light (red patch) would travel from source to detector, separated by a distance *d*. The reflectance geometry is presented in a 3D Cartesian co-ordinate system.

A multilayer skin tissue model was used in this work. The skin sublayers, their optical properties and ratio of thicknesses were found from several literatures [2,5,6]. The skin tissue consists of six sublayers, as given in Table 1. The systole was achieved by increasing the blood volume in the cutaneous plexus layer by fraction 0.2, since this sublayer only contributes in pulsatile flow and the rest contribute mainly to non-pulsatile blood flow [7]. The arterial and venous blood volume was considered to be equal, i.e., 50% of the total blood volume in each layer. Venous oxygen saturation was considered to be 10% lesser than the arterial oxygen saturation of blood. Epidermal sublayer was considered to contain 10% melanin. The optical properties of blood were characterized by the combined absorption and scattering coefficients of oxyhemoglobin and deoxyhemoglobin.

The model was executed at wavelengths 660 nm and 940 nm to record the mean optical path of photons at a range of arterial oxygen saturation 10-100% for different source detector separations within 1 cm. Photon packets with initial weight ($w=1$) and direction (scattering angle=θ, azimuth=ϕ) were supposed to be incident from the source. Incidence of Gaussian beam of radius 1 mm was simulated. The detector was supposed to have a radius of 1 mm with a numerical aperture 0.39.

3. Results and discussion

Mean optical path in red and infrared light for different source-detector separations are shown for different oxygen saturations in Fig.2. The optical paths show significant differences and those differences also change with oxygen saturation. It contradicts with the fundamental concept behind pulse-oximetry theory, where normally it is considered that red and infrared light follow the same path. According to Fig. 2(a-h), both in systolic and diastolic states, pulse oximetry optical pathlengths show different values; infrared light tending to cover longer path than red for lower arterial oxygen saturations and gradually the red pathlength increases over the infrared pathlength for higher arterial oxygen saturations. For $SaO_2 = 80\%$, red and infrared pathlength are almost similar in both systole and diastole. For a more quantified analysis, an example of the percentage difference in red and infrared mean optical path (MOP) with source-detector separations at a certain saturation 60% is illustrated in Fig.2(i). It clearly shows that systolic pathelength difference in higher than diastolic pathlength difference. The increasing difference in optical path with increasing source-detector separation is apparent. Therefore, the normal assumption that red and infrared light would traverse the similar path during pulse oximetry is invalid. At these two wavelengths, light actually interrogates with different parts of the tissue.

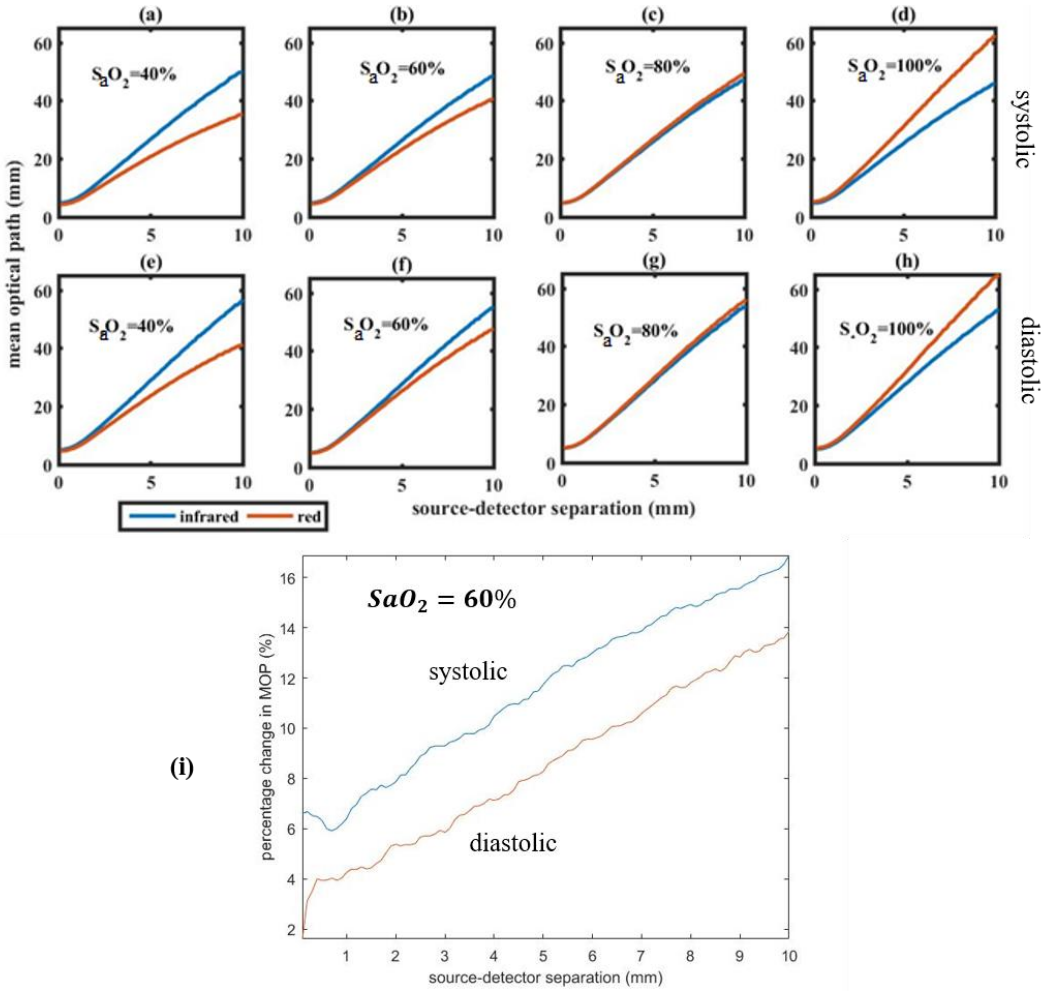

Fig.2. Relationship of mean optical path of red and infrared light with source detector separations for different arterial oxygen saturations 40%, 60%, 80% and 100% are shown for systole in (a)-(d) and for diastole in (e)-(h) respectively. As an example, the percentage change of mean optical path for systole and diastole at a certain $SaO_2 = 60\%$ is shown in (i).

3. Conclusion

The results indicate that oxygen saturation value greatly affects the measurement and also specifies the need for a more detailed study on the theoretical explanation of calibration algorithm. A multilayer pulsatile skin tissue model is presented here which establishes its promises for exploring further towards these problems and help the clinicians and the manufacturers to develop more precise, accurate and flexible commercial sensors.

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