Investigating the influence of blood-vessel depth and sensor location on the light-tissue interactions using a Monte Carlo model

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Abstract

A three-dimensional Monte Carlo model of light tissue interactions with a slab of fat tissue having a cylindrical blood vessel is presented. The model has been explored at an optical wavelength of 660 nm and simulations have been carried out to investigate the influence of – 1) vessel depths and b) sensor location on the associated light-tissue interactions. Such investigation will be immensely useful to design a wearable sensing technology and predicting the sensor outcomes.

Keywords: *Monte Carlo, Photoplethysmography, Scattering, Tissue optics*

1. Introduction

Monte Carlo is a well-known computational method for simulating the precise light-tissue interaction underlying a bio-optic sensing application [1]. Recent research endeavors have explored the Monte Carlo models for characterizing various sensors especially in the applications in biomedicine [2]. Monte Carlo (MC) is a stochastic process to trace the path of photons through any medium. There are several advantages of using MC as a reliable tool for computing biphotonic interactions as it can -1) incorporate any level of complexities and heterogeneities of the tissue-model, 2) provide flexibilities in terms of the sensor geometry (shape and size of the optical source and detector, and any separation distance between then), and 3) produce accurate results that have been experimentally verified [3].

In the recent age of wearable biosensor technology, often the questions raise regarding positioning of the sensor on the tissue surface [4]. The influence of a blood vessel embedded within a tissue volume on the performance of an optical sensor has never been investigated. Such an investigation to understand whether placing a sensor at different orientations with respect to the artery or the diameter of the vessel influences the sensor outcomes is of utmost importance to develop and improve the optical biosensors and predict the potential reasons for any error that might occur.

A robust MC model will be able to elucidate the light tissue interaction with a sensor with the blood vessel which is the aim of this paper. Different essential optical variables such as depth of penetration, optical path length, reflectance etc. can be simulated using such a model which will provide a comprehensive outlook on the associated light-tissue interactions. Reflectance mode sensor geometry is chosen for the simulation which is the standard geometry for a non-invasive bio-optical sensing system. Simulations are explored to investigate the effect of different blood vessel depth within tissue (i.e., 2-10 mm from the tissue surface) and

various sensor positions (i.e., sensor placed along or across the artery) on the associated light-tissue interactions.

2. Method

An in-built MC simulation algorithm has been developed for this work. The details of the steps of the simulation has been described in our previous publication [5]. The schematic representation of the sensor-tissue geometry used in the simulation is illustrated in Figure 1. A three-dimensional cubic volume of fat tissue containing a cylindrical blood vessel was considered in the model. The vessel depth was varied from 2-10 mm, with an interval of 2 mm and the vessel diameter was 3 mm. An optical sensor with a Gaussian beam source and a circular detector, each with a diameter of 1 mm were considered. The separation between the source and detector was varied from 1-12 mm with an interval of 1 mm. Simulations were carried out at an optical wavelength of 660 nm. The details of the parameters used in the model can be found from our previous publication [6].

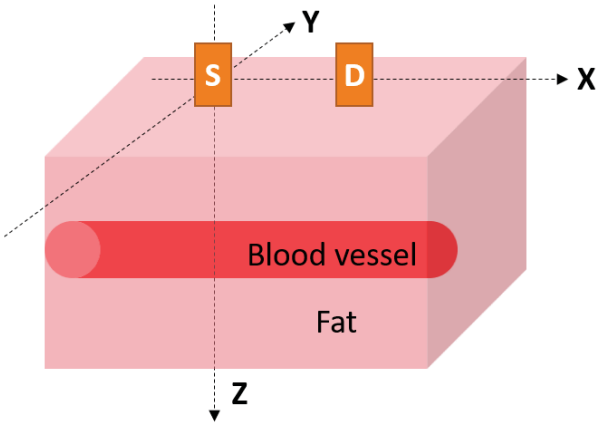

FIG 1. Schematic of the anatomical and geometrical setup for the Monte Carlo simulation. A volume of fat tissue layer having a blood vessel at a depth *d* is presented in a 3D Cartesian co-ordinate system. The optical source S is placed on the origin of the co-ordinate system and the detector D is placed at a distances from the source.

3. Results and discussion

The light-tissue interactions in the vascular tissue bed are illustrated in Figure 2. The simulated result shows an accumulation of photon packets near the source, the detector and within the blood vessel. This photon accumulation is represented by the scattering number density N, distributed between its minimum and maximum values, N_{min} and N_{max}, respectively. The reason of high scattering number density within the blood vessel is the high scattering coefficient of the arterial blood [7]. The light-tissue interaction profile shows clear changes within three geometrical setups as depicted in Figures 2 (A), (B), and (C). Mean penetration depth is higher with the probe along the artery compared to that across the artery. No significant change in the penetration depth is seen whether the source is placed on the top of the artery or 3 mm apart from that.

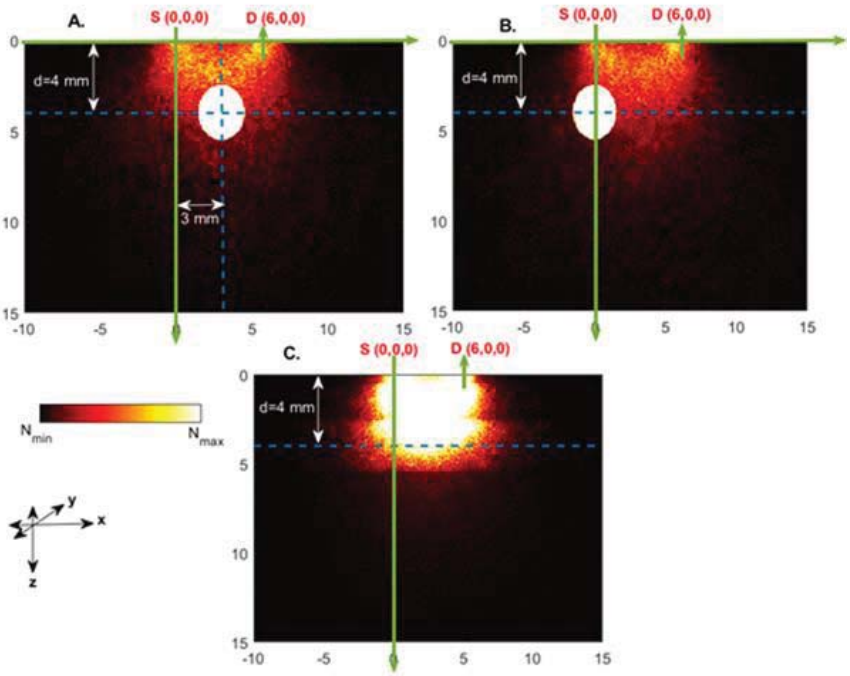

FIG. 2. Three-dimensional distribution of the photons through the fat tissue volume having an embedded cylindrical blood vessel. Above three cases represent – A) sensor placed across the vessel having a source on top of the artery, B) sensor placed across the blood vessel having a source 3 mm away from the artery, and C) sensor placed along the artery. In all cases, the blood vessel is situated at a depth of 4 mm from the tissue surface. The photon scattering density is distributed between its maximum and minimum values, N_{max} and N_{min}, respectively. Depth, thickness and width of the tissue volume are represented along the z-, x- and y-axes, respectively.

The simulated optical variables such as optical path length, penetration depth, reflectance etc. are presented in Figure 3. The details of the calculation have been discussed in our previous publication [5]. With different source-detector separations and varying vessel depth through the tissue, the variables are found to change significantly. The optical path length through the entire tissue volume tends to increase exponentially with the source-detector separation. The relative optical path length only through the blood vessel, however, behaves differently, i.e., increase initially with the increasing source-detector separation and then get plateaued. The overall path length is the highest through blood vessel situated 2 mm below the tissue-surface, i.e., closest to the tissue surface. Therefore, a high optical path length through the entire tissue volume does not necessarily mean that the maximum photons are travelling through the blood vessel. On the other hand, if a sensor is aimed to collect the signal from a large artery, it needs to be placed as the closest possible to the artery.

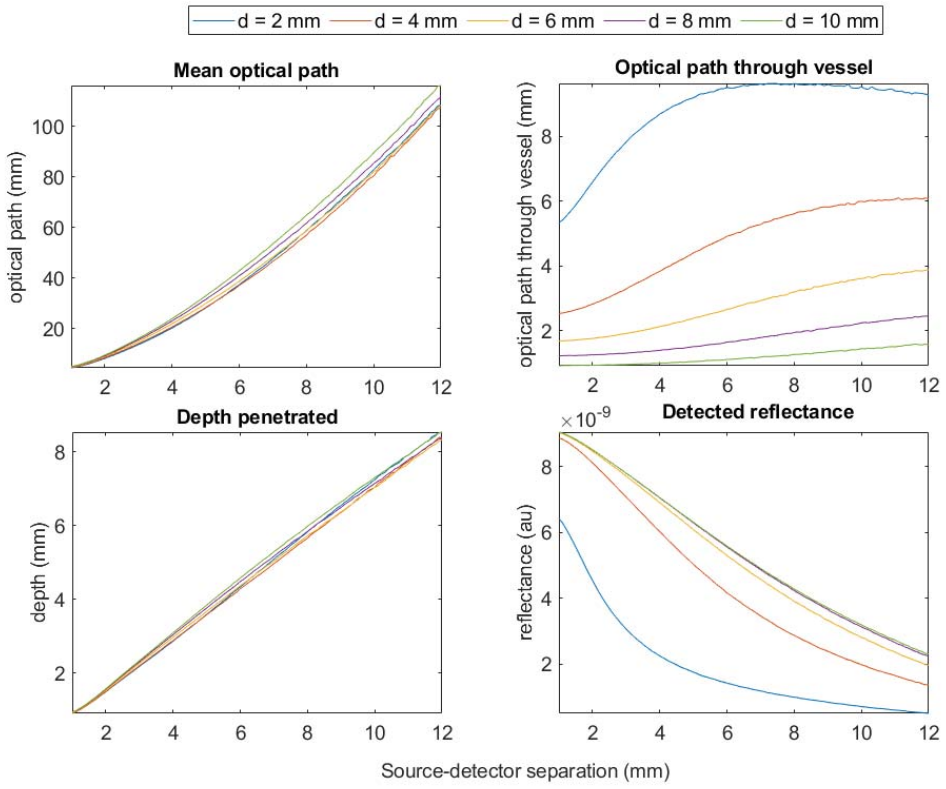

FIG. 3. Simulated results of the optical path length through the entire tissue volume, the fractional path length through the blood vessel, the mean depth penetrated through the tissue and the reflectance detected through a range of source-detector separations (1-12 mm) is presented. Investigations have been carried out for 5 different vessel depths within tissue: 2, 4. 6, 8 and 10 mm.

Simulated penetration depth is seen to increase almost linearly with the source-detector separation. No significant change is seen in the overall penetration depth between the tissue volumes having different vessel depths. The reflectance, which is equivalent to the optical signal amplitude by the sensor, is seen to decrease rapidly with the increasing source-detector separation. With an agreement with the modified Beer-Lambert law, the decay in the reflectance with the increasing source-detector separation follows an exponential pattern. Maximum reflectance is obtained with the simulation with the deepest artery, 10 mm. The simulation with the closest artery, i.e., 2 mm, exhibits the minimum reflectance. This can be explained by the optical properties of blood vessel. Deeper is the vessel situated within tissue, lower is the number of photons travelling through the vessel, leading to lesser absorbance through blood. Blood being much more absorbing compared to fat, amount of non-absorbed light, i.e., reflectance is higher when more photons travel through fat (or non-perfused tissue).

4. Conclusion

A three-dimensional Monte Carlo model is explored to investigate the influence of (a) the sensor location respect to a blood vessel and (b) the vessel depth on the associated light-tissue interactions. Results show significant difference between the interaction profiles obtained placing the sensor

across and along the artery. Simulations reveal that in order to obtain the highest amplitude of the detected signal, the sensor should not be placed on top of an artery. Also, in order to detect signal from a blood vessel embedded within tissue, a higher source-detector separation should be used. Further research will be carried out with a more complex tissue structure and using a higher number of optical wavelengths. The combination of the above results can be utilized to determine the design of a wearable sensor for the most desirable outcome.

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