A Multilayer Monte Carlo Model for the Investigation of Optical Path and Penetration Depth at Different Perfusion States of the Colon

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***Abstract*— There is a great interest in monitoring the oxygen supply delivered to the colon. Insufficient oxygen delivery may lead to hypoxia, sepsis, multiorgan dysfunction and death. For assessing colonic perfusion, more information and understanding is required relating to the light-interaction within the colonic tissue. A multilayer Monte Carlo model of a healthy human colon has been developed to investigate the light-tissue behavior during different perfusion states within the mucosal layer of the colon. Results from a static multilayer model of optical path and reflectance at two wavelengths, 660 nm and 880 nm, through colon tissue, containing different volume fractions of blood with a fixed oxygen saturation are presented. The effect on the optical path and penetration depth with varying blood volumes within the mucosa for each wavelength has been demonstrated. The simulation indicated both wavelengths of photons penetrated similar depths, entering the muscularis layer.**

I. INTRODUCTION

The gastrointestinal tract is known to be the canary of the body as the blood circulation within this region is easily compromised [1]. Hypoxia, a deprivation of oxygen supply, plays a major role in colonic ischemia, resulting in colon dysfunction; progressing to multi-organ dysfunctions [1], [2].

A routine, standardized method for monitoring colon oxygenation is still unavailable. The current gold standard are visual inspections by assessing the color, pulsation and rhythmic muscle contraction of the colon during surgeries. Where the colon is visually inaccessible, monitoring the individuals' vital signs is an indirect indicator, which is commonly overlooked due to several factors affecting such physiological measurements [3].

Monitoring adequacy at alternative sites other than the colon does not guarantee adequate oxygen delivery to the colonic microvascular bed or tissues [1]. Ideally, a technique should be able to continuously monitor the colon to provide an accurate and sensitive indication of impeding oxygenation failure, during surgeries or colon examinations [1]. Several quantitative techniques have been proposed, however unsuccessful in becoming an accepted monitoring method of colon oxygenation [4].

Photoplethysmography (PPG) and pulse oximetry (PO) has been proposed due to its large clinical and research applications [5], [6]. The principle of these techniques is based on light interaction with biological tissues to monitor changes in blood oxygenation and blood volume. Perfusion by definition, is the blood flow or blood volume per unit time, per unit tissue mass [7]. This makes PPG and PO a desirable technique due to its ability in monitoring blood oxygenation and blood volume using optical sensors in a practical, inexpensive and relatively non-invasive manner.

The passage of photons through the tissue depends on the effective optical properties which is the cumulative effect of the optical and physiological properties of the tissue. With the change in the physiological properties, such as the state of perfusion, the light path through tissue is likely to deviate. Such deviation can be quantified by the parameters such as the optical path (OP) and penetration depth (PD). Both parameters are invaluable for predicting and optimizing the performance of a sensitive sensor for monitoring colon perfusion. Currently, no information regarding the detailed analysis of optical interactions within the colon tissue at different states of tissue perfusion is available. Several techniques for simulating the photon path through tissue, including diffusion approximation and the random walk model can be used, however, all have significant limitations when applied to solve problems associated with highly heterogeneous tissue sample and smaller short-detector separations pertinent to PPG and PO [8]. Alternatively, Monte Carlo is a tool that simulates stochastically the propagation of light through tissue and is well appreciated for its accuracy and flexibility to incorporate any sensor-geometry and tissue-heterogeneity [9].

This paper attempts to address the feasibility of utilizing PPG and PO in an intraluminal environment such as the colon. A Monte Carlo technique was developed to investigate the OP and PD of photons at different perfusion states of the colon, using the parameters of a reflectance PPG sensor [4].

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II. MATERIALS AND METHODS

A. Optical properties and tissue parameters

The Monte Carlo model functions by simulating photons propagating through an absorbing and scattering medium. The medium, being the colonic tissue layers, are characterized by its absorption coefficient (μ_a), scattering coefficient (μ_s) and anisotropic factor dependent on the chosen optical wavelengths.

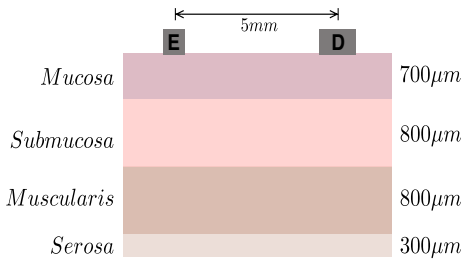

Fig. 1: Illustration of the colon tissue layers and thickness. The emitter (E) and detector (D) with a separation distance of 5 mm corresponds to the dimensions of the designed intraluminal optical sensor.

A multilayer colonic tissue model, consisting of four layers, was used as illustrated in Fig 1, where the mucosa is the inner most layer of the colon which progresses towards the outer surface known as the serosa. The optical properties and thickness for the colonic layers were found in the literature (Table I) [10], [11], [12], [13]. A homogenous mixture of mucosa and blood was assumed to model a perfused colonic tissue, where the volume fraction of blood, V, was characterized by the combination of absorption and scattering coefficients of oxyhemoglobin (HbO) and deoxyhemoglobin (Hb). With the average hemoglobin tissue oxygen saturation (S_tO_2) reported as 70%, [14], [15], the S_tO_2 was kept constant, whilst varying V, using the following equation,

$$\begin{aligned}\mu_a = (1-V)\mu_{a_{MB}} + \dots \\ V\left[S_tO_2\mu_{a_{HbO}} + (1-S_tO_2)\mu_{a_{Hb}}\right],\end{aligned} \tag{1}$$

where μ_{aMB} is the absorption coefficient of a bloodless mucosa layer, μ_{aHbO} and μ_{aHb} are the absorption coefficient of oxyhemoglobin and deoxyhemoglobin, respectively. Equation 1 defines the effective optical properties for the mucosa. With the optical wavelengths chosen to be 660 nm (red, R) and 880 nm (infrared, IR), the values of μ_a and μ_s were determined (Table II). The optical properties for blood having hemotocrit (Hct, proportion of red blood cells in total blood volume) of 45% were collected from published literature [16].

TABLE I: Optical properties the colon sublayers for both emitter wavelengths, red (R) and infrared (IR).

Tissue	$\mu_a(mm^{-1})$ R/IR	$\mu_s(mm^{-1})$ R/IR	g R/IR	ri
Submucosa	0.039 0.050	9.170 8.249	0.939 0.956	1.360
Muscularis	0.025 1.740	9.476 9.848	0.914 0.928	1.357
Serosa	0	0	0.9	1.350

TABLE II: Optical properties for the homogeneous mixture of mucosa and blood (mm^{-1}) for each emitter wavelength (λ), red (660 nm) and infrared (880 nm). Optical properties for blood having 45% hemotocrit (Hct) were collected.

λ (nm)	$\mu_{a_{MB}}$		$\mu_{a_{HbO}}$ $Hct = 0.45$		$\mu_{a_{Hb}}$ $Hct = 0.45$	
	μ_a	μ_s	μ_a	μ_s	μ_a	μ_s
660	0.05	26.33	0.15	92.29	1.64	81.50
880	0.05	22.05	0.56	54.76	0.44	62.50

B. Monte Carlo modelling

In this work, the sensor specification is replicating the designed reflectance mode intraluminal optical sensor which has been previously described [4]. The model simulates photons from a light emitter to a detector, placed on the mucosa, with a fixed separation distance of 5 mm, at wavelengths of R and IR. The detector was defined to have an active area of 0.65 mm^2 to detect 10^3 photons for each wavelength.

The Monte Carlo model was executed for investigating the changes in light interaction with colonic tissue for different V within the mucosa. The range of V within the mucosa was varied between 2–10 %, with increments of 1 %, as seen in [15]. The basic steps for computing the photon path through a multilayer tissue geometry has been previously described [5]. The tissue-model was considered to have a slab geometry, presented by a 3D Cartesian co-ordinate system. The center of the optical source was considered to be placed at the origin of the co-ordinate system. Each photon launched had an initial weight ($w = 1$), an initial photon position co-ordinate (x, y, z) and a randomly generated direction (θ, ϕ). The photon propagates through tissue where scattering is most likely to occur with a step-size (l) of,

$$l = -\frac{ln(\xi)}{\mu_a + \mu_s}, \tag{2}$$

where ξ is a random number between 0 and 1, providing a free path length between scattering events [17].

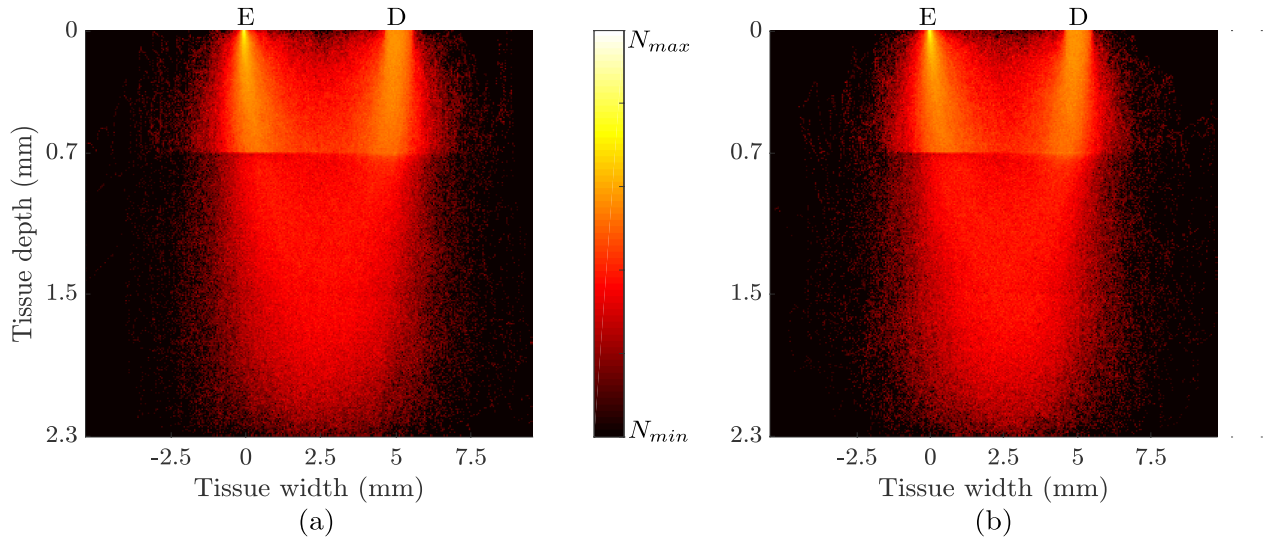

Fig. 2: Image of scattering distribution in the multilayer model of the colon, between the emitter (E) and detector (D), when the mucosa contains a blood volume of 7% at a saturation of 70%. The scattering distribution is shown for the emitter wavelengths of (a) red and (b) infrared. The color bar represents the number of scattering events where black and white represents the minimum (N_{min}) and maximum number (N_{max}) of scattering events respectively. For better representation, the logarithm of the data points have been taken.

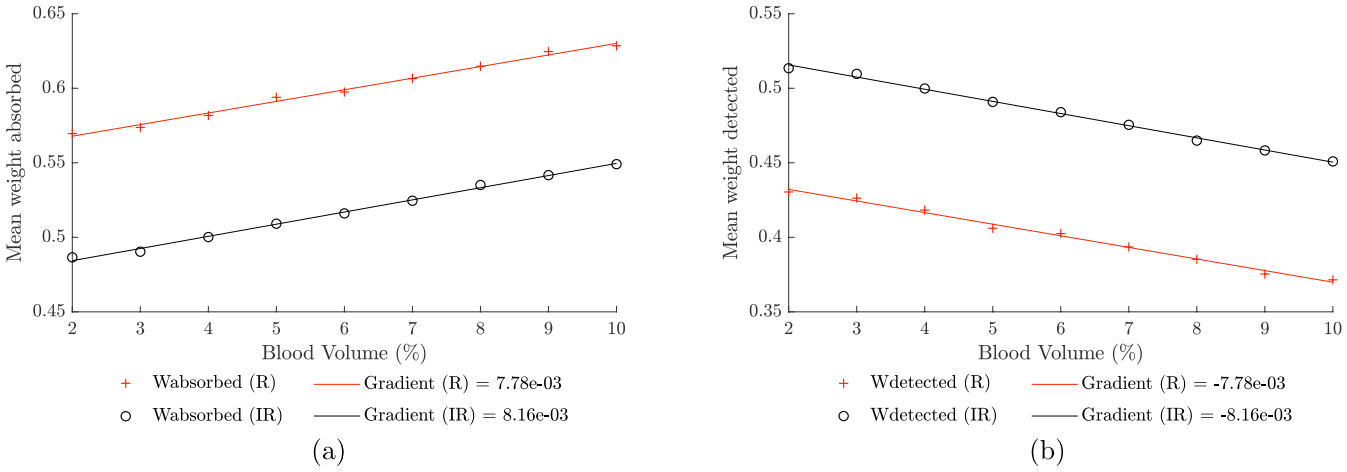

Fig. 3: Mean absorbance (a) and mean weight (b) for the 10^3 photons detected when the blood volume varies between 2-10%. Data points for each wavelength are shown as red (+) and infrared (o). In addition, a linear fit has been created for easier data analysis.

For each simulation, quantities from the detected photons including the total OP, the remaining weight, absorbance and reflectance were recorded. The computational program was written in MATLAB®. A computer with 3.0 GHz processor running Windows 10 was dedicated for the simulation.

III. RESULTS

Fig 2 presents a 2D image of the scattering distribution within the multilayer colon with the mucosa containing a V of 7%. As expected for both wavelengths, a 'banana' shaped distribution of the scattered photons was obtained. It should be noted that only the detected photons have been shown in the image. A clear boundary has been observed between the mucosa-submucosa layer, which is a result of very different scattering coefficients between the two layers.

As seen in Table III, at both wavelengths, photons penetrated through similar tissue depths, corresponding to the muscularis layer. However, R photons were

TABLE III: Mean penetration depth (PD) and optical path (OP) of photons propagating through the colon tissue layers at red (R) and infrared (IR) wavelengths, as the blood volume (V) increases from 2% to 10%.

V (%)	R		IR	
	Mean PD (mm)	Mean OP	Mean PD (mm)	Mean OP
2	1.75	11.60	1.68	9.98
3	1.74	11.49	1.66	9.90
4	1.74	11.50	1.68	9.96
5	1.74	11.63	1.68	9.92
6	1.74	11.48	1.67	9.92
7	1.74	11.46	1.67	9.90
8	1.74	11.48	1.67	9.96
9	1.74	11.50	1.67	9.90
10	1.73	11.41	1.67	9.88

found to penetrate deeper compared to the IR photons. Including the mean OP, both quantities do not vary considerably with variations of V. This is due to V only affecting the photon absorbance within the mucosal layer. Although the changes in the path length and the PD are not high, an abrupt change in the blood volume may result in a sudden change in the tissue-volume interrogated by the sensor.

As V increases, the mean weight absorbed by the detected photons linearly increase for both wavelengths, where R photons have a higher absorbance than IR. As the absorbance corresponds to the number of interactions, the result of lower remaining weight of R photons at the detector was reasoned, as shown in Fig 3(b).

IV. Conclusion

In this investigation, the distribution of the optical path and photon penetration depth within a multilayer colon model using parameters of a reflectance intraluminal PPG sensor has been presented. The model has been carefully designed by using the optical and anatomical parameters available in the literature to replicate a healthy human colon tissue as close as possible.

The effect on the OP and PD with varying perfusion state for the chosen optical wavelengths has been demonstrated. The variable perfusion state has been implemented in the model by altering the blood volume within the mucosa. Utilizing the reflectance PPG sensor geometry, the sensor is assumed to be placed within the colon, in contact with the mucosa. Thus the consideration of a slab geometry for the simulation was justified since the spatial dimension of the photons are much smaller than the width of the tissue. The investigation showed a consistent decay in the detected light intensity with increasing V, together with small, yet persistent changes in the optical path length and penetration depth of photons through the colon. With sudden changes in the blood volume may result in sudden change in tissue-volume interrogated by the sensor.

The present investigation aids to predict the sensor functionality at the current state of tissue perfusion. Future work will be followed to optimize the sensor geometry for an assessment of colon perfusion. The volume of information gathered from the computational model-based studies will be crucial for designing a novel sensor based on PPG to aid in continuous monitoring of colon perfusion.

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