Subcutaneous Veins Depth Estimation Method Using Monte Carlo Simulations

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***Abstract*—Subcutaneous veins localization is basic and important step for any intravenous medication administration. Due to different physiological characteristics, mainly darker skin tone, scars or dehydrated condition of patients, medical staff face difficulty in veins localization. Through near infrared imaging technology the veins can be visualized due to high contrast between veins and skin tissue in this modality. Information on the depth of veins is equally important for proper catheterization or venipuncture procedures. Patients have different veins depth due to the different amount of fat present in the subcutaneous layer. The depth of veins from the skin surface cannot be estimated by simple imaging technique. In this paper a mathematical model to estimate the depth of veins based on measured diffused reflectance is presented. A layered model of Monte Carlo simulations for light transport in turbid medium was used to validate the results.**

Keywords— Intravenous (IV) Catheterization; Subcutaneous Veins; Diffused Reflectance; Monte Carlo; Near Infrared.

I. INTRODUCTION

Intravenous (IV) catheterization is a process of passing catheters to the patient's veins. Subcutaneous veins localization is perormed prior to catheter insertion in order to select suitable vein for medication or blood sampling. This job is carried out by medical staff who locate the veins either by sight or by merely feeling with hand. The medical staff face difficulties in veins localization due to many physiological differences including skin tone, vein depth, scars, presence of hair etc. The risk of wrong catheterization, vein rupture, skin bruise and nerve damage increases due to difficulty in veins localization process. In this case the number of painful attempts also increases. It is reported in [1] that more than 2 venipuncture attempts are required on average per patient who needs IV medication. The patients (especially infants) suffer a lot of pain due to the multiple attempts for catheter insertion. A very serious consequence of unsuccessful attempt for venipuncture is the delivery of medication to the tissues surrounding the IV catheter. This may result in infiltration and extravasations which may lead to surgical intervention [2].

For the normal catheterization/ blood sampling process; it is required to localize the subcutaneous veins present in hypodermis which is the third layer of skin. Using Near Infrared (NIR) imaging subcutaneous veins can be visualized making use of the higher absorption spectra of Hemoglobin (Hb) present in the veins as compared to skin tissues. Due to this characteristic, veins appear darker in NIR images contributing to the higher skin/vein contrast. The radiations used for illumination in this range are non-ionizing which mean these have no harmful effects on the patient even if applied multiple times [3]. There are few devices in market which use NIR imaging for veins localization but none provide information on the depth of veins [4]. Veins depth information is necessary to avoid wrong catheterization and piercing through the back wall of veins during IV medication process. In this paper a method to estimate the depth of veins from measured reflectance is presented. Monte Carlo simulations are used to simulate the light transport inside the layered structure of human skin. The measured diffused reflection parameter is analyzed to model layer structure of skin. Subcutaneous veins are assumed to be present in the hypodermis layer. The width of hypodermis layer is increased gradually in simulations and output parameters are recorded. These output parameters are then fed to the mathematical model to estimate the depth of blood vessels. Results are shown against the plots of Monte Carlo simulations performed with same optical parameters. Section II in this paper presents the state of the art on the methods of blood vessels/blood region depth measurement. Section III presents the methodology followed in the proposed work. Results are given in Section IV. Section V concludes the paper with future work.

II. STATE OF THE ART

A method of topographical imaging of an absorbing object implanted in a highly scattering medium is proposed in [5]. In this method image is reconstructed `from the backscattered light coming from the scattering medium having an absorbing object embedded within. Here the scattering medium can be considered as the skin tissues and the absorbing object as the veins present in the hypodermis layer of skin. The principle given in Eq. 1 described that the certain maximum path length 'L'is proportional to the spatial integration probability distribution function of backscattered light from the highly turbid medium.

$$P(L) = \frac{\int_0^L p(s)\,ds}{\int_0^\infty p(s)ds} \approx \frac{\int_\Sigma I_a dS}{\int_\Sigma I_0 dS} \qquad (1)$$

Where *p(s)* is the probability density function of turbid medium, I_a and I_0 are backscattered light intensity distribution from medium with and without absorbing object. S is the path length for the semi- infinite medium. The maximum path length L is defined to be proportional to the depth 'd' of the absorbing object. Optimization of proportionality constant was done through Monte Carlo simulations and L is defined as L=3d. This method is likely to misestimate the depth with the variation of maximum path length which is dependent on the optical properties of the hemoglobin which varies with oxygenation state.

A noninvasive method to estimate the average depth of blood vessels is presented in [6]. The ratio of optical densities (ODs) of the backscattered light at two isosbestic wavelengths (420 and 585 nm) is used to estimate the average depth of blood vessels underneath skin. However in this method two wavelengths used from visible light spectrum cannot penetrate deeper inside skin. Hence this method is not applicable for the case of estimating depth of deeper subcutaneous veins and it is also affected due to the disparity of the melanin content in different subjects.

In [7] a method is presented using three isosbestic wavelengths 420, 585 and 800nm, for the estimation of depth and thickness of blood region. The concentration of melanin was estimated from the reflectance of skin tissues surrounding blood region. This estimation is then used to compensate the variation of optical densities in different subjects. The experiments were performed on tissue like phantom using Monte Carlo simulations of light transport in turbid medium. However due to the higher error rate in depth estimation, this method cannot be used in the cases where the vein depth should be known accurately.

In this paper we presented a mathematical model to estimate the depth of blood vessels in the layered structure of skin. This model is derived from state of the art literature on the light propagation in turbid medium. Monte Carlo simulations for light transport were used to validate the calculation of vessel depth through our proposed model.

III. METHODOLOGY

A. Determine the Optical Properties of Human Skin

When a light beam is made incident on a medium, the energy of this beam (photons) is either reflected back, get absorbed or transmitted through the medium. In this work the backscattered diffused light from a layered skin structure is of interest to estimate the depth of blood vessels. While propagating in the medium, photons get scattered by hitting against cells and follow a new direction changing significantly the propagation process.

Intensity distribution of backscattered light depends upon the spatial position of highly absorbing element like blood vessels. In the model of light transport in skin tissue which includes 4 layers of human skin, veins are supposed to be present in the hypodermis (4th) layer. Monte Carlo simulations for light transport in tissues are used to analyze the propagation of light inside the layered structure of skin [8]. The optical parameters used for simulations are obtained from literature [9- 11] and are tabulated in Table 1. Here μ_a is the absorption coefficient, μ_s is scattering coefficient, g is the anisotropy factor, n is the refractive index and t is the thickness of the layers in millimeters. These parameters are considered for the wavelength of light λ =800nm. A total of '25000000' photons are projected on to the layered medium. Two separate simulations are done with varying depth of veins. The thickness of the fourth (hypodermis) layer is varied with each simulation. For the first simulation it is varied from 0.1 to 1.8 mm making total depth of veins to be 2.1mm minimum to 3.8mm maximum. For the second simulation, it is varied from 0.1 to 3.0 mm, making the total depth of veins to be 2.1mm minimum to 5.0 mm maximum. For every iteration in case of both simulations the width of hypodermis layer is increased by 0.1 mm. While changing the width of hypodermis layer diffused reflectance parameter "R_d" is recorded for each iteration. Since veins are present in hypodermis layer, the accumulated width of all four layers is supposed to be equal to the depth of veins. Hence "R_d" is plotted against the depth "z" of veins in the results section.

TABLE 1: Optical Characteristics of Human Skin layers at wavelength λ =800nm [8-10] .

Layers	***n***	μ_a (cm^{-1})	μ_s (cm^{-1})	***g***	***t (mm)***	
					Sim-1	Sim-2
Layer 1	1.55	3.3	1050	0.85	0.02	0.02
Layer 2	1.34	4	90	0.80	0.18	0.18
Layer 3	1.4	0.8	90	0.85	1.8	1.8
Layer 4	1.44	1.36	12	0.75	0.1-1.8	0.1-3.0

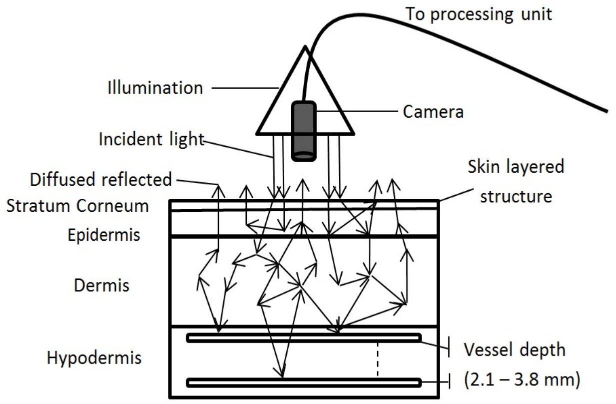

Figure 1: Diffused light propagation model in layered structured of skin

Fig. 1 depicts the idea of focusing light on the layered medium and collection of backscattered light energy with camera sensor. Skin is the largest organ of human body, which covers full body and has numerous functions for normal living. It has layered anatomy in which the very first, thin and horny layer is called stratum corneum. This layer reflects about 5 to 7% of the incident light [12, 13]. It consists of millions of dead cells which are replaced constantly by the living cells in an ongoing process.

Underneath the stratum corneum is the epidermis layer. This layer has high absorption coefficient and consists of melanin pigmentation which are responsible of skin color. This pigmentation absorbs harmful radiation to protect the internal organs. The third layer represents dermis, which lies between the epidermis and subcutaneous tissues. It consists of the fibrous tissues, collagen, sweat glands and hair follicles. The fourth layer is hypodermis which consists of subcutaneous tissues. This layer contains connective tissues, fat and blood vessels. These blood vessels (veins) are used for intravenous medication during venipuncture procedures.

B. Vessels Depth Calculation

For analytical computation of veins depth from the diffused reflectance parameter, we have adopted the following approach. The intensity of light traveling in the turbid medium can be expressed as

$$\begin{aligned} I_o &= I_c + I_d \\ I_o &= (R_d + A)I_o \end{aligned} \qquad (2)$$

Here I_o, I_c and I_d represent the incident light, absorbed component and diffused component of light respectively. R_d and A are diffused reflectance and absorption fractions respectively. Hence, we can re-define R_d and absorption fraction, A as

$$R_d = \frac{I_d}{I_o} \quad and \quad A = \frac{I_c}{I_o} \qquad (3)$$

Intensity of light propagation in Scattering-Dominant limit (diffusion approximation) [4] can be expressed as:

$$I_c = I_0\left(1 - {R_d}^2\right)exp[-(\mu_a + \mu_s)z] \qquad (4)$$

Substitute equation (4) into (2)

$$I_o R_d^2 \, exp[-(\mu_a + \mu_s)z] = I_d \qquad (5)$$

Since we are considering multilayered-tissue skins, hence the summation terms of absorption coefficient 'μ_a' and scattering coefficient 'μ_s' can be replaced with the term of effective attenuation coefficient, μ_{eff} , we can re-write (5) as

$$I_d(z) = I_o\left({R_d}^2\right)exp\left[-\left(\mu_{eff}\right)z\right] \qquad (6)$$

Where $\mu_{eff} = \sum\sqrt{3\mu_a(\mu_a + \mu_s')}$, $\mu_s' = (1-g)\mu_s$ and 'z' is the depth of layered medium (in other sense veins). Here 'μ_s'' is the transport scattering coefficient and 'g' is the anisotropy parameter i.e. the mean value of scattering cosine angles. The value of 'g' is within the range of 0 to 1[9, 10].

Rearranging equation (6) in order to estimate the depth of subcutaneous vein as a function of diffuse reflectance, R_d will give the following equation.

$$z = \frac{ln\frac{I_d}{I_o({R_d}^2)}}{-\left(\mu_{eff}\right)} \qquad (7)$$

Noting that $I_d = R_d I_o$, by substituting it into (7) , we can simplified the equation to

$$z = \frac{ln\frac{R_d I_o}{I_o({R_d}^2)}}{-\left(\mu_{eff}\right)} = \frac{ln(R_d)}{\mu_{eff}} \qquad (8)$$

IV. RESULTS AND DISCUSSION

Diffused reflectance R_d recorded from the output of both MCML simulations is plotted against the depth of layered structure of medium. With same value of R_d the depth 'z' of blood vessels is computed using Eq.8. Some adjustment has been made in the final calculation of 'z' to compensate the initial point of simulation. This adjustment made by the division of calculated 'z' by the initial depth factor (0.02) in this case. The results of this analytical calculation of 'z' are plotted in along with R_d in Fig. 2 and Fig.3 for first and second simulation respectively. These results indicate

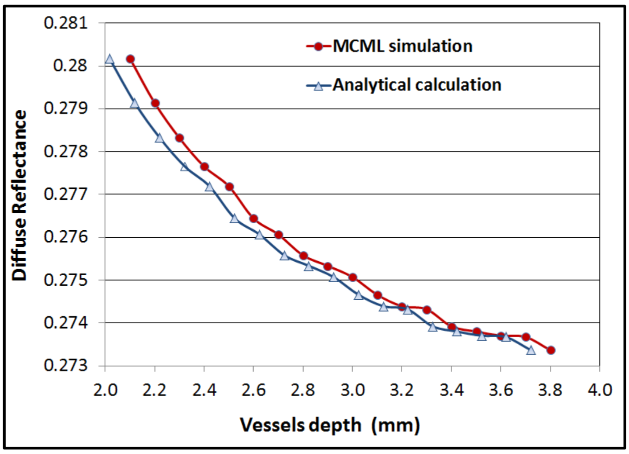

Figure 2: Plot of vessel depth calculated from the mathematical model against the diffused reflectance computed from first MCML simulation with maximum vessel depth of 3.8mm

that the diffuse reflectance gradually decreases as the total thickness of layered medium increases. Both the plots from MCML and analytical calculation show the same trend and look similar with a marginal error. Table 2 tabulates the error for the first simulation. The mean error value is 7.72% in this case which mean the estimation of veins depth through our analytical model will be within the error margin of 0.0772 mm. The mean error for second simulation is 8.09%.

TABLE 2: Comparison data between analytical estimation and first MCML simulation for subcutaneous vein depth

	Subcutaneous vein depth		
R_d	Analytical estimation (mm)	MCML simulation (mm)	Error (%)
0.280179	2.02	2.1	8.26
0.279140	2.12	2.2	8.03
0.278321	2.22	2.3	7.89
0.277656	2.32	2.4	7.80
0.277193	2.42	2.5	7.81
0.276442	2.52	2.6	7.59
0.276068	2.62	2.7	7.60
0.275581	2.72	2.8	7.51
0.275334	2.82	2.9	7.58
0.275073	2.92	3.0	7.63
0.274660	3.02	3.1	7.53
0.274393	3.12	3.2	7.54
0.274320	3.22	3.3	7.71
0.273923	3.32	3.4	7.57
0.273800	3.42	3.5	7.68
0.273703	3.52	3.6	7.80
0.273673	3.62	3.7	7.98
0.273367	3.72	3.8	8.26
	Mean Error		7.72%

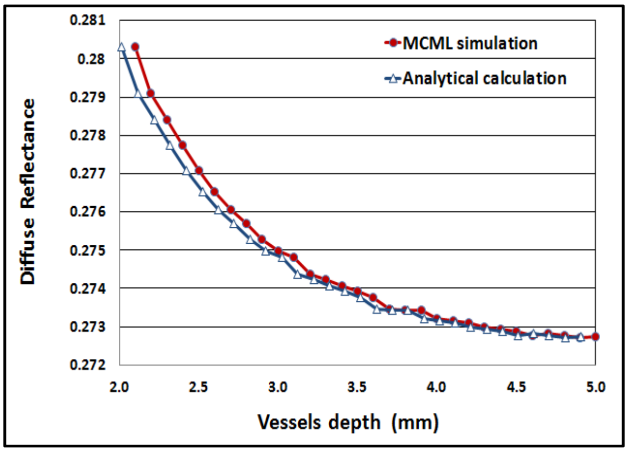

Figure 3: Plot of vessel depth calculated from the mathematical model against the diffused reflectance computed from second MCML simulation with maximum vessel depth of 5mm

This model can be used to estimate the blood vessel depth, where the prior knowledge of vessel depth is important e.g. in case of IV catheterization process.

The parameters given in Table 1 can suffer with uncertainty. The effective attenuation coefficient μ_{eff} which is calculated with μ_a, μ_s and g can vary ±5% to ±10% [10]. In order to measure the sensitivity of the mathematical model proposed in Eq.8, the vessel depth is calculated with the ±5% margin of μ_{eff}. The results are given in Fig.4. The analytical-5% and analytical+5% calculations were done with the parameter $\mu_{eff} - 5/100\,\mu_{eff}$ and $\mu_{eff} + 5/100\,\mu_{eff}$ respectively. The mean errors for both calculations are 10.1% and 24.672% which show that calculation of vessel depth can be effected notably with the change in the optical parameters. This shows that the determination of accurate optical parameters is vital in order to reduce the error in vessel depth estimation.

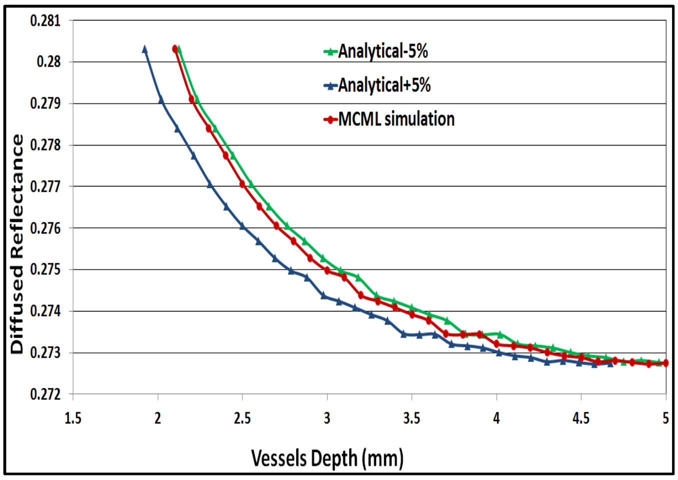

Figure 4: Plot of diffused reflectance against the vessel depth calculated with ±5% margin of μ_{eff}.

V. CONCLUSION

Near Infrared imaging can be used to visualize the position of subcutaneous veins. The information on depth of veins is very important in some cases like IV catheterization process. A method to estimate the veins depth using measured diffused reflectance is presented in this work. A mathematical model has been derived from the literature on the optical properties of human skin and light transport in turbid medium. MCML simulations are used in order to validate the results. The consistency in results is found with variation of vessels depth from 2.1mm up to 5mm maximum. It is observed that the presented model can estimate the veins depth within the marginal error of 8.09%. In future work experimentation on layered tissue phantoms will be carried out to further validate the results and fine tune the model in order to reduce the error in estimation. These phantoms can be customized for the application of near infrared light, which can penetrate deeper as compared to visible light. The layered tissue phantoms must contain similar optical properties such as human skin and blood vessels incorporated in phantoms must match with the deoxygenated hemoglobin.

ACKNOWLEDGMENT

This work is carried out in Center for Intelligent Signal and Imaging Research (CISIR) with joint supervision from Le2i Laboratory, University of Burgundy. Financial support was provided by Universiti Teknologi PETRONAS under Graduate Assistance scheme.

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