A Prefatory Study using COMSOL Simulation on Multi-Layered Tissue for Developing an Optical Non-Contact Oxygen Saturation Device

Mannat Uppal
Department of Biomedical Engineering
Sri Sivasubramaniya Nadar College of Engineering
Chennai, Tamil Nadu
mannat21uppal@gmail.com

Pauline John
Department of Biomedical Engineering
Sri Sivasubramaniya Nadar College of Engineering
Chennai, Tamil Nadu
paulinej@ssn.edu.in

Abstract—**Detection of oxygen saturation percentage is considered an important vital sign of the patient in the medical field, as variation could lead to severe symptoms such as hypoxemia, anaemia, breathing problems and severe inflammatory disease such as sepsis, and pneumonia. This work describes and investigates the design and characterisation of multi-layered tissue of the skin and vasculature with their mechanical, and optical properties. The simulated model includes the epidermis, dermis, and hypodermis skin layers (blood vessels) using the COMSOL software. The result of the simulated study portrays the possibility of light interaction with tissue due to the non-contact method. A circuit prototype was designed, to study the feasibility of measuring oxygen saturation at different wavelengths using a non-contact setup.**

Keywords— *near-infrared, non-contact, pulse oximeter, COMSOL.*

I. INTRODUCTION

The skin is the most important protective organ in the human body, accounting for 15% of total adult weight and functioning as the body's first line of defence against the environment. It defends the body against external physical, chemical, and biological hazards while also limiting excessive water loss and aiding thermoregulation. The skin is continuous, and the mucous membranes line the body's surface [1]. Figure 1 shows the three layers of the skin: epidermis, dermis, and hypodermis [1]. Keratinocytes, a kind of cell that generates keratin, a long, threadlike protein with a protective function, make up the epidermis. The dermis, or middle layer of the skin, contains collagen, which is a fibrillar structural protein. The panniculus is a subcutaneous tissue layer that sits atop the dermis and is made up of little lobes of fat cells called lipocytes. These layers vary in thickness depending on where you are on the body's structure. The dermis of the back is 30-40 times thicker than the epidermis [3]

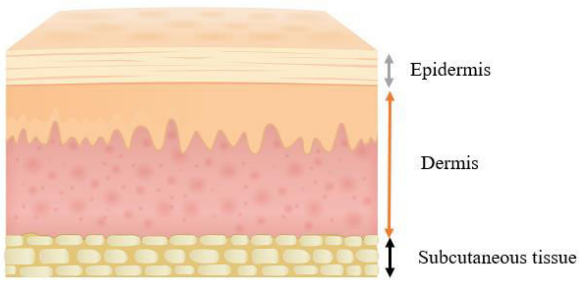


Fig.1. Different layers of skin.

The diagnostic and therapeutic uses of light are influenced by a tissue's optical characteristics. The capacity of light to permeate a tissue, probe its components, and then exit the tissue for detection, as well as deposit energy via the tissue's optical absorption qualities, is critical for diagnostic and therapeutic purposes. As a result, defining the optical characteristics of tissue is the first step in appropriately developing equipment, interpreting diagnostic results, or establishing therapy regimens. The second stage is to forecast the light dispersion and energy deposition using optical parameters in a light transport model. [2] discussed that Liver tumor division in restorative pictures has been generally considered as of late, of which the Level set models show an uncommon potential with the advantage of overall optima and functional effectiveness. [6] discussed that Tumor segmentation required also the identical automatic initialization as regarding the liver. This phase was applied only in order to liver volume, obtained following automatic delineation of lean meats surface: this latter, used to original dataset quantity, was used as a new mask in order to be able to prevent processing overloads and even avoid errors related to be able to arsenic intoxication surrounding tissues delivering similar gray scale droit. [9] discussed that Live wire with Active Appearance model (AAM) strategy is called Oriented Active Appearance Model (OAAM). The Geodesic Graph-cut calculation creates much better division results than some other completely programmed strategies distinguished in writing in the expressions of exactness and period preparing.

The absorption coefficient, the scattering coefficient, and the scattering function are shown in figure 2, where is the deflection angle of scattering and is the azimuthal angle of scattering, and the real refractive index of the tissue explains in the figure 6. Reflection refers to the bounce-back of the light from the surface, without getting absorbed. Absorption refers to the absorption of the light on the surface, whereas transmission refers to when light passes from one layer to another layer. Mie scattering refers to scattering by particles that are comparable to or larger than the wavelength of light, whereas Rayleigh scattering refers to scattering by microscopic particles or mass density changes that are considerably smaller than the wavelength of light. [7]. [11] discussed that Automatic liver tumor segmentation would bigly influence liver treatment organizing strategy and follow-up assessment, as a result of organization and joining of full picture information.

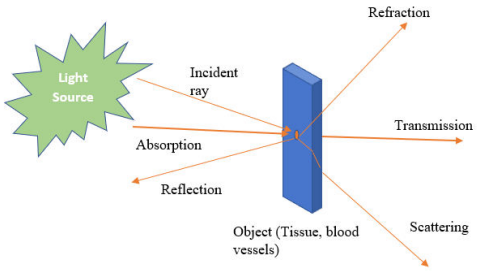


Fig. 2. Schematic of light tissue interaction.

A pulse oximeter is a non-invasive device that measures oxygen levels in the blood (saturation). Oxygen saturation is a test that determines how much oxygen is dissolved in the blood by detecting haemoglobin and deoxyhaemoglobin. The wavelengths of red (630 nm, 660nm) and infrared (915 nm) light are used. Deoxygenated Hb absorbs less infrared and more red light, whereas Hb that has been oxygenated absorbs more infrared and red light (915 nm) (660 nm). Two techniques are generally used for detecting oxygen saturation: Transmission and Reflectance. Pulse oximeters that measure through the transmittance and reflectance that are used to measure oxygen saturation are commercially available and work on certain wavelengths. Nonetheless, the clinical industry relies on the arterial blood gas (ABG) test for precise readings because it is the most trusted gold standard for measuring across the medical field [8]. Deoxygenated haemoglobin absorbs red wavelengths (600 nm) and oxygenated haemoglobin absorbs infrared light (900 nm) as shown in fig. 3.

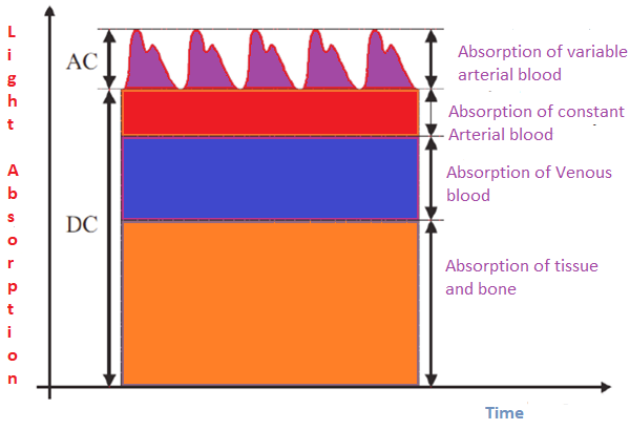


Fig. 3. The signal transmission through the finger tissue.

This article investigates the concept of light propagation in air and without air. Two light sources (660 nm and 915 nm) were employed in the experiment. The comparison plots with air and without air to analyse the influence of air as the light travels through different layers of skin. The results showing the comparison have been plotted using the Origin 2021 programme. A non-contact prototype using LEDs at wavelengths of 630 nm, 660 nm, and 915 nm, was used to designed after verification with the simulation study to show the negligible influence of air in measuring the oxygen saturation. [4] discussed about diabetic retinopathy from retinal pictures utilizing cooperation and information on state of the art sign dealing with and picture preparing. The Pre-Processing stage remedies the lopsided lighting in fundus pictures and furthermore kills the fight in the picture.
The non-contact approach will be more beneficial compared to the contact method as in conventional pulse oximeter due to the following reasons:

1. Frequent measurements by conventional pulse oximeter (wearable devices) in contact with skin may irritate the skin.
2. Clinical use of conventional pulse oximeters on different patients may lead to contamination (one of the main concerns during current pandemic situations).
3. Motion artefacts and other biological artefacts like skin impedance could lead to confounding results.

These drawbacks related to conventional pulse oximeters necessitate the development of a non-contact optical device for the measurement of oxygen saturation.

II. Methodology

A. *Light Interaction in Biological tissue*

The diffusion equation is used to study light propagation in biological tissues.
The diffusion equation is given by [12]:

$$\frac{\partial u(\vec{r},t)}{v\partial t} + \mu_a u(\vec{r},t) - c\nabla^2 u(\vec{r},t) = I(\vec{r},t) \quad (1)$$

Where r refers to the photon vector position, t is time, I referred to as intensity of the given source, c refers to the photon or diffusion coefficient and u refers to the fluence rate. Fluence rate is referred to as the energy flow per unit area per unit time in a particular medium and is defined as the fluence rate [12].
Where c can be calculated as:

$$c = \frac{1}{3(\mu_a + \mu'_s)} \quad (2)$$

Where μ_a is the absorption coefficient and μ'_s is the reduced scattering coefficient of the medium.
The diffusion equation can be used in different skin layers to research light propagation since it meets the requirements. However, approaching a boundary (such as the one between the dermis and epidermis in typical human skin), the radiance ceases to be isotropic, and hence appropriate boundary conditions must be given to the Diffusion equation (DE) [10].

Some of the requirements for the DE given in (1) can be considered for the study of light propagation, The source must be isotropic, with little fluctuation in photon flow over time, since the scattering coefficient is substantially bigger than the absorption coefficient and the light brightness is virtually isotropic across the volume.

B. *Optical parameters of the skin for the two wavelengths considered in this study*

Tables I and II show the values of the absorption and scattering coefficient at each layer for the simulation.

TABLE I: OPTICAL PARAMETERS OF SKIN FOR THE WAVELENGTH AT 660 nm

Optical parameters *Layers of tissue*	*Absorption* *Coefficient [1/cm]*	*Scattering* *Coefficient [1/cm]*
Epidermis layer	27.196	22.452
Dermis layer	0.288	22.335
Hypodermis layer	25.4	17.50

TABLE II: OPTICAL PARAMETERS OF SKIN FOR THE WAVELENGTH AT 915 nm.

Optical parameters *Layers of tissue*	*Absorption* *Coefficient [1/cm]*	*Scattering* *Coefficient [1/cm]*
Epidermis layer	27.196	34.10
Dermis layer	0.48	19.52
Hypodermis layer	0.89	12.27

C. *Simulation Model*

In COMSOL, the generic form of the Helmholtz equation is:

$$\nabla(-c\nabla u) + au = I \quad (3)$$

Where u refers to the fluence rate, c is the photon or diffusion coefficient and the absorption coefficient is referred to as a.

The Helmholtz equation module in COMSOL Multiphysics 5.5 was used to examine light propagation in a skin tissue model, as it duplicates the diffusion coefficient.

A block was being constructed up with width × height as 0.01 m × 0.01 m. The study was done by constructing 3D model of skin layers with and without the air media. The two models were constructed one with the epidermis and dermis layer for studying the light propagation through tissue whereas another with the epidermis, dermis and hypodermis for the study of light propagation through the blood vessels.

Three different air media were taken into consideration (1 mm, 3 mm, and 5 mm) for studying the characteristics of air and how air plays a role in light propagation. The thickness of the epidermis, dermis and, hypodermis was taken into consideration (0.0001 m, 0.01 m, and, 0.02 m).

The refractive index was applied to each of the layers. In diffuse optics approaches, low-power laser sources are employed. Whereas, for this investigation, a 100 mW source was put on the surface of the model. The position of the light source was placed on the surface of the model.

The fluence distribution fluctuates with changes in optical characteristics, and it may be calculated with reasonable simplicity using COMSOL.

D. *Experimental setup*

After a successful simulation model, the influence of air in non-contact is negligible and will not affect the working of a pulse oximeter.

A prototype for the measurement of oxygen saturation was developed. Table III list all the components used in building up the prototype.

The prototype was designed with 3 LED sources which act as a transmitter and a photodiode which act as a receiver, as shown in the schematic, figure. 4 The reflectance type prototype has been developed and a microcontroller is used to program it. Detection of the reflected light using a photodiode from the desired location that is fingertip.

TABLE III. CIRCUIT SPECIFICATIONS

Components	*Specification*
Photo Diode (with amplifier)	TIOPT101 (Texas Instruments)
Resistors	100 Ω, 1 k Ω
Microcontroller	STM32F103C8
Power source	5 V
LEDs	630 nm, 660 nm, 915 nm

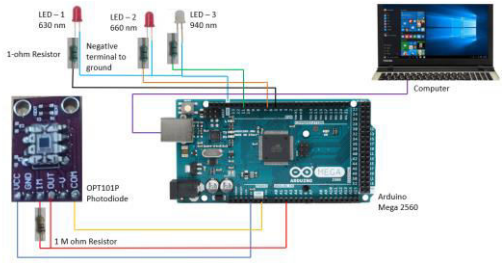


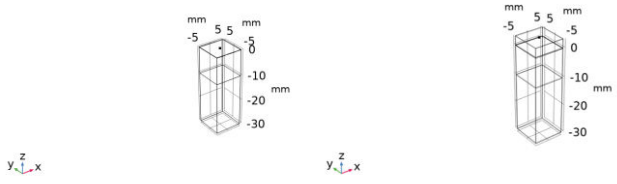
Fig.4. Schematic of the circuit connections

III. RESULT AND DISCUSSION

3D layered plots and 1D line plots of the skin model were used in the analysis. The intensity is maximum in the area where the source is close to the surface, and it gradually decreases as the air media keeps on increasing. As light penetrates deeper into the skin tissue layers, the intensity decreases, indicating the role of absorbers and their concentration of light in each layer. The study also found that as the wavelength is increased, the penetration and fluence distribution rise across the created model.

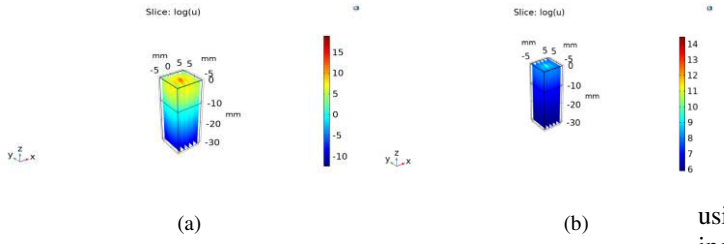
This study mainly shows the light propagation through different layers of skin and the importance of the air media in the propagation of light. The source wavelengths (660 nm and 915 nm) were used in the study.

Typical results are shown in fig. 5 shows the 3D geometry of the hypodermis model with air media and without air media, whereas fig. 6 and 7 show the fluence distribution along with the different layers of skin with and without air media.



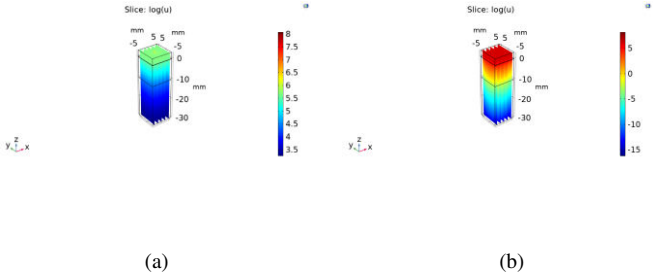
(a) (b)

Fig. 5. 3D geometry of the skin model (a) without air and (b) with air media.



(a) (b)

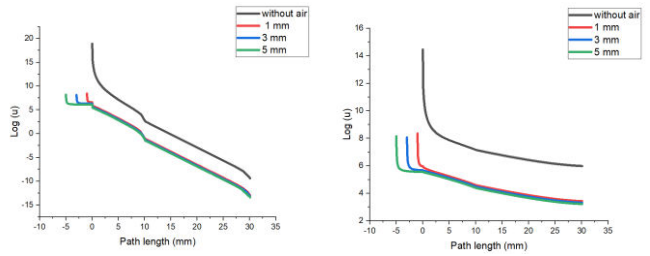
Fig. 6. Fluence distribution along with the 3D hypodermis model without air media for a wavelength of (a) 660 nm and (b) 915 nm.



(a) (b)

Fig. 7. Fluence distribution along with the 3D hypodermis model with air media for a wavelength of (a) 660 nm and (b) 915 nm.

A typical result was shown in Fig. 8 with the comparison with air media and without air media for 660 nm and 915 nm for the 3D hypodermis block which includes the epidermis, dermis and, hypodermis layer (blood vessel). The study showed that absorption and scattering decrease with an increase in the path length, graph shows as the path length increases there is a decrease in the intensity.



(a) (b)

Fig. 8. The graph shows the comparison of with and without air media for (a) 660 nm and (b) 915 nm

IV. Conclusion And Future Work

We discussed the design and construction of tissue that replicates the mechanical and optical properties of four peripheral layers of skin tissue, which include the epidermis, dermis, hypodermis, and blood vessels, using COMSOL Multiphysics. COMSOL Multiphysics was used to examine the distribution of fluence across several skin layers. The thickness or diameter of the tissue was among the mechanical qualities. The research revealed that the fluence distribution at a source and distance changes with variations in optical characteristics and that it can be computed using COMSOL with relative simplicity. The diffusion equation, which is typically used to analyse light dispersion within a tissue, was replicated using the Helmholtz equation module. The optical properties included optical absorption and scattering at wavelengths of 660 nm and 915 nm.

This preliminary work will further be extended towards developing an optical non-contact prototype by designing a shield to eliminate ambient light falling on the photodiode and performing simulations considering pulsatile flow using COMSOL.

References

[1] Lin, W.C., Motamedi, M. and Welch, A.J., 1996. Dynamics of tissue optics during laser heating of turbid media. Applied optics, 35(19), pp.3413-3420.

[2] Christo Ananth, M Kameswari, Densy John Vadakkan, Dr. Niha.K., “Enhancing Segmentation Approaches from Fuzzy-MPSO Based Liver Tumor Segmentation to Gaussian Mixture Model and Expected Maximization”, Journal Of Algebraic Statistics, Volume 13, Issue 2, June 2022,pp. 788-797.

[3] Bashkatov, A.N., Genina, E.A. and Tuchin, V.V., 2011. Optical properties of skin, subcutaneous, and muscle tissues: a review. Journal of Innovative Optical Health Sciences, 4(01), pp.9-38.

[4] Christo Ananth, D.R. Denslin Brabin, Jenifer Darling Rosita, “A Deep Learning Approach To Evaluation Of Augmented Evidence Of Diabetic Retinopathy”, Turkish Journal of Physiotherapy and Rehabilitation, Volume 32,Issue 3, December 2021,pp. 11813-11817.

[5] Bashkatov, A.N., Genina, E.A. and Tuchin, V.V., 2011. Optical properties of skin, subcutaneous, and muscle tissues: a review. Journal of Innovative Optical Health Sciences, 4(01), pp.9-38.

[6] Christo Ananth, Bindhya Thomas, Priyanka Surendran, Dr.A.Anitha, “Enhancing Segmentation Approaches from GC-GGC to Fuzzy K-C-Means”, Annals of the Romanian Society for Cell Biology, Volume 25,Issue 4, April 2021,pp. 2829 – 2834.

[7] Wilson, B.C., Patterson, M.S., Flock, S.T. and Wyman, D.R., 1989. Tissue optical properties about light propagation models and in vivo dosimetry. In Photon migration in tissues (pp. 25-42). Springer, Boston, MA.

[8] Kiruthiga, A., Alex, A., Balamugesh, T., Prabhu, D., Christopher, D.J., Preejith, S.P., Joseph, J. and Sivaprakasam, M., 2018, June. Reflectance pulse oximetry for blood oxygen saturation measurement from the diverse locations-a preliminary analysis. In 2018 IEEE International Symposium on Medical Measurements and Applications (MeMeA) (pp. 1-6). IEEE.

[9] Christo Ananth, Ruchin Jain, “Enhancing Segmentation Approaches from Oaam to Fuzzy K-C-Means”, The Journal of Research on the Lepidoptera, Volume 51, No. 2, 2020,(1086-1108).

[10] Lister, T., Wright, P.A. and Chappell, P.H., 2012. Optical properties of human skin. Journal of biomedical optics, 17(9), p.090901.

[11] Christo Ananth, D.R.Denslin Brabin, “ENHANCING SEGMENTATION APPROACHES FROM GAUSSIAN MIXTURE MODEL AND EXPECTED MAXIMIZATION TO SUPER PIXEL DIVISION ALGORITHM”, Sylwan, Volume 164, No. 4, 2020,(15-32).

[12] Vasudevan, V. and Sujatha, N., Light-tissue interaction modelling using COMSOL Multiphysics for multi-layered skin tissues, 2021.