# Light propagation through multilayer finger model

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ABSTRACT

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Non-invasive methods of measuring the composition of blood is of interest in the medical field. One such method is the spectroscopic study of how near-infrared light interacts with a human finger. Modeling theoretically the propagation of photon packets through a simulated multi-layer human finger provides useful information concerning the scattering and back scattering of light. This knowledge will increase the understanding of such medical devices as pulse oximeters and make strides in the possibility of measuring other compositions in blood.

Keywords: Propagation of Light, Monte-Carlo, Light Model, Homogeneous Layer

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# Contents

# List of Figures

# Chapter 1

# Introduction

## 1.1 Medical Field

Medicine is traditionally designed to fix problems after they occur. This approach is rooted back to an era when treatments were ineffective or suspect and the idea of preventative medicine was not well developed. However studies have shown that the earlier a problem is diagnosed, the greater the chances are for a cure. To catch problems early we must continually be looking for them. So constant physical checkups improve health.

Passive ways of monitoring our physical bodies are a convenient way to evaluate health. People are busy and do not think to regularly schedule expensive and time-consuming doctor visits. A typical visit takes three hours including travel and waiting time which is prohibitively long. And the battery of possible tests is huge. It would be good if there were ways of monitoring a few broad aspects of human health in a convenient manner.

The most important part of a human body to monitor is the blood. Blood visits every part of the body. If one organ or structure is malfunctioning there is nearly always a blood protein present or absent as a result. Blood tests are plentiful but not necessarily convenient. However, they are being

made more convenient in devices such as pulse oximeters that measure oxygen content through an infra-red finger probe.

The success of pulse oximeters illustrate how light can be used as a convenient blood probe. Indeed they are so successful that this is the most common way to measure blood oxygen levels, even in hospital exams. But after 20 years this technology still measures only oxygen levels despite the need to measure other quantities such as urea, hemoglobin, glucose, and hematocrit. This is because the light absorption characteristics of these proteins differ in only subtle ways. So looking for absorption features is too coarse for measurements beyond oxygenation (Schmitt 1991).

To extend pulse oximetry technology to measure other blood chemistry, accurate models of how light interacts with human tissue must be developed. Without them there will be no hope of finding the important, small optical signatures that are unique to proteins of interest in a blood stream.

## 1.2 General Research

There is research underway to better understand how light interacts with human tissue. Much of this research is theoretical models written in computer languages. These models start off very simply with a one layer modeling one part of the human body i.e. skin, blood. Wang, among others, has written simple Monte Carlo simulations that are accessible for free (Wang et al. 1995). However such models lack the complex nature of a human finger.

Multi-layer simulations are more complex than single-layer models and so can better predict how light propagates through a multi-layer substance such as a human finger. One such model, made by Zhang et al, simulated a two-layer human blood model of cylindrical dimensions (Wang et al. 2009). Data was collected how many photons were absorbed, reflected, or refracted. They concluded that as the refraction index of the tissue increased, photon absorption density also in-

creased. Adding to such research, Nichole Maughan developed a model that intermixed two layers into one homogenous mixture (Maughan et al. 2013). This allowed for a more accurate model of light propagation through human-like layers. Through this model we understand that the two-mix layers are not fully linearly dependent. In other words, the tissue with the greater molecular volume interacts more with photons than the smaller molecular tissue.

## 1.3 Human Finger Model

Building off such models of research we felt a complex and detailed model was needed. Combining discrete layers and homogeneously mixed layers, our model extends the basic techniques others have used to simulate to a human finger. We take into consideration, human skin, fat mixed with blood, arteries, and muscle.

Human anatomy structure was taken into consideration in the development of our model. This includes the proper depths and general structure of a typical adult human index finger (Lin et al. 1989). After the structure was constructed in software, photons were shot through the it and their propagation was tracked to see exactly how each layer affected their path. This data are the first information needed to extend pulse oximetry technology to measure blood chemistry.

# Chapter 2

# Method

This chapter will discuss the general physics of the project. I first discuss of how light scatters and absorbs in human tissue. I then consider the anatomy of a human index finger. Lastly a basic understanding of the theoretical model of how light propagates through tissues is discussed.

## 2.1 Scattering and Absorption

The human index finger is the candidate for our light propagation model. The reason for the finger rather than other body parts comes from the more practical usage of technology. It is easy to construct a light propagating tool where a human finger can easily fit between the detector and the light source. That human finger does have the necessary blood to allow adequate light interaction is precisely the success of pulse oximeters.

Modeling a human finger however is very complicated. Most models are simple and avoid multiple layers. There are lots of different material, elements, and tissues with which light can interact. Each wavelength interacts differently as well. The physics behind this interaction is a modification of Beer's Law.

$$I = I_0 e^{-\alpha * d}$$

$I$ is the absorbtion of light. $I_o$ is the intensity of light emitted from the source and $d$ is the physical separation of the light source and detector. The bulk attenuation coefficient $\alpha$ is defined as

$$\alpha = \sqrt{3\mu_a(\mu_a + \mu_s)}$$

$\mu_a$ is the absorptive coefficient and the $\mu_s$ is the scattering coefficient. For blood, scattering coefficient $\mu_s$ is two orders of magnitude larger than the absorption coefficient $\mu_a$ (Wang et al. 1995).

Different materials scatter and absorb as a function of wavelength. To reduce complexity in this model, we have chosen the wavelength $\lambda$ = 810 *nm* because that is the wavelength at which light interacts the same with oxygenated or deoxygenated hemoglobin. Therefore variant oxygen levels does not affect our results.

## 2.2 The Index Finger

Our model finger contains layers of epidermis, dermis, fat mixed with blood, artery, and blood in veins. To make an appropriate model we felt it was instructive to see the anatomy of a human index finger. I had the opportunity to participate in a dissection of a cadaver human finger at Brigham Young University. Through the University of Utah Donor Program, we were given a human cadaver hand to dissect. After removing the index finger, extensive dissection was done to verigy the general anatomy of the human index finger; especially the location of the nerve and artery. The figure 1.1 shows this dissection.

The outer skin layer is known as the epidermis. This layer is about 500 micrometers in


**Figure 2.1** This picture shows a the dissection of a male fifty year old cadaver index finger. Our goal was to confirm where the nerve and artery located in the human index finger. In this picture, the stringy part above the other is the nerve, and the other is the artery. This confirmed that location of the nerve and artery are parallel to the bone but lying next to the bone; not underneath the bone.

depth(Tuchin 2007). The next layer, the dermis, has about the same properties as epidermis. It lies below the epidermis and is approximately 500 micrometers in depth as well. The absorption and scattering of both these layers are well-characterized and easy to model.

Surrounding the bone on all sides is a layer of fat around 3000 micrometers thick. Most of the human finger is made up of fat. Measuring fat is more complicated than the skin layers as it is imbedded with approximately 5% blood. Maughan et al discovered that as photons propagate through the material they interact non-linearly in accordance with the blood to fat ratio.Following up the two sides of the finger along the bone are the veins, arteries, and the nerves. As shown in figure 2.1.

Veins and arteries are full of blood; the most important diagnostic material. Blood highly refracts with light. Veins are typically 2000 micrometer in diameter. While arteries are a little smaller ranging from 400 to 500 micrometers in diameter. The actually tissue of the vein and artery walls was not modeled. The assumption here is that they are 100% blood, as the walls are very small and thin. The nerves are much thicker. Maughan's model of light propagation did not have the coefficients of nerves for scattering and absorption at the desired wavelength. We decided to model nerves by using the coefficients of muscle instead. Nerves are comparable to veins in diameter and are modeled at 2000 micrometers.

There are other materials in a human finger which we did not take into account, such as muscles. Muscle, though present close to the hand, is not very present at the tip of the finger. The dissection of the index finger confirmed that the muscle lies directly under the bone on the inside of the hand. Since pulse oximeters and other such devices are attached to the end of the finger and light is shot on the side of the bone, muscle is not directly exposed to light and so not needed in the model. We also left out bone. This may seem like a large variable to leave out but we assumed that most light

| | depth($d$) | $\mu_a$ | $\mu_s$ |
|---|---|---|---|
| Epidermis | 500 | 4.0 | 42 |
| Dermis | 500 | 0.23 | 17.5 |
| Fat | 3000 | 0.010 | 0.198 |
| Vein | 2000 | 0.65 | 69 |
| Artery | 2000 | 0.65 | 69 |
| Nerve | 400 | 0.025 | 0.7 |

**Table 2.1** The thickness $d$, $\mu_a$ is the absorptive coefficient and the $\mu_s$ is the scattering coefficient.

propagation that hits bone will be absorbed.

## 2.3 Models

There are many light propagation models that only interact with one material (Prahl et al. 1989). Such models are appropriate for analysis of single materials but are too simple for a complicated system such as a human finger. Stepping up from one-layer models are two-layer models (Zhang et al. 2007). These models still lack the detail for a model of a human finger. Maughan et al took this a step further. Their research was mixing two layers into one homogenous mixture. They compared the theoretical Monte Carlo results of a two-layer model with their mixed model. They discovered that having two different tissues imbedded in each other favors ineratctions with the material with the larger $\alpha$ in a non-linear way. So when a smaller volume of a tissue is mixed throughout another tissue, if that smaller tissue has a molecular size that interacts better with the specified wavelength, then it will interact even more with the light than it would if it was its own layer. In other words, the tissues do not interact more because of volume but more based

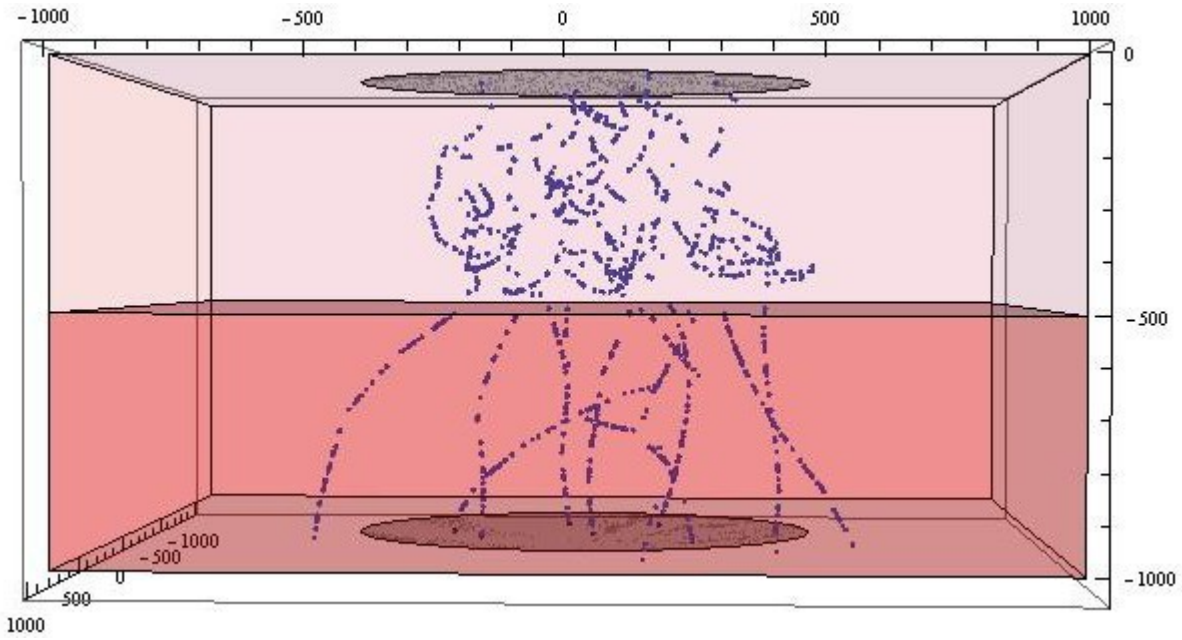


**Figure 2.2** In Maughan's model, ten photons propagate first through a water layer then a blood layer. It is interesting to note how the path of the photons change through different mediums. This is due to different absorption and scattering coefficients.

off of their molecular size. Maughan found that light attenuates nonlinearly when compared to the volume fraction of each constituent. Figure 2.2 show a simple example of how a two tissues interact differently.

We combined homogenous mixtures with multi-layers to create a model of the anatomy of the human finger. Our model is based off of Maughan's model. Using her model allowed us to have layers of different tissues and allowed us to create layers that were mixed with other layers. This best optimized our modeling of a human finger. We created nine different layers modeling light passing on one side of the tip of a human index finger. These layers are in order as follows, epidermis, dermis, fat, then artery, vein and nerve in parallel, then fat, dermis, and epidermis. This model goes from the top of an index finger, through nine layers, and out the bottom.

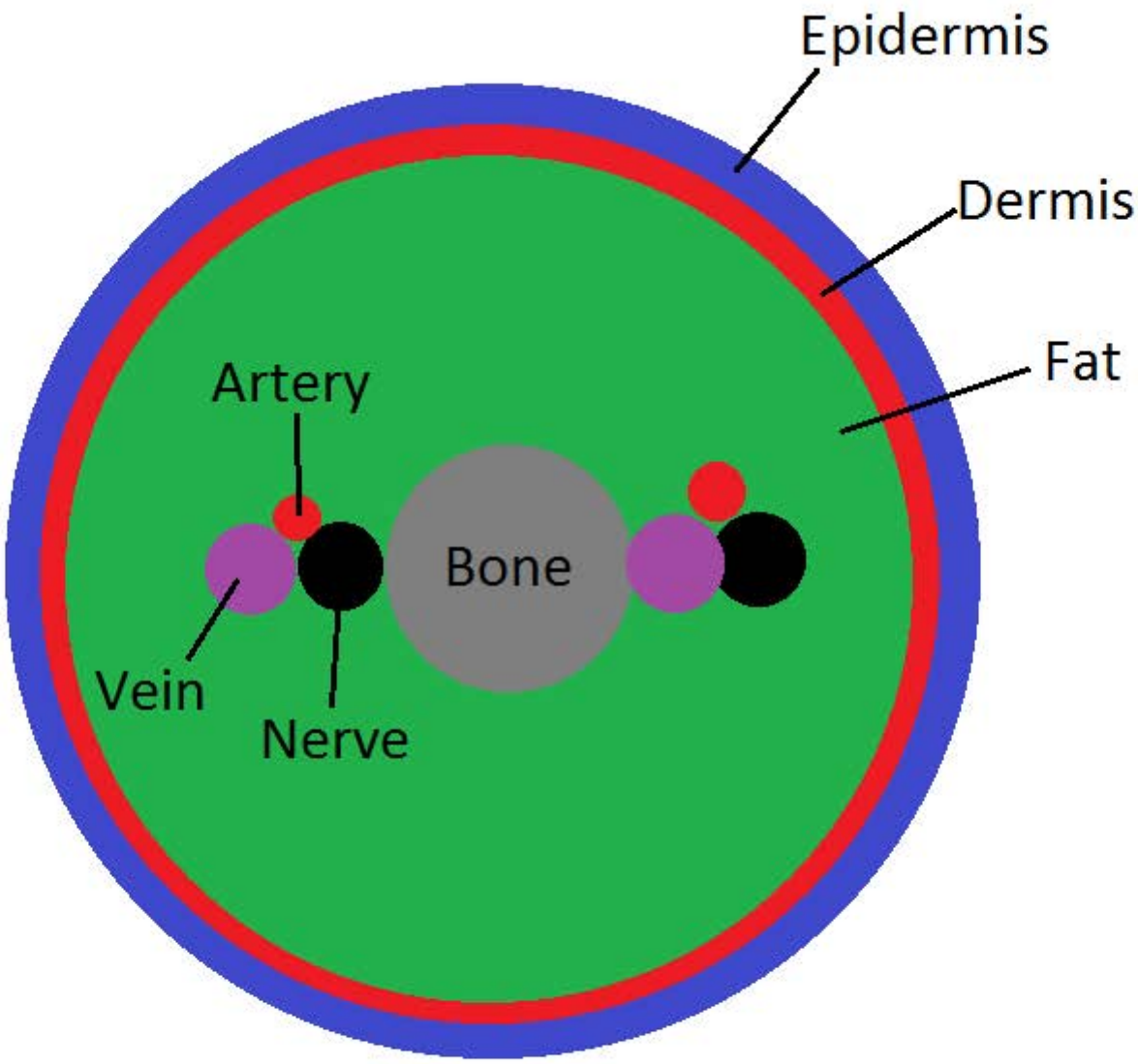


**Figure 2.3** This model includes epidermis, dermis, fat, nerve, and artery layers. We modeled the artery and nerve layers in one layer.

## 2.4 Procedure

Our modeling is based off of the mathematica model that Nicole Maughan used in her paper "Monte Carlo Simulation of Near-infrared Light Propagation through Homogeneous Mixed Media" (Maughan et al. 2013). Her model specified on the amount of photon packets sent through two layered materials with their respective coefficients and at a given thickness. We use her model to recreate one layer of our model at a time. We set the thickness of the material based on the relative values given in table 1. We use the tissue coefficients of those material as well.

The first layer run was epidermis. We set the depth at 500 micrometers, the wavelength at 810 *nm*; and the number of photon packets at 100. As the model stepped through the tissue it would record the positions in space ($x$, $y$, $z$) and their vector angles ($\mu_x$, $\mu_y$, $\mu_z$) into a matrix. After this layer simulation finished, the model would take the positions in space and vector angles of the photons that made it all 500 micrometers through the material. This would exclude all photons that got turned around or were absorbed into the material. The software would then write a text file of the $x$, $y$, $z$, $\mu_x$, $\mu_y$, $\mu_z$ values for each photon that passed through the whole material.

The next layer uses the exact same model except the photons are not assigned random positions at the beginning but are based off of the written text file from the previous layer. Before running the next layer we would set new tissue coefficients and layer thickness as needed. We then are able to run multiple layers using Maughan's model. The fat layer was set up as a homogeneous mixture of 5% blood; utilizing maximum use of Maughan's model.

The artery, vein and nerve were modeled differently. They are side by side. I assumed that both the artery and vein are 100% blood so we combined those two layers. I layed these two layers side by side and put them at the same thickness, which is another approximation. I then placed a nerve layer of the same thickness by the blood mixture in parallel. When the fat layer model above these two parallel layers finished, the model would separated the photon packets that would hit the nerve and those that would hit the blood. I then ran two separate simulations, one of the nerve and the

other of the blood. Then I combined those photons that made it through those simulations and put them together through the next fat layer.

I ran through all nine layers, about 1 centimeter of tissue, in 40 min. Each layer had statistics run on it calculating how many photon packets got absorbed, turned around, and made it through the material. To show the propagation of light, we also counted how many hit a typical sized detector once exiting the last layer.

# Chapter 3

# Results

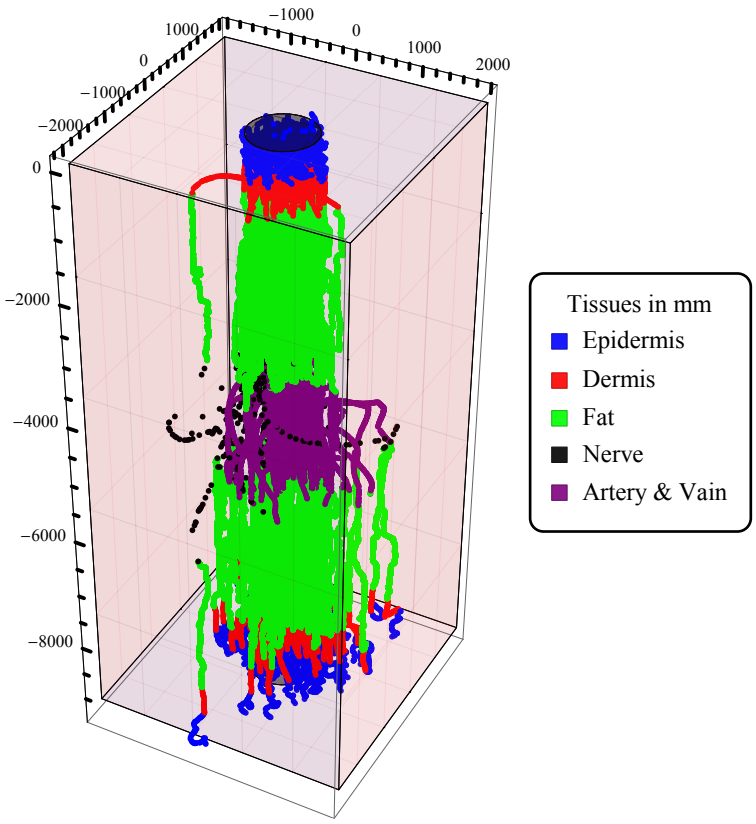


**Figure 3.1** One Hundred Photons propagating through a multi-layer and homogenous mixture layers modeling a human finger. The axes are in millimeters.

Figure 3.1 is a multi-layer model of a human finger. The blue photon paths are interacting with the epidermis layers, red photon paths are interacting with the dermis layers, green photon paths are interacting with the fat layers, purple photon paths are interacting with the vein/artery layer, and black photon paths are interacting with the nerve layer. From observation we find some important results. Even though the nerve layer, represented by the black dots, is small in comparison to the other layers it causes the greatest scattering (see Fig. 3.1). These results are important in seeing which materials in the human finger will affect the spectroscopy of light the most. We learn that the nerve causes a block of some of the light propagations.

## 3.1 Scattering

For each layer we compiled how many photons made it through the layer's thickness, and the amount of photons that back-scattered out of it. Table 3.1 shows these results.

Figs 3.1-3.3 show how some layers scatter light more than others. Both fat layers have very little scattering. The light appears to go straight through them. This is a surprising results as it does have 5.0% blood in the fat. Blood has a large cross section so we expected more scattering. Though that probably did occur, the scattering was minor compared to other layers. The artery layer, which is 100% blood, does cause lots of scattering. Figure 3.1 shows that the photons (purple dots) are well scattered in that part of the index finger. This layer is encouraging because it means light is sensitive to the presence of blood. The skin layers cause more scattering than the fat layer. Especially the epidermis layers. This scattering occurs when light enters and exists the human finger. This scattering is not encouraging because it causes the light to already be spread

| Tissue Layers | Photons Start | Photons End | Back-Scatter |
|---|---|---|---|
| Epidermis | 100 | 89 | 11 |
| Dermis | 89 | 89 | 0 |
| Fat | 89 | 89 | 0 |
| Artery/Vein | 69 | 67 | 2 |
| Nerve | 20 | 18 | 2 |
| Fat | 85 | 83 | 2 |
| Dermis | 83 | 82 | 1 |
| Epidermis | 82 | 72 | 10 |

**Table 3.1** Statistics of 100 photons passing through 8 layer tissue model.

out as it begins to enter the more uninteresting layers of the model.

## 3.2 Back-Scattering

With each layer being made up of different cross sectional sizes and different tissue coefficients back-scattering occurs differently across the index finger model. Surprisingly, a layer that causes scattering does not necessarily cause great back-scattering. Again, the fat layers cause the least amount of back-scattering. Only the second layer of fat scattered just two photons back.

The nerve layer scattered the light the most but only had one photon back-scatter. This is a surprising result. It is natural to believe that if a layer scatters the light a lot it must back-scatter a lot too. However, this layer seems not to suggest that. Greater research is needed to discover the reasons for this occurrence.

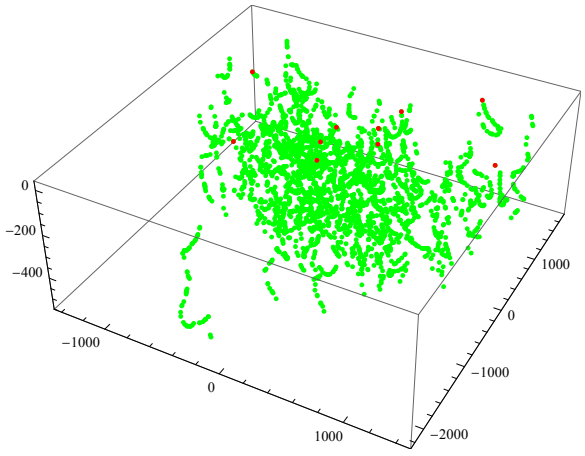


**Figure 3.2** Ten photons back-scattering in the second layer of epidermis. The red dots are the photons that back-scatter. The axes are in millimeters.

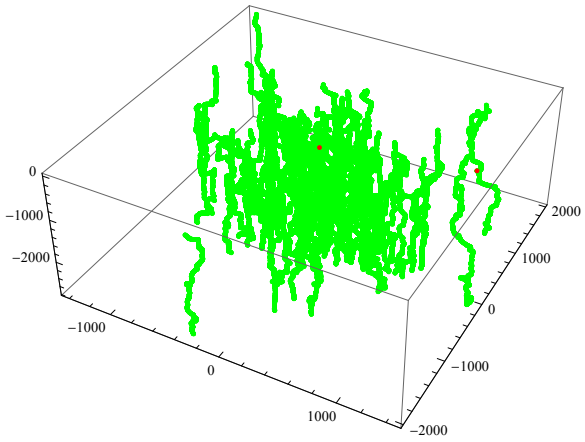


**Figure 3.3** Two photons back-scatter in second fat layer. The axes are in millimeters.

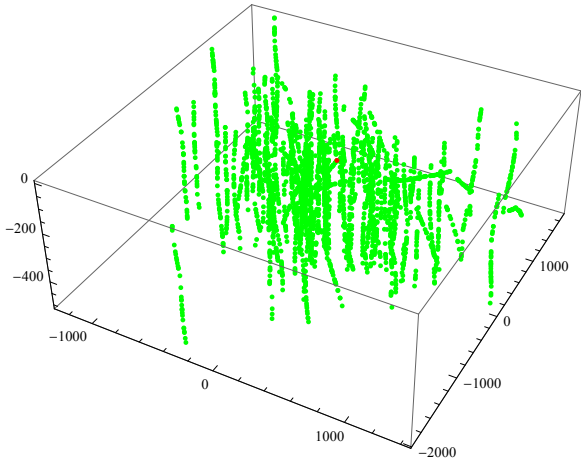


**Figure 3.4** Only one photon back-scatters and the photons paths are very straight through the second dermis layer. The axes are in millimeters.

The epidermis layers definitely cause the greatest back-scattering (see table 2). This seems reasonable as the epidermis layers scatter the light; but not as much as the nerve layer. Both epidermis layers scatter about ten times the amount more than the other layers. Since we cannot see veins or bone in our hand, it is obvious that light back scatters from our epidermis. Figures 3.1-3.3 shows the back-scattering of epidermis compared to other layers. The red dotes show the photons which back-scatter.

## 3.3 Detection

Of most importance, we would like to know how many of the one hundred photons actually pass through the artery and vein and still hit the detector on the other side. The blood carries the vital proteins. These proteins carry the information desired. Out model showed that twenty-four of the one hundred photons pass through the blood and hit the detector on the other side.

## 3.4 Further Research

Our results only scratch the service of finding specific proteins in human blood by the method of light propagation. There needs to be more done with how the energy of the light is absorbed due to the $\mu_s$ coefficient. Also, our theoretical model does not take into account for diffraction coefficients when light moves from one tissue to another. We made a large assumption that nerve has similar scattering coefficients as muscle; as we only had the parameters for muscle tissue programmed into the model.

## 3.5 Conclusion

Using layered and homogenous layers and Monte Carlo simulation we modeled how light propagates through a human index finger. This can aide in medical research to better pulse-oximeters and find ways to measure glucose in human blood in a non-invasive way. We find that the epidermis layers cause the greatest back-scattering while the nerve layer causes the greatest scattering. Only twenty-four of our one hundred photon packets made it through the finger and hit a detector on the other side. Back-scattering occurs but not in much quantity.

# Appendix A

# Appendix

## A.1 Instructions for using "Monte Carlo Simulation of Photon Propagation" with the mixed model

There are three main notebooks. The Tissue Coefficients one needs to be executed so that the .mx files can be generated on your computer and then be read in through the main simulation notebook. This notebook is used for reading in $\mu_s$, and $\mu_a$, for each type of material. Any time you run the simulation on another computer, you have to regenerate those .mx files as they are unique to each computer. You also have to regenerate those files if you ever make a change to the Tissue Coefficients notebook. Once those files are generated, you can close the notebook.

In the Monte Carlo Simulation notebook, in the first cell, there are two symbols: "tissue1name" and "tissue2name". This is where you define which materials to simulate with. Even if you want to just work with one material, you need to define both.

Lambda ($\lambda$) is the wavelength, and you need to pick one where there are tissue coefficients for both materials at that specific wavelength. You can check to see which wavelengths will work by looking in the Tissue Coefficient notebook.

The symbols "tissue1" and "tissue2" define how much of each material you want. So, if you have H2O defined in your "tissue1name", then tissue1=1.0 means that you have 100% volume fraction of H2O and 0% volume fraction of tissue2.

The second cell is the simulation. The symbol "min" is the minimum thickness that the simulation runs through, defined in microns. The symbol "max" is the maximum thickness that the simulation runs through, also in microns. The symbol "spacing" is the interval spacing to the next thickness that the model runs through (in microns as well). So, if min= 1, max= 5000, and spacing= 1, the simulation runs through a loop starting at a thickness of 1 $\mu$m, then the next simulation will start over but run through a thickness of 2 $\mu$m, and so on and so on until the simulation resets and runs again with a thickness of 5000 $\mu$m. The Monitor command shows the thickness that the simulation is currently running though at the bottom on the code.

Each full simulation (running through the entire loop, from "min" thickness to "max" thickness) creates six .txt files.

The txt file with the title "data" gives all the information including the thickness, side-scattering, detected energy, number of photon packets, etc. I rarely use this file, since it is a lot of information. Sometimes, though, it is useful to reference when debugging.

The "energy data...txt" file tells you the intensity of the photon packets that hit the detector for each given thickness. This file can be read into a Mathematica notebook using the ReadList command.

The "Interactions...txt" file keeps track of how many photon packet interactions occur for each material at a given thickness. There is an ordered pair of the form thickness, tissue1 interactions, tissue2 interactions for each thickness the simulation runs through.

The fifth text file is created by running the last cell on the mathematica code. It creates a text file called "positionMatrix...txt". This just has all the $x$, $y$, and $z$, of all points the light has propagated through. The combinations of all these text files created figure 3.1 of this paper.

The last text file is created by running the last cell on the mathematica code. This code creates a matrix of the position and directional coefficients of every photon that propagates all the way through the material. It writes this information in the text file named "finalpositionMatrix....txt". Then copy this txt file into the looped mathematica code that runs the mixed model based on previous layers. This mixed model code runs the exact same except instead of randomly assigning starting position, it will take the position and directions from the "finalpositionMatrix...txt".

The last file is "Track Packets...txt". It keeps tracks of where each photon packet finishes its course given there are only four options for where the packet dies (exit out the top, absorbed in the material, exit out the bottom but do not hit the detector, or hit the detector). This file can also be imported using the command ReadList. The ordered pair has the form thickness, exit out the top, absorbed in the material, exit out the bottom but do not hit the detector, or hit the detector. The total of the second part of that pair should always equal the number of photon packets for each thickness.

The last notebook, "Attenuation Coefficient," is used for analyzing the "energy data...txt" file and the "Track Packets...txt" file. The first part fits an attenuation coefficient ($\alpha$) for each composition of material. The blue points are the data points from the simulation; the black curve is a fit to the data points from the simulation; the red curve represents the curve with an attentuation coefficient following the $\alpha = \sqrt{\mu_a(\mu_a + \mu_s)}$ relationship. The "Track where all photon packets stop" section is for looking at individual compositions (e.g. 100% water or 95/55 fat and blood: i.e. like we had in our finger model) of the simulation, and seeing where most of the packets end up (exiting out top, being absorbed, etc).

# Bibliography

Lin, G.-T., Amadio, P. C., An, K.-N., & Cooney, W. P. 1989, The Journal of Hand Surgery, 14A, 949

Maughan, N. M., Moody, J. W., Turley, R. S., & Busath, D. 2013

Prahl, S., Keijzer, M., Jacques, S., & Welch, A. 1989, SPIE Institute Series, 5, 102

Schmitt, J. 1991, IEEE Transactions on Biomedical Engineering, 38, 1194

Tuchin, V. 2007, Tissue Optics: Light Scattering Methods and Instruments for Medical Diagnosis, 2nd edn. (Bellingham, Washington: Society of Photo-Optical Instrumentation Engineers (SPIE)), 10–21,145–191

Wang, L., Jacques, S. L., & Zheng, L. 1995, Computer Methods and Programs in Biomedicine, 47, 131

Wang, Z., Wang, L., Zhang, Y., & Chen, X. 2009, Bioinformatics and Biomedical Engineering, 3, 11

Zhang, L., Wang, X., Sun, M., Chai, Y., Hao, Z., & Zhang, C. 2007, Journal of Modern Optics, 54, 1395