

# Optical Tissue Modeling Applied to Photoplethysmography

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## Abstract

*An optical tissue model has been proposed to simulate the typical photoplethysmographic (PPG) amplitude and characteristics. The model parameters have been chosen to reproduce the classic finger PPG signal amplitude, as well as the wrist PPG signal amplitude from the ulnar and radial arteries. The PPG simulations have been validated with experimental data. The model uses a commercial simulation program, and is capable of simulating the effects of skin pigmentation, LED/photodiode separation, laser sources, angle of incidence effects, skin thickness, light polarization, and motion artefact amplitude.*

## 1. Introduction

There is increased interest in using light and optical methods as a non-invasive tool for diagnostics and therapies due to its safety, simplicity, and low cost. Photoplethysmography (PPG) has been a particularly successful technology in this regard. The PPG signal has found widespread clinical use as a heart rate monitor and a blood oxygen saturation monitor in the form of a pulse oximeter. Despite its widespread adoption, PPG measurements, especially those outside the well-controlled clinical environment, suffer from inaccuracies. Better understanding of the PPG signal through optical tissue modeling is an important tool in improving the performance of PPG technologies.

### 1.1. Principal of PPG

A light source (such as an LED) emits a beam of light of a particular wavelength that then passes through human tissue. A certain amount of this light is absorbed within the tissue, and a certain amount is scattered within the tissue. A photodiode detects part of the light exiting the tissue. The signal detected by the photodiode consists of an unchanging or slowly changing DC signal, as well as a small pulsatile AC signal. The AC component is due to the changing volume of blood in the light path over the course of a heartbeat [1].

Depending on the LED and photodiode placement either reflectance or transmission PPG may be used (see figure 1). The model presented has been studied with regard to reflectance PPG.

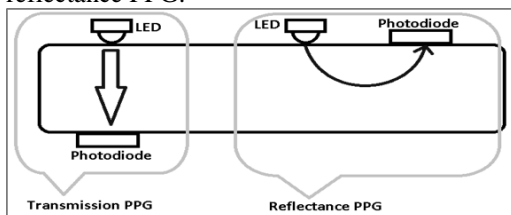


Fig 1. Transmission and reflectance PPG

Various studies have shown that the PPG and pulse oximeter signals are affected by factors such as LED wavelength[2] (which suffers from manufacturing variability), probe contact pressure[3], blood perfusion[4], presence of chromophores[5], temperature effects[6], LED/photodiode separation[7], as well as suffering from interferences such as ambient lighting and movement artefacts.

## 2. Methods

### 2.1. Modeling method

Modeling methods in this field can be broadly classified into two categories: closed mathematical forms such as those that are based on Radiative Transfer Theory, or Monte Carlo based models. The model presented is based upon the Monte Carlo method. Monte Carlo models trace the propagation of a large number of individual rays subject to statistical absorption and scattering. The accuracy of the solution to the Monte Carlo model can be chosen to any degree by increasing the number of rays traced, and is only limited by processing power and time [8].

The model presented has been developed using TracePro from Lambda Research, a commercial ray tracing program for optical analysis of solid models (<http://lambdaresearch.com>). This approach takes advantage of state-of-the-art optical modeling while allowing more time to focus on accurate representation of the tissue physiology and optical properties. In addition to the Monte Carlo based modeling engine, TracePro provides a 3D drawing environment and control over light source parameters (such as wavelength, or whether a collimated polarized laser source is used or a lambertian pattern LED). In addition it provides powerful analysis tools (ray histories, illuminance maps, optical-time-of-flight analysis etc.), as well as control over detailed simulation parameters (ray splitting, flux thresholds etc.).

### 2.2. Model description

The model is based on the multilayer model in [9] and [10]. The top level model represents the wrist where one might wear a portable PPG device. It shows the ulnar and radial bones and arteries. Simplified model sections were used for model verification (see Fig 2).

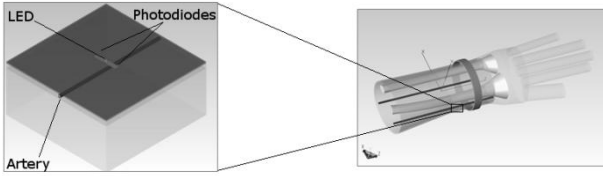


Fig 2. Simplified model (left) and top level model (right)

The LED and photodiodes were simulated within the model. The photodiodes could be simulated at various distances from the LED. Within the model, the main physiological layers in skin are represented with their relevant optical coefficients and physiological thicknesses (see Fig 3 and Table 1).

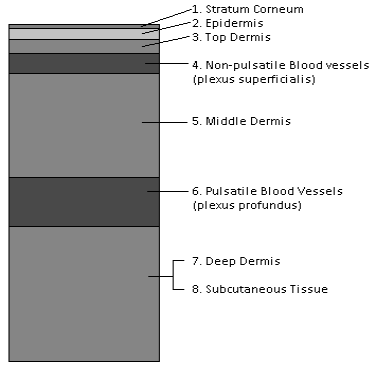


Fig 3. Model tissue layers

### 2.3. Simulation of PPG

The technique for simulating the PPG signal was adapted from that of [11]. The tissue is simulated in two states representing the diastolic state and the systolic state. The signal change between the two states represents the PPG amplitude.

The two states are calculated by assuming the plexus profundus experiences expansion of its blood volume during the systolic state. The absorption and scattering coefficients are then weighted accordingly. To simplify the model it was assumed that the plexus superficialis was dermal tissue with 4% blood volume during diastole and 4.25% during systole. This value is a compromise between the values chosen in [11] and those from [12].

The ulnar artery was similarly simulated in the diastolic and systolic state (see Fig 4) with typical physiological dimensions taken from [13][14][15]. An arterial expansion of approximately 15% was used, a value taken from [16], the expansion of the carotid artery.

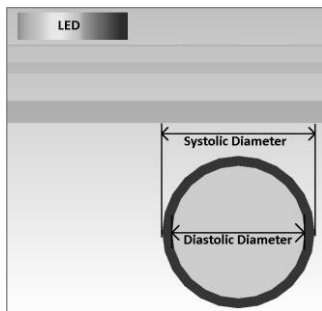


Fig 4. Example of artery and various skin layers in the model

### 2.4. Measurement Methods

The PPG signal was measured in the laboratory using one healthy male volunteer. Currents and LED/photodiode separation were varied as necessary. The LED used was 810nm, and model simulations were also done at 810nm. This is because 810nm is wavelength at which both oxygenated and deoxygenated blood have the same absorption coefficient (an isobestic point). The variable of oxygen saturation was therefore effectively removed from measurements, simplifying model verification.

The PPG signal amplitude shows great variability between measurements due to the number of factors that affect the PPG signal. This caused significant difficulty in obtaining repeatable measurements. In order to reduce the magnitude of this variability averaging of 20 measurements was used.

### 3. Results

In order to verify the model simulation data is compared with laboratory data in Fig 5. This chart shows the pulsatile component of the PPG signal as a percentage of the DC component for both the laboratory data and the simulation data over a range of LED/photodiode separations. A similar comparison, shown in Fig 6, was carried out using the signal from the ulnar artery.

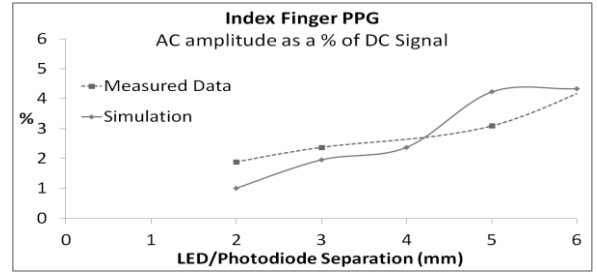


Fig 5. Index Finger - relative PPG amplitude

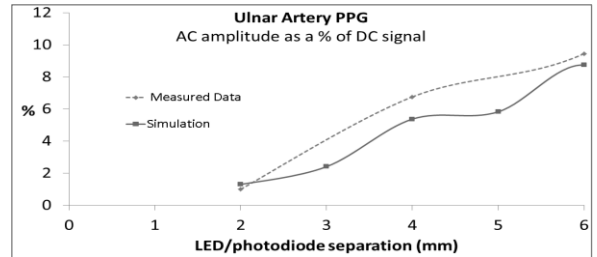


Fig 6. Ulnar artery PPG - relative PPG amplitude

In both figures the simulation precision suffers from the use of a relatively small number of rays as a sacrifice to reduce simulation time. The variations in the lines are not a property of the model. The model can easily be adapted to other characteristic PPG signals by adjusting the model parameters (depth of layers, blood volume etc.). The simulations shown here extend the work of [11] to include simulations of the wrist arteries, and demonstrate the importance of these arteries to the PPG signal in the wrist.

A useful property of any model is the ability to simulate effects that are difficult, tedious and time consuming to measure in the laboratory. One such effect is the impact of melanin on the PPG measurement. It is possible with

this type of model to simulate the effects of increased absorption in the epidermis layer due to increased melanin [11], as seen in Fig 7.

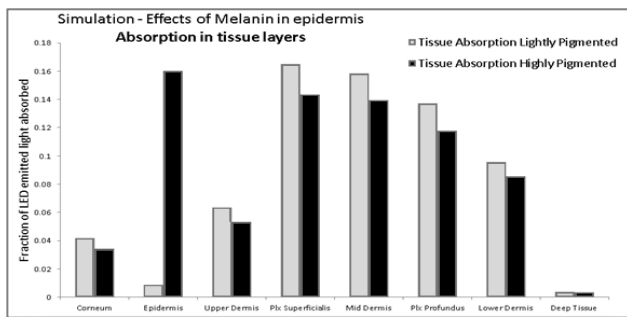


Fig 7. Effect of pigmentation: absorption by layers

Unsurprisingly, the simulation shows that highly pigmented epidermis absorbs more light than lightly pigmented epidermis. However, the simulation also allows us to quantify this effect.

It is also possible to simulate the effects of different characteristic light sources. In Fig 8 a simulation of a laser source with an angle of incidence of 45 degrees is shown. The scale in the figure is in approximately 300 $\mu$ m by 150 $\mu$ m, yet even in this small range it is possible to see the immediate diffusion of light once it has entered the tissue. Fig 9 shows the relative change in amplitude due to the use of a laser at 45 degrees compared to 90 degrees to the skin.

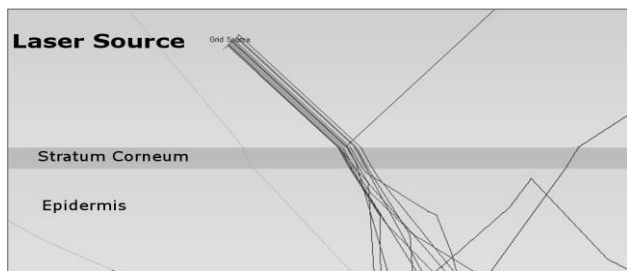


Fig 8. Laser source at 45 degree angle of incidence

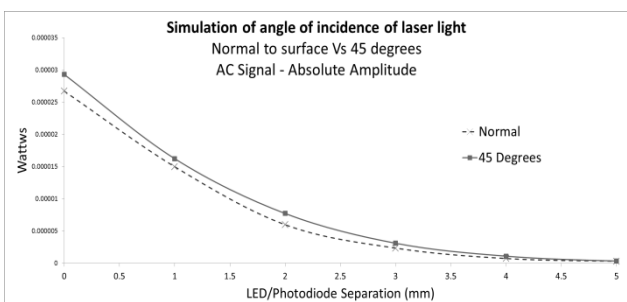


Fig 9. Simulation of the effect of the angle of incidence of laser

This simulation suggests that the use of laser light angled towards the photodiode results in little improvement in the PPG signal. Importantly it is a demonstration of the ease of performing imaginative PPG simulations using this model in TracePro.

## 4. Conclusions

The work of [11] has been extended to include simulation of the PPG signal in the arteries of the wrist, as well as

other simulations such as the role of the angle of incidence of laser light.

While the accuracy of the model can, and needs to be improved, the value of this model is not in simulating the precise value of the PPG signal, but in simulating the effects and trends that are difficult to study in the laboratory.

Previous studies into tissue models such as [11] used publicly available MCML and CONV code to carry out the simulations. It is the author's opinion that the use of commercial programs can greatly improve the ambition of optical tissue model simulations. The professional quality of modern optical ray trace programs mean that no time need be spent in the coding of the simulation engine. In addition, the many features available in these programs can greatly facilitate the creation of imaginative simulations and aid in-depth analysis.

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Table 1. Model parameters used in simulation

Tissue Layer [810nm wavelength]	Absorption mm <sup>-1</sup>	Scattering mm <sup>-1</sup>	Anisotropy (g)	Refractive Index	Thickness (μm) Finger [ Wrist Extended]	References
Blood	0.65	69	0.993	1.393	-	[17][18][19][20]
Stratum Corneum	0.7	20	0.95	1.55	20	[9]
Epidermis Pigmentation: Light/Medium/Heavy	0.03/0.3/0.7	5.29	0.8	1.4	100	[9][17]
Dermis (Top)	0.109	9.792	0.817	1.4	200	[9]
Dermis (Mid)	0.109	9.792	0.817	1.4	800 [500]	[9]
Dermis (Deep)	0.109	9.792	0.817	1.4	Infinite	[9]
Plexus Superficialis	0.131	12.16	0.824	1.4	200	[21]
Plexus Profundus: Diastolic	0.131	12.16	0.824	1.4	600 [400]	[21]
Plexus Profundus: Systolic	0.1324	12.308	0.824	1.4	600 [400]	[21]
Bone	0.024	28	0.93	1.56	-	[9]
Ulnar Artery: centre depth / diastole radius / systole radius	0.65	69	0.993	1.393	~3.4mm / 1.2mm / 1.38mm	[13] [14] [15] [16]