BIOCONTROL
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TECHNICAL REPORT

#TECHRP REV. D

RECORD #

TITLE	FILENAME	REVISION
Monte Carlo Model of Photon Transport Through Skin		
PROJECT OR PROGRAM NAME	PROGRAM ROOT NUMBER	
PROGRAM TASK DESCRIPTION	PROGRAM TASK NUMBER	
NAME	DEPARTMENT	DATE
Jeremy Grata		

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Analysis

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Monte Carlo, Photon Path Length, Photon Penetration Depth, Absorbtion Coefficient, Scattering Coefficient

DOCUMENTATION TYPE

- ☐ Validation
- ☐ Error Budget
- ☐ Reliability
- ☐ Sensitivity
- ☐ Verification
- ☐ Product Support
- ☐ Risk Analysis
- ☒ Other

ASSOCIATED REPORTS
960927MD.DOC,Marbach Paper.pdf,Instrumentation Metrics Paper.pdf,Marbach's Thesis

Abstract

Assumptions for building a Monte Carlo model of photon transport through skin are discussed and input parameters are chosen for a simple model. A skin model based on 80% water is constructed which can be used for various analyses. Absorbance based on the model agrees with empirical skin absorbance measurements to within 10% between 1200 and 1860 nm. Potential causes of deviations of the model from empirical observations are discussed along with the physical meaning of the output parameters of the model.

Present a condensed synopsis of the report including a brief description of the setup of the work, its purpose, the results, and the conclusions. This overview is short, concise, and no longer than this page.

Background

Monte Carlo modeling has been performed in the past to address specific topics of interest regarding photon transport through skin such as determining mean photon path length, photon penetration depth, etc [Marbach, Difrancesco]. It has also been used to determine the specific scattering coefficients required in fabricating a suitable skin phantom [Instrumentation Metrics]. It has become apparent in developing research prototypes of probes for the Gamma project that a tool is needed capable of assessing potential probe performance with respect to glucose prediction without the need of a clinical trial. In addition to the known clinical performance of the Diasensor with a standard probe and the Diasensor with the D1K differential probe, a suitable Monte Carlo model of skin is a tool that can be used to provide the information that relates a specific probe design to its effect on glucose prediction performance. Until now, a suitable model of sufficient size had not been generated and stored with the purpose of being used as a tool for assessing future probe performance.

Present a summary of the technical information and preceding work forming the basis for this work.

Introduction

A Monte Carlo model of photon transports makes use of the laws governing both the wavelike and quantum properties of electromagnetic radiation. It is well known that EM radiation, or light, can be treated either in a quantum fashion as photons or as a wave with the use of classical EM theory. When treated as a photon a "particle" of light either exists or it doesn't; the number of photons defines amplitude or intensity. The photon can interact with mater, as classical mechanics would dictate, assigning some "mass" to the photon (based on its wavelength or energy) and allowing collisions with matter to be either purely elastic or annihilating. When treated as a wave, the intensity of the light is defined as the amplitude of the EM wave. Interactions with matter occur based on wave mechanics and coefficients of extinction that are properties of the matter's electric and magnetic susceptibilities. Typically, when light is treated as a wave, complex interactions with matter yield complex mathematical representations as well.

A Monte Carlo model makes use of the simplicity of the quantum nature of light by following only the wave fronts of an EM wave through an elastic scattering medium. Scattering events are randomly placed in the EM wave-front path selected based on a model input called the scattering coefficient. The direction the wave fronts take after the collision is also randomly chosen based on a model input called the anisotropy. Anisotropy can be defined a number representing the statistical probability that a photon would progress through a scattering event with no directional change or un-scattered. The index of refraction of the scatter and medium between scatters is also a necessary input parameter since these indices govern wave speed in the medium and are needed to calculate the wave front direction. The model keeps track of intensity by assigning the amplitude of each incoming wave a value of one and by treating the EM wave between scattering events in a classical fashion allowing the amplitude to decrease based on the distance between scattering events and an input parameter indicative of the medium between scatters called the absorbance coefficient.

Building a Monte Carlo model of skin in this fashion makes it possible to follow an EM wave front through an absorbing/scattering medium such as skin. For simplicity each wave front is called a photon, even though the true definition of a photon has no amplitude associated with it. Some of the wave fronts or photons put into the model of skin will experience multiple scattering events and exit the plane defining the surface of the skin. Others will experience an amplitude reduction beyond a point capable of being detected with a real-world electrical system. By launching multiple photons into the model, information about the average paths, trajectories and amplitude attenuations experienced by photons in the model are stored and used to characterize the model. For example, since each photon is followed individually, its total path length (length between scattering events), penetration depth (maximum distance traveled normal to the plane of the surface of skin) and amplitude attenuation can be saved for a large number of photons and the information of each "flight" compiled and summarized.

This model of skin can be made quite elaborate or simple as needed. A simple model would be one in which there is only one homogenous layer governed by a set of scaled absorbtion coefficients of one constituent in the skin, one set of scattering coefficients and fixed values for anisotropy and index of refraction. Increasing the number of parameters such as "layers" (regions having different scatter and absorbing characteristics from other regions), "in-homogeneity" (variable absorbance or scattering parameters within a layer) and by incorporating information from multiple constituents allows for more accurate modeling of a dynamic optical medium such as skin. Propagation can be calculated in 1D for a simple model or in 3D for a complicated model (or 4D when keeping track of phase information). Photon launch parameters can be restricted to a single point on the plane of the surface of the skin model with all photons being launched normal to the surface or placed away from the skin in various locations with varying angles of incidence. Only photons exiting the plane of the skin surface with an amplitude value greater than the Diasensor noise limit would typically kept track of, but other amplitude limits can be set for various other analyses.

Present a detailed statement of the problem that is the subject of the technical report. The statement should proceed logically from the previous background summary.

Purpose

The purpose of this work was to build a sufficiently representative Monte Carlo model of skin in the wavelength range between 1200 and 1860nm to use for use in various analyses.

Present a concise statement of the purpose of the work.

Description of Apparatus and Setup

As the model complexity grows so does the computation time. It is necessary however to retrieve enough data from the model to be statistically useful. The Monte Carlo model here has been constructed so that statistically there would be enough data retrieved at each wavelength and still be computationally feasible. The model was constructed to be as simple as possible and still be fairly representative of empirically measured data.

This model was designed with one homogenous layer with only one set of absorbtion and scattering coefficients. The anisotropy and indices of refraction were fixed at 0.8 and 1.37 respectively. All photons launched into the model were launched into the skin layer at the surface of the skin layer normal to the surface with an input weight of one. The model was computed at wavelengths 1200 to 1860 nm in steps of 10 nm (67 wavelengths total). The model stopped tracking photons with weights less than 7e-5, which is approximately the Diasensor noise floor (~3uAU). Information from 600000 photons exiting the surface of the skin model was saved at each wavelength. Information save consisted of radial distance in mm (distance along skin layer surface from entry point), azimuth (in degrees), exit weight (7e-5 - 1), exit angle (in degrees), average penetration depth in mm, maximum penetration depth in mm, and path length in mm. Total computation time using code compiled for MATLAB running on two 500 MHz processors with approximately 512 MB of RAM was approximately 5 days.

The dominant absorber in the skin is water. Water also makes up approximately 70% or more of the composition of skin and therefore absorbs far more NIR energy than any other constituent of the skin. Because of this, the absorbance coefficients of the skin layer of the model are defined as some fraction (say 0.7) of the absorbtion coefficients of water. The exact fraction used in constructing a model can be determined empirically by comparing model results of various fractions with empirically measured skin spectra.

There are many literature references, including the references for this report, that suggest that the scattering coefficient for skin in the NIR follow a trend such as $wavelength^{-x}$, where x is a number between 1.3 and 1.5. Similar to the fraction of the water absorbance coefficients, x can be determined empirically by comparing model results of various powers with empirically measured skin spectra.

In determining the absorbance and scattering coefficients for a suitable skin model, skin spectra from patient 868 (D2K with Ge array covering the wavelengths between 1100nm and 1850 nm) was used for comparison. The optimal fraction for the water absorbance coefficients was found to be 0.8. The optimal scattering coefficient power was found to be 1.4, which is the power suggested by Marbach. These values were determined by collecting and analyzing 2500 escaped photons modeled at 5 wavelengths between 1200 and 1860, varying the water absorbance fraction between .1 and 1, varying the powers between 1.3 and 1.5.

The water absorbance coefficients used in this model were measured empirically in house on the BioRad FTIR. Absorbance measurements were performed using ultra pure water generated by a Diamond water purification unit. Three path lengths were measured, normalized and averaged from water in 0.5, 1.0 and 2.0 mm quartz cuvettes. The resulting average was offset corrected (necessary to compensate for losses due to Fresnell reflection and cuvette surface scatter) to coincide with common values of water absorbance at 1250nm found in various literature references.

Give a description of the equipment used in the work and the setup design of the experimentation or analysis. Always give a full description of the existing conditions at the time of the work. If the existing conditions are not relevant to the results of the experiment, include a statement as such in the report with a brief explanation as to the reasons for this determination.
Provide a drawing and procedure for any experimental apparatus and equipment. Reports must contain drawings for any specially fabricated apparatus and text to describe the apparatus and procedure. If there were no devices or apparatus used in the experiment, include a statement as such in the report. If the devices used are not specified, and substitution of common test equipment or measuring devices will not impact the results, include a statement permitting such action in the report.

Summary of Data and Results

Present a description of the data and results. Attach raw data to the technical report.

Conclusions

Present conclusions from the work in precise, unambiguous terms.

Suggestions for Further Work

Present suggestions for analysis and experimentation to further investigate this problem or related subjects. If no further work is deemed necessary as of the release of the report, include a statement as such in the report.