Monte Carlo modeling of corneal and retinal Optical Coherence Tomography imaging

A.Gerakis, M.Yu. Kirillin, E.A. Sergeeva, M.Makropoulou, and A.A.Serafetinides

Abstract—**Monte Carlo simulations of OCT images of cornea and retina was performed for various setup parameters. Several models of cornea and retina were implemented; the optical parameters or the model were chosen basing on the experimental results. Obtained simulated image exhibits qualitative agreement with the experimental ones allowing for preliminary numerical study of OCT technique for ocular structure and ophthalmologic diseases diagnostics.**

I. Introduction

As Optical Coherence Tomography (OCT) has become a daily practice in the medical field, new researches about emerging technologies and techniques on the specific area rise up continuously.

An important aspect of this research comes from the necessity of evaluating the proper OCT system parameters, such as light source and focusing conditions with the provided imaging depth, prior to start an OCT application basing on the properties of the tissue one wishes to image. Monte Carlo (MC) simulations have been used for the evaluation of the effectiveness of various conventional diagnostic techniques since Wilson and Adam [1] used MC as a way to study light propagation in tissues. In addition, the increase in computing power, led many researchers to apply this technique for simulating signals obtained with an OCT or other optical diagnostic setup [2,3,4]. Inverse Monte Carlo methods have also been used for quantification of the values of physical properties of media, such as the scattering and absorption coefficients and anisotropy factor [5]. Thus, Monte Carlo techniques have become a valuable and accurate tool for prediction and interpretation of optical measurements results.

Retinal and corneal imaging is of huge importance nowadays. Ocular diseases seem to dominate as the world population is aging. As many of them can be prevented [6], the necessity of early diagnosis of retinal condition is very important. Apart of that, LASIK (Laser Assisted in Situ Keratomileusis) operations require knowledge of the exact topography and thickness of the cornea. This fact raises the need for an accurate simulation tool which can help in effective analysis of OCT ability for this application. Such tool could provide simulation of corneal topography by OCT after the ablation performed by the laser, or visualization of very fine layers of the retina and of the cornea, such as the Descemet's membrane, which cannot be observed with modern OCT commercial setups.

In this work, we have applied a novel Monte Carlo algorithm developed originally to model OCT images from strongly scattering media, such as skin or paper, to simulate the OCT images of the cornea and the retina. We have used images obtained by a clinical OCT setup as a reference for comparison with the simulation results.

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II. Methodology

A. Cornea Model

The study of the cornea in ophthalmology dates back over centuries, as the knowledge of its exact curvature was needed for the treatment of myopia and hypermetropia with glasses. In the recent years, with LASIK operations becoming more popular, the high accuracy in the corneal pachymetry and curvature measurements is required in order to increase the operation's performance quality. Usually, in corneal pachymetry and topography conventional optics and special components such as the Placido disk are used. Only in recent years the application of OCT in corneal pachymetry and topography has come to life [7, 8, 9, 25].

The cornea is the most powerful refractive medium of the eye as it is responsible for about the two thirds of the eye's total refractive power. It consists of five layers, which are: the *corneal epithelium*, the *Bowman's membrane,* the *stroma*, the *Descemet's membrane* and the *corneal endothelium*. The respective thickness of each layer as well as its refractive index, which values were found from the literature, can be shown in Table I. Due to the lack of published values for the absorption and scattering coefficients as well as for the anisotropy of the corneal layers at the near infrared wavelength range, we have chosen some approximate values based on the experimental images and the fact that the cornea consists of about 85% by water [10]. For stroma, the most scattering layer of cornea, we have tried two values of scattering coefficient of 1.5 and 5 mm^{-1}, while for the rest layers it was supposed to be equal to 1 mm^{-1}. The anisotropy fractor of all corneal layers has been chosen as g = 0.97. Consequently, the simulation results may not be numerically accurate for human ocular tissues but should be

meaningful for qualitative evaluation of the OCT images formation.

One of the most important aspects concerning corneal modeling is the tissue's geometry as it is different among the population. Many models of the cornea's geometry have been proposed over the years, starting from the one proposed by Christiaan Huygens in 1702 to that of Johann Benedict Listing in 1845. The geometry we decided to use in our study was proposed by the Nobel winner Allvar Gullstrand in 1911, which is still considered as an accurate model of the cornea's geometry (Figure 1).

TABLE I
CORNEA'S LAYERS, THEIR THICKNESS AND REFRACTIVE INDEX

Layer	Thickness (μm)	Refractive Index (n)
Epithelium	60	1.401
Bowmann's layer	15	1.401
Stroma	440 (in the center) – 500 (in the corners)	1.376
Descemet's membrane	15	1.373
Endothelium	10	1.373

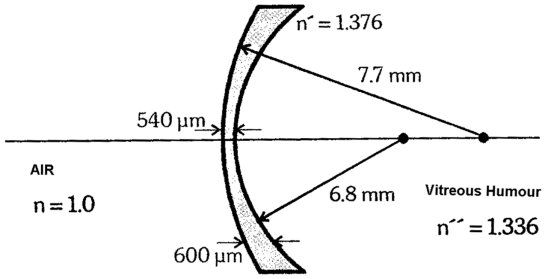

Fig. 1. The corneal geometry proposed by Allvar Gullstrand, which we used in our simulations

An experimental OCT image of the human cornea is presented in Figure 2.

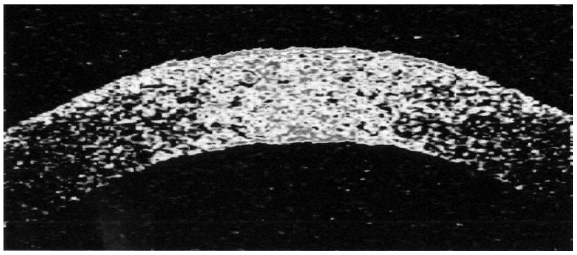

Fig. 2. OCT image of a healthy human cornea *in vivo* with higher reflectivity of epithelium and endothelium and lower in the corneal stroma, from [7].

B. Retina Model

The retina is the eye's tissue responsible for imaging, as it delivers image information acquired by the cones and rods, transformed in bioelectric signals, through the optic nerve to the brain. It consists of a number of 5-6 layers through which the light has to pass in order to reach the cones and rods. The retina imaging has become one of the major objectives of

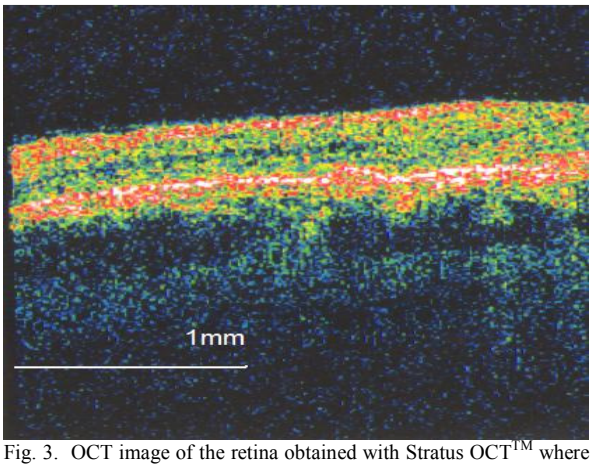

Fig. 3. OCT image of the retina obtained with Stratus OCT™ where the relevant planarity of the layers compared to the beam's spot size can be observed.

OCT, as for now it is the only way for its *in vivo* diagnostics [6, 11, 12, 13, 14]. Modeling the retina is quite a complex task, as one has to take into consideration the layers that actually could be distinguished in the OCT image, as many of them have a thickness of only two or three cells.

Retinal geometry is also complex to be precised, as the retinal layers except for having a curvature, also have different thicknesses in different retinal locations. However, in OCT, the beam spot size is very small compared to the retinal surface which occupies almost the whole interior chamber of the eye, so in our simulations we considered the layers to be quasi-planar [Figure 3].

In our simulation we separated only four of the total number of layers to be contributing to the OCT image [3, 5, 16], which are: the *neural retina*, the *retinal pigment epithelium,* the *choroid* and the *sclera,* the optical properties and thicknesses of which can be found in Table II [3].

C. Monte Carlo algorithm

The basic idea of the Monte Carlo method (MCM) is obtaining the required solution via numerous repeating of random tests and further statistical analysis of the obtained results. Applied to the study of light propagation in scattering medium, the Monte Carlo method consists in numerous calculations of random photon trajectory based on the preset medium characteristics [2, 17].

Theoretical solution of the problem of light propagation in scattering media implies solution of the radiative transfer equation (RTE). However, MCM was shown to be a convenient tool for simulation of light propagation in biotissues [21-24] because application of RTE is strictly limited by the complexity of boundary conditions. The main limitation of the MCM is the requirement of large computation power, but it becomes less important thanks to modern development of computers.

TABLE II
RETINA'S LAYERS, THEIR THICKNESS AND OPTICAL PROPERTIES

Layer	Thickness (μm)	Refractive Index (n)	Absorption Coefficient μ_α (1/mm)	Scattering Coefficient μ_s (1/mm)	Anisotropy factor g
Neural Retina	200	1.47	0.05	20	0.970
Retinal Pigment Epithelium	10	1.47	8	170	0.840
Choroid (50% blood)	250	1.47	1	45	0.900
Sclera	700	1.47	0.01	42	0.945

The program code developed in the present study allows one to simulate photon transport in single and multilayer media of various geometries.

The refractive index, n, of the medium surrounding the object is also taken into account which allows for simulation immersion.

When simulating the OCT signal, the photon tracing inside the object under study is performed by the Monte Carlo technique. For the calculation of the OCT signal only the photons fitting the given detection conditions (detector position, size and numerical aperture) were selected.

For calculation of the OCT signal a process of interference signal formation resulting in interaction of the waves reflected from the reference mirror and backscattered from the object should be simulated. The beam splitter reflection coefficient is supposed to be 0.5 and the number of photons injected in the reference and sample arms of the OCT setup is the same.

When simulating the photon propagation in the object its optical pathlength is calculated. After completing the simulations for a large number of photons the distribution of the detected photon weight over their optical pathlengths is obtained as the output data. This distribution can be considered as an envelope of the OCT signal with very narrow (δ-function) coherence function, because it characterizes the in-depth distribution of object optical properties.

As photon packets are considered in the simulations it is necessary to account for interference of each detected photon packet with reference radiation and the simulated OCT signal should be calculated as a superposition of these partial interference fringe patterns. Allowance for speckle formation is an important problem for the simulation of OCT signals.

In our simulations the coherence function is supposed to have Gaussian shape, and the OCT signal is calculated by the following equation:

$$I(z) = \sum_i \sqrt{W_r W_s(\Delta l_i)} \cos\left(\frac{2\pi}{\lambda}(z-\Delta l_i)\right) \exp\left(-\left(\frac{z-\Delta l_i}{l_{coh}}\right)^2\right) \quad (1)$$

where $I(z)$ is the intensity of radiation at z depth, Δl_i is its pathlength mismatch, l_{coh} is the coherence length of the probing radiation at wavelength λ, while W_r and W_s are the numbers of photons detected from the reference and the object arm in the OCT setup respectively.

When performing simulations, the photons are actually not propagated in the reference arm, however, their pathlength there is determined and accounted in further calculations. The number W_r is assumed to be equal to the total weight of photons launched into the medium. To the number $W_s(\Delta l_i)$ contribute that photons which meet the detecting conditions (exiting point and angle) when leaving the scattering medium. To obtain the envelope of the simulated OCT signal the cosine part is omitted and the following equation is used:

$$I(z) = \sum_i \sqrt{W_r W_s(\Delta l_i)} \exp\left(-\left(\frac{z-\Delta l_i}{l_{coh}}\right)^2\right) \quad (2)$$

The parameters of the OCT setup are chosen as follows: central wavelength is 1050nm, two values of coherence length l_{coh} of 5 and 15 μm are considered, the numerical aperture NA is 0.2 the transversal scanning step is 20 μm, The image consists of 100 A-scans. Typical time for calculation of one OCT image depends on the object parameters, for retina and cornea it is about 8 hours with Intel™ Core2 processor at 2.40 GHz. Each A-scan is obtained with 5 mln weighted photons.

III. RESULTS AND DISCUSSION

A. Cornea

As can be shown on Fig.2, as well as in Figure 4, the most reflective layers of the cornea are the epithelium and the endothelium.

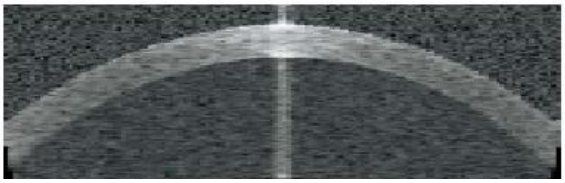

Fig. 4. Experimental OCT image of the cornea where the reflectivity of the epithelium and the endothelium can be clearly seen. [25]

If one simulates the cornea by only taking into consideration the contribution of the stroma, which is the thickest tissue of the cornea, in the tomographic OCT image, one would lack the information about the tissues named above, with results like those shown in Figure 5.

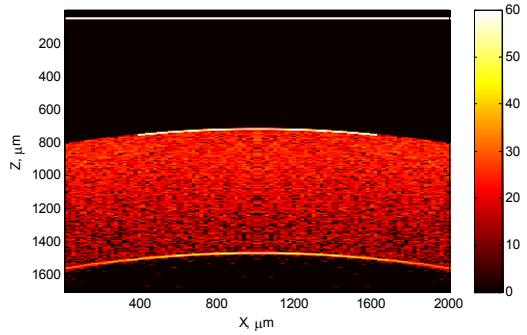

Fig. 5. Simulated OCT images of corneal one-layer model with immersion (l_{coh} = 5 μm, μ_s = 5 mm^{-1})

Immediate comparison between Figures 5 and 7, show that the cornea must be simulated considering all four of its layers to be contributing to the tomographic image. All the presented figures in this section are shown in micrometer scale, over the X-axis the physical length is shown whereas over Z-axis the optical length is shown.

Another aspect one has to consider is the immersion. Immersion is widely used in OCT imaging for decrease of refractive index mismatch in the studied object boundary. In the case of ophthalmologic OCT water or tears serve as immersion liquid. In our simulation we consider immersion liquid to be non-scattering with refractive index of 1.33. The tear film of the cornea also adds to the reflectance of the epithelium (Fig.6). Simulated image of all four layers of the cornea, with and without immersion are shown on Figure 9.

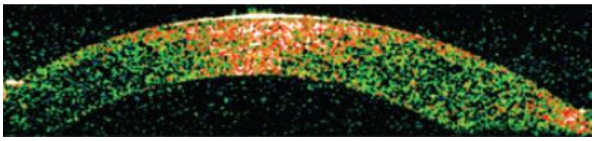

Fig. 6.The cornea, after a blink of the eye [26].

Figure 7 demonstrates the capabilities of the simulation we performed in the present study as it is in complete coherence with both OCT experimental images, as well as with histological ones (Figure 8), obtained from the literature [27]. All four layers can well be distinguished in the simulation images, as well as the bigger reflectance of the epithelium and the endothelium compared to that of the sclera, and with immersion, we can get even more accurate results, in complete accordance to the experimental images. Thus, the simulation method we used in this study could prove to be an accurate tool in the hands of researchers setting up an OCT apparatus intended for corneal imaging and, of course, to doctors performing LASIK operations, as they will be able to observe in advance the effects of laser ablation on the corneal tissue. Also, the use of a liquid of a lower refractive index, rather than the plain tear film could be studied, so that more precise tomographic images could be produced.

We have to observe though that, for more accurate simulations to be able to be performed, more information and research is needed, concerning the correct values of the absorption and scattering coefficients, as well as of the anisotropy factor for the spectral range of 800nm-1500nm, in which most OCT sources operate.

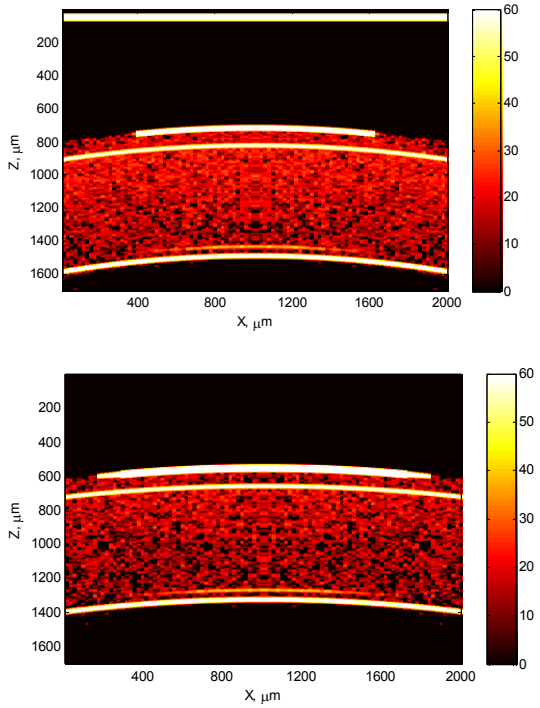

Fig. 7. Monte Carlo simulated OCT images of corneal four-layer model without (top) and with (bottom) immersion (l_{coh} = 15 μm, μ_s = 1.5 mm^{-1}).

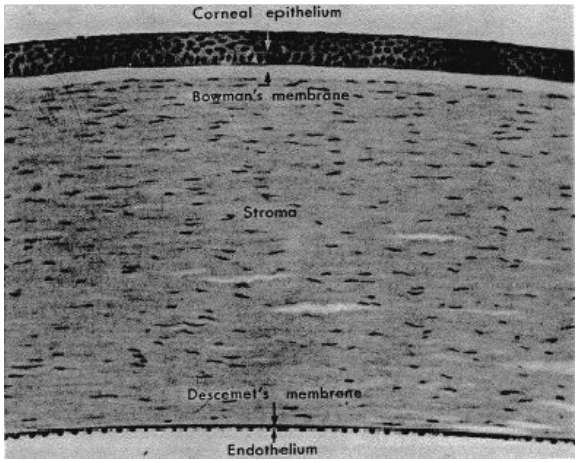

Fig. 8. Histological image of the human cornea, obtained from [27].

B. *Retina*

Figure 9 shows the OCT image of a healthy human retina, recorded during examination of a volunteer with a Stratus OCT^{TM} device, in similar conditions as those in Figure 3.

As we mentioned above, retina's geometry determination is a complex task to be performed. Hence, the relatively small spot size of the beam scanning the retina, in correlation with the fact that the latter presents quite the same layer thickness in small regions, allows one to able to model the tissue as planar (Figures 3 and 9). In the clinical images, some scatterers of the very fine layers can be differentiated, but those layers cannot be easily simulated, as they don't follow a precise geometry. However, if their geometry and optical properties are given, then they could also be simulated.

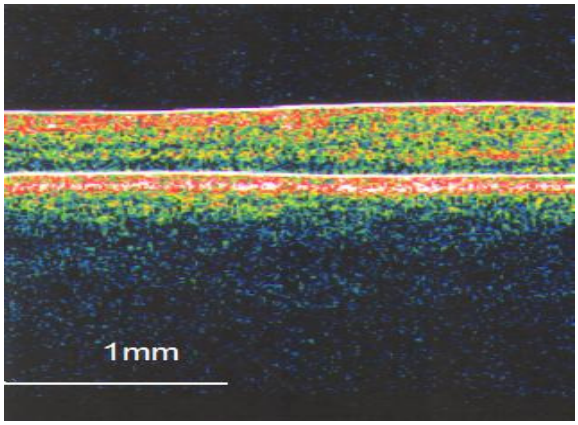

Fig. 9. OCT image of a healthy human retina *in vivo* (obtained with Stratus OCT^{TM}).

In our study we simulated images of the retina both with planar and non-planar layers (Figure 10). For the second case we have introduced some sinusoidal geometry in the boundary of the layers, in order to show the capabilities of the algorithm, given the correct geometry. As we mentioned in the simulation results concerning the cornea, we have to notice that we lacked the information concerning the optical properties of the retinal layers. Further research on the specific field, providing this information, would consequently result in better simulation results.

Image comparison between Figures 9 and 10, immediately demonstrates the accuracy of the used algorithm in imaging of the retina. One can observe the high reflectance of the Neural Retina in both the experimental and simulated images, as well as the gradually decreasing reflectance of the Choroid. Of course, in the simulated image, one cannot distinguish the scatterers observed in the clinical ones, for reasons mentioned above.

IV. CONCLUSION

Retinal imaging is maybe the most common use of OCT nowadays. Macular diseases, ocular tumors and glaucoma can easily and precisely be diagnosed with OCT, resulting in better treatment for the patients. Simulation of retina OCT imaging could be used for a better study of retinal diseases, as well as for the effect of the change of some parameters in the retinal condition, i.e. the increase of the pressure of the vitreous humour causing glaucoma. Three-dimensional models of the retina could also be created providing an extra tool not only for educational purposes, but also for the rise of emerging technologies, such as spectral domain OCT.

Optical Coherence Tomography has served its audience as a non-invasive, non-radiant technology for over a decade, providing tissue imaging with micrometer resolution. As time passes by, the challenges emerging by this technology have become more complex and require constant and consistent research so that they can be solved. As was the case with other technologies in the past, from MOSFET design to software development and MRI, and with the given increase in computing power, simulations have always had a leading role in decision making and strategy planning for scientists facing a certain problem. With the present study, we believe we have presented another useful tool in the arsenarium of OCT researchers.

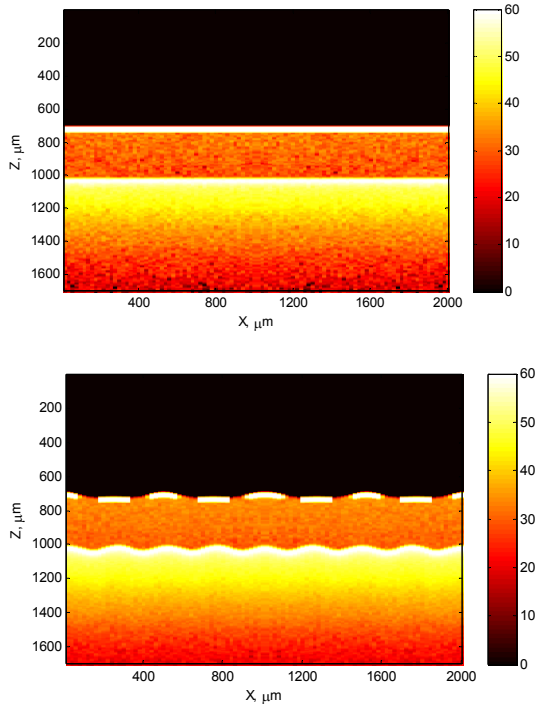

Fig. 10. Simulated OCT images of retina model with planar (top) and non-planar (bottom) interlayer boundaries (l_{coh} = 15 μm)

V. ACKNOWLEDGEMENTS

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