COMSOL CONFERENCE 2018 LAUSANNE

3D Optical Human Eye Model Based on COMSOL Multiphysics®

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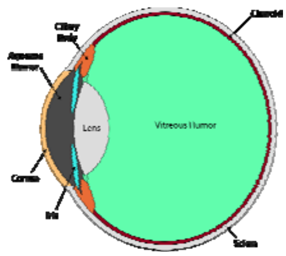
INSPIRING INNOVATION SINCE 1816

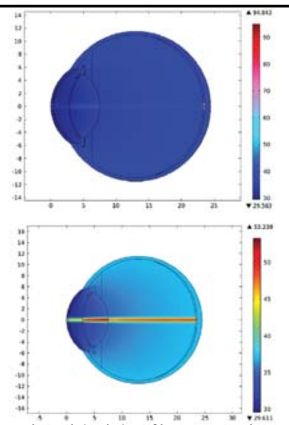
Light propagation inside human eye

- **Human eye is a complex structure**
- **Applications**
  - Test ophthalmology equipment
  - Laser surgery
- **Need to evaluate the propagation of the light on the different parts of the eye**
- **Issue**
  - Difficult to obtain human eyes
- **Solution**
  - Simulation and physical model



Eye model

- **Advantage of the model**
  - Simplicity
  - Adaptability
  - Reproducibility
  - Predictive
- **Our goal**
  - Model all parts of the eye
  - Develop a model with non standard light propagation
  - Create a simple test bench for light propagation in the eye



Thermal simulation of human eye under Nd:YAG laser radiation (top) and Nd:YAP laser radiation (bottom)[1]

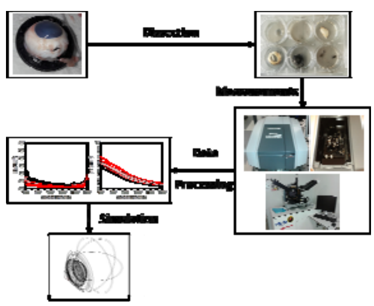
1. Mirnezami et al. - 2013 - Temperature distribution simulation of the human

Outline

A. **Optical measurement of the eye**
   1. Motivation
   2. Measurement setup
   3. Results

B. **Simulation model**
   1. Parameters and validation
   2. Simulation

Conclusion and outlook



Optical measurement of the eye
Measurement setup

- **Work on porcine eye**
  - Anatomically close to human eye[1]
- **Spectrophotometry**
  - Used an integrated sphere
  - Measured
    - Total reflection
    - Total transmission
- **Ellipsometry**
  - Refractive index measurement


Spectrophotometer, *Shimadzu*

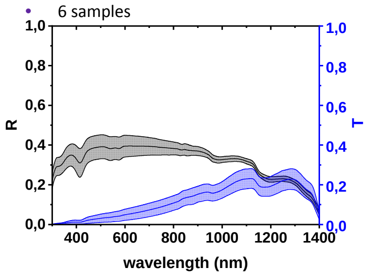

Integrated sphere

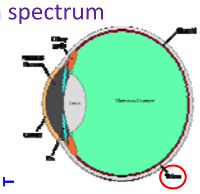

Ellipsometer, *Semilab*

1.Sanchez et al, The parameters of the porcine eyeball. Graefes Arch. Clin. Exp. Ophthalmol. 249, 475–482 (2011).

Optical measurement of the eye
Transmission and reflection spectrum

- **Sclera study**
  - 6 samples





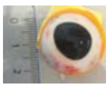

Sclera sample

- ➢ **The measurements' spread is due to the thickness**
- ➢ **Raw data used in the analysis**

Simulation model
Parameters

- **Extracted from the measurements**

Sample	μa (mm^-1) @850 nm		μs' (mm^-1) @850 nm		n @632,8 nm
	KM	IAD	KM	IAD	
Sclera	0,2748	0,1417	2,4671	3,0502	1,410±0,081
Lens	0,0041	0,0061	0,0204	0,0099	1,452±0,033
Vitreous	0,0151	0,0235	0,1192	0,0854	1,324±0,029
Iris	1,6975	1,4361	1,2312	1,7496	1,385±0,041
Choroid	2,0614	2,1583	1,2593	2,2270	1,389±0,061
Eyelid	0,1526	0,0809	0,4784	0,5959	1,395±0,067
Cornea	0,0123	0,0064	0,1458	0,1362	


Complete eye


Sclera


Lens


Iris


Choroid

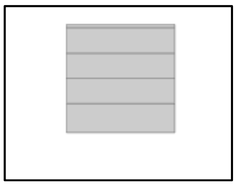

Cornea

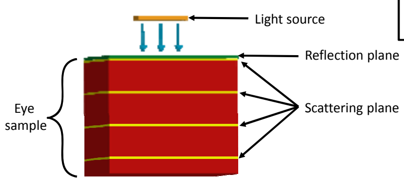
- ➢ **Each of these parameters are used in the simulation**

Submitted on Journal of biophotonics

Simulation model
Modeling of the scattering effect

- **No model exists on COMSOL**
  - Need to develop the model
- **ls =$^1/_{\mu s'}$ mean free path**
- **Number of scattering interfaces = $^d/_{ls}$**

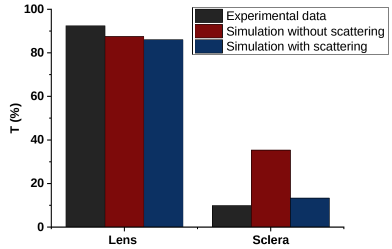




- ➢ **Develop a scattering transmission model using COMSOL**

Simulation model
Validation of the model and simplification

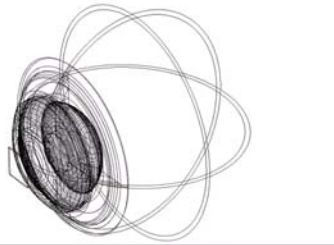
- Comparison between no scattering (lens) and scattering (sclera) samples



- ➢ For the transparent samples we can ignore the scattering effect
- ➢ We need to consider it on diffuse samples

Simulation model
Simulation of the eye

- Convergence of light on the retina



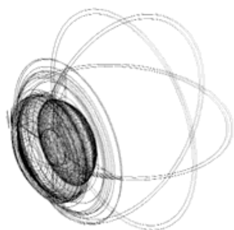
- ➢ 95% of the light is received on the retina
- ➢ This is in agreement with literature

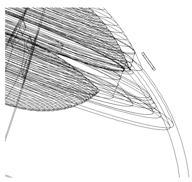
Submitted on Journal of biophotonics

1. 1968-Geeraet and berry- Ocular spectral characteristics as related to hazards from lasers and other light sources

Simulation model
Simulation of the eye

- Non standard light propagation simulation





- ➢ 90,5% of the light is absorbed by the ciliary body
- ➢ This allows the possibility to treat the glaucoma

Conclusion and outlook

- Dissection of porcine eyes
- We measured the optical parameters for different parts of the eye
- We extracted µs' and µa from the reflection and transmission measurements
  - IAD and KM methods give similar results
- Measured the refractive index for different parts of the eye
- Created a complete simulated model
  - Defined for wavelengths from 400 to 1400 nm
  - All parts of the eye configured
- Outlook
  - Add other physic variables like temperature during the simulation

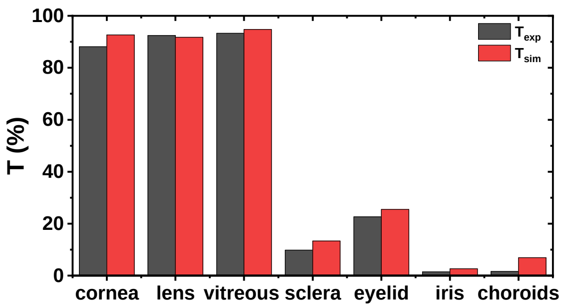
Acknowledgements

Thanks to Flexible electronics department members: Marc Ramuz, Roger Delattre, Séverine De Mulatier, Mohamed Nasreldin, Yanid Arango, Aravind Ravichandran, Stuart Hannah, Bastien Marchiori, Omar Kassem, Sylvain Blayac and Thierry Djenizian.

Thank you for your attention!

Simulation model

Summarize of the sample simulation

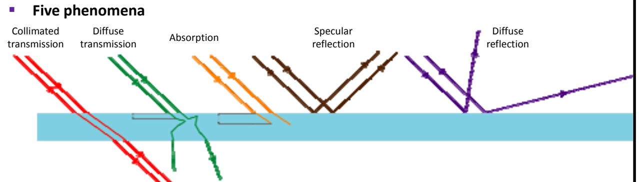


- **The simulation result are close to the measurement values**

Introduction to optics in the eye

Light behaviour at an interface

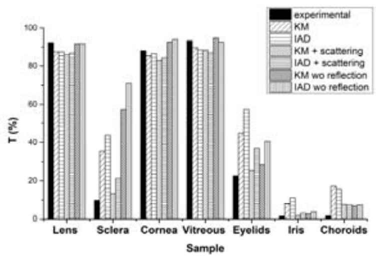
- **Five phenomena**



- **Issue**
  - Parameters depend on the media's thickness
- **Solution**
  - Define coefficients depending on penetration depth
    - Absorption coefficient : µa (mm^{-1})
    - Reduced scattering coefficient : µs' (mm^{-1})

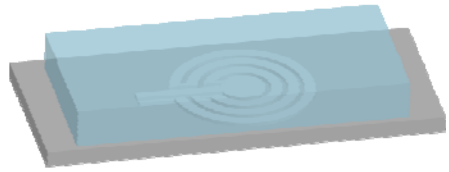
Simulation model
Simulation of the all eye

- **Comparison between the simulation and the measurement**



- **The result are very close**

Model iris



Physical Model

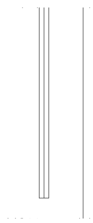
Introduction to optics in the eye
Light behaviour at an interface

- **Five phenomena**

- **Measurable with a spectrophotometer**
  - R total
  - T total
  - T collimated

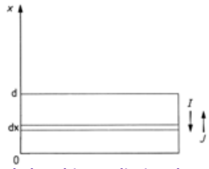
- **Problem**
  - Depending on the media's thickness

- **Solution**
  - Defining coefficients depending on distance
    - µa
    - µs



Kubelka-Munk method

The fundamental differential equations[1,2]



- **Take a sample which is capable of both scattering and absorbing radiation, be irradiated in the - x-direction (thickness d) (see figure)**
- **We can find the two fundamental simultaneous differential equations which describe the absorption- and scattering-process**

$$-\frac{di}{dx} = -(S+K)\,i + S\,j \;(1)$$

$$\frac{dj}{dx} = -(S+K)\,j + S\,i \;(2)$$

- **With S is the coefficient of scatter defined by the corresponding thickness of layer and K is the coefficient of absorption defined by the corresponding thickness of layer**

1. Kubelka, P. New Contributions to the Optics of Intensely Light-Scattering Materials. Part I. JOSA 38, 448–457 (1948).
2. 1969-Kortüm -Reflectance Spectroscopy_ Principles, Methods, Applications

Kubelka-Munk method

Solution of the equation [1,2]

- **For ideal case, non reflecting background when we integrate between x=d and x=0, we have the solution**

$$d = \frac{1}{Sb}\coth^{-1}\left(\frac{1-aR}{bR}\right) \text{ with } a = \frac{S+K}{S},\, b = \sqrt{a^2-1} \text{ and } R = \frac{j}{i} \;\mathbf{(3)}$$

- **R is the reflection of the sample**
- **We can find**

$$R = \frac{1}{a + b\coth(Sbd)} \;(4)$$

1. Kubelka, P. New Contributions to the Optics of Intensely Light-Scattering Materials. Part I. JOSA 38, 448–457 (1948).
2. 1969-Kortüm -Reflectance Spectroscopy_ Principles, Methods, Applications

Kubelka-Munk method

Solution of the equation [1,2]

- **To obtain a similar expression for the transmission. From the eq.4 and R =** j/i

$$j = Ri = \frac{i}{a + b\coth(Sbd)} \;(5)$$

- **Inserting this in Eq.1**

$$-\frac{di}{Sdx} = -ai + \frac{i}{a + b\coth(Sbd)} \;(6)$$

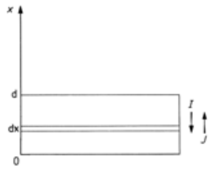
- **After solving the Eq.6. We obtain**

$$T = \frac{b}{a\,\mathrm{sh}(bSd) + b\,\mathrm{ch}(bSd)} \text{ with } T = \frac{i}{i_0} \;(7)$$

1. Kubelka, P. New Contributions to the Optics of Intensely Light-Scattering Materials. Part I. JOSA 38, 448–457 (1948).
2. 1969-Kortüm -Reflectance Spectroscopy_ Principles, Methods, Applications

Kubelka-Munk method

Determination de a[1,2]



- **From the Eq.4,7, we can define**

$$T^2 + b^2 = (a - R)^2 \;(8)$$

- **We can define a with only T and R**

$$a = \frac{1 + R^2 - T^2}{2R} \;(9)$$

- **From the Eq. 7 we can find**

$$Sd = \frac{\left(\mathrm{sh}^{-1}\left(\frac{b}{T}\right) - \mathrm{sh}^{-1}(b)\right)}{b} \;(10)$$

1. Kubelka, P. New Contributions to the Optics of Intensely Light-Scattering Materials. Part I. JOSA 38, 448–457 (1948).
2. 1969-Kortüm -Reflectance Spectroscopy_ Principles, Methods, Applications

Kubelka-Munk method

Equations to calculate μa and μs[1,2]

- From the Eq (10)

$$S = \frac{1}{bd}\ln\left[\frac{1-R(a-b)}{T}\right] \quad (11) \quad \text{Where } a = \frac{1+R^2-T^2}{2R};\ b = \sqrt{a^2-1}$$

$$K = (a-1)S \quad (12)$$

- Calculate μa and μs from S and K[3,4]

  ➢ $\mu a = \frac{K}{2}$ and $\mu s = \frac{4(S+\frac{K}{2})}{3(1-g)}$

1. Kubelka, P. New Contributions to the Optics of Intensely Light-Scattering Materials. Part I. JOSA 38, 448–457 (1948).
2. Vogel, A., Dlugos, C., Nuffer, R. & Birngruber, R. Optical properties of human sclera, and their consequences for transscleral laser applications. Lasers Surg. Med. 11, 331–340 (1991).
3. Cheong, W.-F., Prahl, S. A. & Welch, A. J. A review of the optical properties of biological tissues. IEEE J. Quantum Electron. 26, 2166–2185 (1990).
4. Thennadil, S. N. Relationship between the Kubelka-Munk scattering and radiative transfer coefficients. JOSA A 25, 1480–1485 (2008).

Inverse adding doubling method

Principle of the method[1]

- **Hypothesis**
  - The distribution of light is independent of time
  - Samples have homogeneous optical properties
  - The sample geometry is an infinite plane parallel slab of finite thickness
  - The tissue has a uniform index of refraction
  - Internal reflection at boundaries is governed by Fresnel's law
  - The light is unpolarized
- **The IAD method consists of the following steps:**
  - (1) Guess a set of optical properties
  - (2) Calculate the reflection and transmission by using the adding doubling method
  - (3) Compare the calculated values with the measured reflection and transmissions
  - (4) Repeat until a match is made.

1. Prahl, S. A., van Gemert, M. J. & Welch, A. J. Determining the optical properties of turbid mediaby using the adding-doubling method. Appl. Opt. 32, 559–568 (1993).

Inverse adding doubling methods

Parameters to determine the optical properties[1]

- **3 parameters characterize the light propagation in a turbid media**
  - Albedo (a) $a = \frac{\mu s}{\mu a + \mu s}$
  - Optical thickness (τ) $\tau = d(\mu a + \mu s)$ *with d is the thickness of the sample*
  - Anisotropic coefficient (g)
- **Measurements available**
  - 3 (total reflection, total transmission and unscattering transmission). We can find all the parameters
  - 2 (total reflection and total transmission). We need to fix one parameter (typically g is fixed)
  - 1 (total reflection). The sample is usually too thick for a transmission measurement to be made. τ is assumed to be infinite and g is fixed

1. Prahl, S. A., van Gemert, M. J. & Welch, A. J. Determining the optical properties of turbid mediaby using the adding-doubling method. Appl. Opt. 32, 559–568 (1993).

Inverse adding doubling methods

Calculation of the initial values[1]

- **Values to start the iterative method**
- **Used reduced optical parameter** $a' = \frac{a(1-g)}{1-ag}$ *et* $\tau' = (1-ag)\tau$
- **Formulas to determine a' et τ'**

$$a' = \begin{cases} 1-\left(\frac{1-4R-T}{1-T}\right)^2 & if\ \frac{R}{1-T} < 0{,}1 \\ 1-\frac{4}{9}\left(\frac{1-R-T}{1-T}\right)^2 & if\ \frac{R}{1-T} \geq 0{,}1 \end{cases} \qquad \tau' = \begin{cases} \frac{-\ln(T)\ln(0{,}05)}{\ln(R)} & if\ R \leq 0{,}1 \\ 2^{1+5(R+T)} & if\ R > 0{,}1 \end{cases}$$

- **We can generate a single set of starting values (a, τ, g)**

1. Prahl, S. A., van Gemert, M. J. & Welch, A. J. Determining the optical properties of turbid mediaby using the adding-doubling method. Appl. Opt. 32, 559–568 (1993).

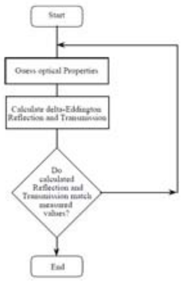
Inverse adding doubling methods

Explication of the calculation[1]

- For our experiments R and T are measured → g is fixed according to the literature
- The reflection and the transmission are calculated for a particular set of a and τ according to delta-Eddington approximation
- We compare to the measured values with this relation

$$M(a,\tau,g) = \frac{|R_{calc} - Rmeas|}{R_{meas} + 10^{-6}} + \frac{|T_{calc} - T_{meas}|}{T_{meas} + 10^{-6}}$$

- If the distance is too big, we determine new a and τ based on "N-dimensional minimization algorithm based on the downhill simplex method"[1]



1. Prahl, S. A., van Gemert, M. J. & Welch, A. J. Determining the optical properties of turbid mediaby using the adding-doubling method. Appl. Opt. 32, 559–568 (1993).

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