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The human eye: From Gullstrand's eye model to ray tracing today

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Abstract

In order to understand how the vision process works, than to develop and design precise optical systems and instruments, the optical modelling of the human eye and the accurate prediction of the optical performance is a crucial topic for the light engineering as well as vision science.

In the past, various optical eye models with different features were developed, among them the Gullstrand's schematic eye model won the Nobel prize in 1911 [1]. He illustrated relevant optical surfaces (the cornea and the crystalline lens) of an eye and described their geometry quantitatively.

After 100 years, today, the development of optical simulation software and ray tracing methods enable us to reproduce the optical system of the human eye quantitatively with more accuracy. For instance, to construct a statistical eye model, at first the biometrical data of the human eye was assessed using clinical devices, than new simulated data were generated and finally validated with biometric data [2]. However, previous eye models focused particularly only in some features like only corneal data, only accommodation or aging, used personalised or average population data and either mono- and polychromatic light. To the best of our knowledge, there is no eye model of the complete optical system. Therefore, developing a complete eye model may prove advantageous to understand the vision process and its application in the ophthalmology, the medical technology and the light engineering. This paper presents a review of optical eye models and provide insight into which facts will play an important role to develop a complete eye model by using contemporary technology.

Index Terms: Human eye model, optical system, ray tracing, simulation

1 Introduction

The understandings about how the optical system of the human eye works and the influence of each optical components in the retinal image formation are essential to explain the visual quality assessment and perception. Therefore, an accurate modeling of the human eye is important.

On the one hand, in the ophthalmology, for instance, through the refractive surgery the anatomical structure of the eye is changed, which means the optical component properties are automatically changed. As a result, the person's visual perception will be different before and after the surgery. The issues is, how precisely the visual function can be compared before and after surgery, i.e. to predict whether the surgery improved the vision or not. Similarly, it is difficult to calculate and design spectacles, intraocular lenses and contact lenses when there is little known about the whole optical system of the eye. Because each optical surfaces geometry affects the image formation process by causing the refraction, reflection and scattering etc.

On the other hand, in the light engineering, an example of real situation, when a person is driving a car on the road in a day opposite to sunshine. That person looks forward outside, he will experience glare effect from the sun, when he looks inside the car and looks outside there are different illuminances, in order to recognize the objects clearly his eyes must adapt abovementioned illuminance environment. The correlation between the photometric measurement of such effects, image formation and the role of each optical component were described with different eye models, but no eye model summarized that description in one model.

However, from that time to modern days many scientists such as Gullstrand, Le-Grand, Emsley, Navarro and others developed optical eye models based on the average population and specific features e.g. age, accommodation and wavelength etc., but there is no model of the human eye with complete optical system is designed. Hence, this paper aims to summarize the comparison of some existing eye models, which points must be considered and methodical approach using contemporary technology such as ray tracing to obtain required knowledge to develop a complete eye model. This knowledge will make an important contribution to the ophthalmology and vision science to understand and evaluate the visual function and diagnosis as well as to the light engineering to improve camera system, to modify the illumination environment in road traffic safety, colorimetry and high performance of the light emitting products.

2 Optical eye models

2.1 The human eye

The eye is the photosensitive sense organ in the human body. The shape of the adult eye is slightly asymmetrical sphere with an approximate sagittal diameter 25 mm and average power is 60 D (=1/m). Each individual eye is different from one another because of own unique anatomical structure depending upon factors such as age, gender, ethnical origin, color and genetic etc. The structure of the human eye and the image formation of an object is shown in Fig. 1. As can be seen, the light beam from the object enters through the cornea, than the aqueous humor, after that the amount of entering light is regulated by the iris and pupil opening, called aperture of the eye. Thereafter, light beam passes through the lens and the vitreous humor and finally being focused on the retina, where the inverted image is formed. Therefore, those components and their optical as well as geometrical properties are important to understand how the human optical system works.

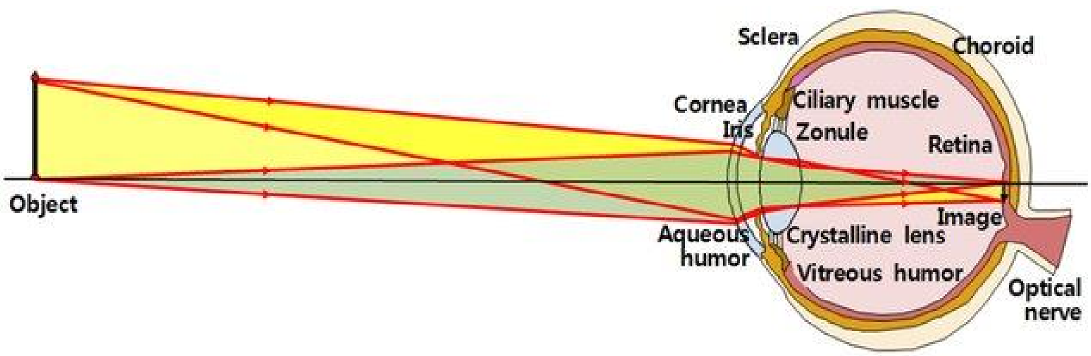

Fig. 1 The human eye structure ad image formation of an object on the retina [3]

In the past, various eye models were developed to illustrate the correlation between the anatomical structure and optical properties, i.e. optical modeling of the human eye. Some eye models with population-based biometric data and optical parameters are described below.

2.2 Gullstrand eye model

Fig. 2 presents a well-known eye model with optical components and values proposed by an ophthalmologist Allvar Gullstrand, who won the Nobel Prize in physiology and medicine in 1911 for his work concerning the dioptrics of the eye. Prior to his eye model, no optical eye model have included as many optical refracting surfaces as he described with his model. The idea behind the eye model is that for him as an ophthalmologist, if more optical surface parameters, e.g. radius of curvature and refractive index, are described, it helps to predict the eye diseases effect in which optical component either on the cornea or lens or on other components is and how much optical parameter value deviates from the healthy and disease eye. This knowledge leads to evaluate about the disease severity, progression and diagnosis outcomes after the treatment.

He had measured the optical surface parameters of the human eye by using techniques and devices (slit lamp, ophthalmoscope) available at that time and collected and averaged data for each optical component of healthy eyes[4,5]. Those values were considered as gold standard values for the healthy eye. He assumed following six-refracting surfaces which are essential to model a human eye: air to anterior cornea, aqueous humor and posterior cornea, aqueous humor to lens outer surface(cortex), lens core to lens cortex and vitreous humor and lens cortex. His eye model's corneal total refractive power around 43 D, which was two-third of the eye's focusing power (58 D) and average lens power was approximately 19 D [5]. He considered refractive index values, distance next to next surface, radius of curvature and shape as parameters. In addition, he introduced the term astigmatism in eye optics.

Furthermore, he described for the first time the mechanism of intracapsular accommodation, which was not considered before his eye model. This mechanism means that the human lens is made up of different fiber layers on the lens cortex and nucleus (Fig. 2), thus the refractive index differs, resulting the focusing of the object varies in lens cortex and nucleus. This knowledge helped in the future to understand and invent Intra ocular lens with different focal power for cataract.

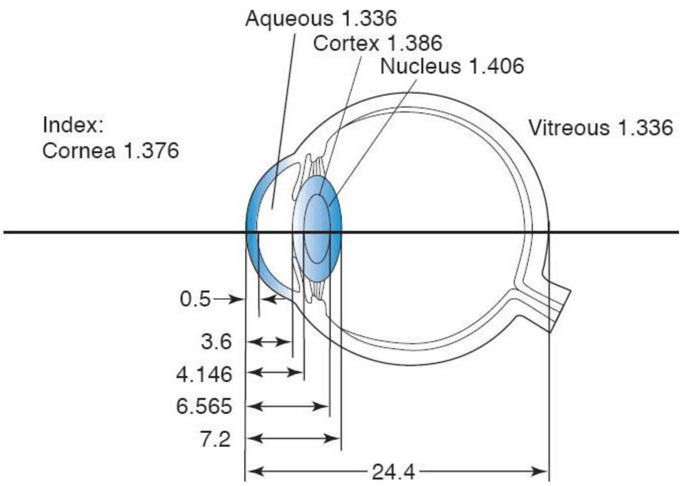

Fig. 2 Optical components of the Gullstrand's schematic eye in relaxed form; all values are in mm [6]

His eye model does not provide information about apshericity about the optical surfaces, the curved form of the retina, many layered lens structure (GRIN Structure) and the opening size of the pupil. The values were for healthy eyes, which does not illustrate which age or ethnic group was taken, which wavelength was sent to form an image and in which illuminance enviroment the values were measured.

2.3 Emsley reduced eye

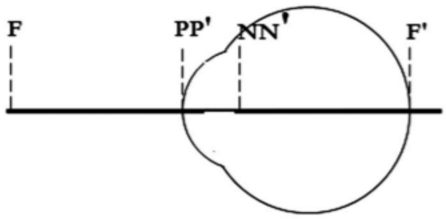

Fig. 3 Emsley reduced eye model with one refracting surface with cardinal points (PP‘ as Principle points and NN‘ as Nodal points) and focal point [7]

Some years later, Emsley designed a reduced eye model which has only one refracting surface from air to cornea (Fig. 3) with 60 D whole eye power. The cornea, lens and other optical components were taken as one refracting surface. This eye model is widely used for the optometry practices, due to its only one refracting surface. This model helped to calculate easily the spectacle power, eye model for optical device calibration and learn the refraction. This model cannot be used for detailed vision process and to investigate the defect, whether in cornea or lens or in the other optical components etc.

2.4 Navarro eye model

Afterwards, scientists [5,8,9] developed an eye models which were either based on previous one or with new one with new biometric data. The problem was those simplified paraxial eye models do not describe the effect such as aberration and diffraction.

However, it is not possible to describe effects like higher order aberration and diffraction only with the spherical surfaces. Similarly, the optical components of the eye have different rotational axis and not their optical axis coincide with the line of sight. Also, the retinal surface shape, chromatic dispersion, lens gradient structure, intraocular optical component distances regarding the accommodation as a function, some based on monochromatic or polychromatic light, wide angle and apshericity of the optical surfaces were not considered in eye models. To address those points, Navarro et. al. developed and finite schematic eye model based on the Le-Grand full schematic eye [8]. In contrast to Gullstrand eye model, Navarro’s eye model and the quantitative parameters are dependent on the age, accommodation, apshericity, retinal shape and other important parameters [9,10].

Table 1: The quantitative data of the Navarro eye model 1985 [10]

Medium	Refractive Index	Radius of curvature [mm]	Q	Distance to next surface[mm]	Equivalent Powers [D]		
					Surface	Component	Whole eye
Air	1.000						
		7.72	-0.26		48.705		
Cornea	1.3771			0.55		42.882	
		6.50	0		-5.983		
Aqueous	1.3374			3.05 d2			60.416
		10.2 R3	-3.1316 Q3		8.098		
Lens	1.420*n3			4.00 d3		21.779	
		-6.0 R4	-1.0 Q4		14.000		
Vitreous	1.336			16.4040 d4			
Retina		-12.0					

Table 1 shows the quantitative parameters values for Navarro's eye model, where the total power of an eye is around 60 D. He took 6 optical refracting surfaces. In contrast to Gullstrand eye, he defined the lens structure with a coefficient, i.e n3, means that every layer of the lens structure can be differentiated with this coefficient. Similarly, for the apshericity he defined also the coefficient Q, which is different for lens anterior and posterior surface. For the retina, he determined the radius of curvature as -12.0, which is more curved than lens posterior surface -6.0 R4. This knowledge helps to explore more about how the lens altering process and cataract is: which layer of the lens is at first deteriorate, than compared with the health lens, as a result either lens outer surface or inner surface is degraded will be defined. By using curved retina, the image formation calculation will be more accurate.

However, abovementioned eye models explored and determined many parameters for the modeling of the human eye, they did not mentioned some facts such as the low refracting surface like tear film, Iris and pupil's function, the coefficient for scattering, absorption, polarization, transmission and reflection based on the wavelength and phase shift. They do not provide information about how the image contrast will be with different illuminance background.

3 Ray tracing and optical modeling of the human eye

To determine the retinal image quality, the amount of ray of the light coming from the object can be followed and quantified, this process is called ray tracing [10]. The ray tracing can be done for forward and backward, which means the light propagating through the cornea, aqueous humor, lens and vitreous humor to the retina or backwards from the retina to the cornea. Ray tracing demonstrates how much light ray is diffracted by each optical surfaces and from which specific points on the surface and their impact on image formation on the retina. Therefore, it is crucial to define at first the input data, which carries the object information, e.g. plenoptical function defines the object's position, direction, intensity and chromacity. For the simulation, following points are important:

1) an eye model, this eye model should include each anterior and posterior surface and their geometrical parameters such as radius of curvature, refractive index, surface shape, distance to next surface and thickness distribution. Also, the absorption, transmission, polarization and diffraction coefficient for each optical medium and surface must be considered. The optical surface and pupil are misaligned and non-rotationally symmetrical, thus not only the plenoptic function but also angular position in between optical component should be considered.

Fig. 4 Steps for the eye model simulation process

2) Next step is to determine the values for each component of an eye model. In literature from Gullstrand eye to the Navarro eye [10], huge number of eye models have quantified values for the optical surface. Though there is no complete model, at first one detailed eye model such as Gullstrand eye model can be taken and the missing components and parameters, for instance, coefficient for apshericity can be added from Navarro eye model or other eye models to describe each optical component with uniform parameters.

3) The simulation software should be able to demonstrate detailed image formation by each optical component. It should provide an overview about the correlation between illumination and impact on image contrast.

4) The output data compares the difference in plenoptical function and image quality by each optical components. Only a psychophysical test can validate the in- and output data of simulation and human perception of image quality.

Using the ray tracing method Rodriguez et al. developed a stochastic systhetic eye model to generate data in general population for optical calculation. This eye model is specifically based on the corneal shape parameters. They converted the measured corneal parameters to eigenvectors and create around 91 eigenvector parameters only to describe the cornea. Than after the simulation they compared obtained output data of cornea with the original measured cornea data. The comparison showed a positive correlation. The main limitation was they calculated lens parameter using multiple linear regression and not measured with phakometry, the original data was based on 312 caucasian population. Their result however did not provide information about the age, ethnic origin, accommodation, adaptation , individual eye and lens parameter [2].

Recently, a 3D-spectral scene is simulated with Image system engineering toolbox (ISET) using an existing eye model. They quantified the 3D scene with a plenoptical function, than simulate 3D spectral radiance to 2D retinal image and considered accommodation, retinal eccentricities and pupil size. They modeled the retinal image for planar and distant object based on wavelength dependent function. They did not considered astigmatism, phase shift and higher order aberration [11].

4 Conclusion

Finally, observing all the existing eye models and the development of the techniques to simulate the optics of the eye could provide a wide knowledge about the optical system of the human eye as compared 100 years before. The optical model of the human eye is complex system, hence it is a difficult to consider each optical component and influencing factor to model an human eye. Existing eye models are not a complete optical system of the human and provide only feature-based informations. But it is possible to analyze the existing models and design a complete model.

However, there are several simulations of the eye model with some software available for the ray tracing with different features like illumination light, refracting surfaces, and wavelength dependent ray tracing. The input data should determine as possible information such as position, direction and wavelength about an object to be simulated, so that the result can be compared.

Furthermore, measured human eye data have limited accuracy, because every measurement obtained from the clinical device has deviations and uncertainties due to the measurement process itself.

5 Outlook

Modeling an complete eye model would be an important milestone for the vision science research and in the light engineering. A model serve to understand about the photometry of the eye and visual perception. Similarly, an eye model will serve to predict and compare the surgical outcomes and device calibration in ophthalmology, also for the diagnosis and treatment. Next point is the image quality analysis for better camera system and calibration. Finally, an eye model will serve to explore more about the optical components and optical effects (visual acuity, contrast sensitivity and electroretinogram etc.).

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