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Comparison of Numerical Eye Models and its Representation within a Mechanical Eye Model ⋆

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Abstract: Today the increased computer power admits very detailed numerical modelling of the human eye. Simultaneous new technologies as well as the defined production of aspherical lenses permits the realization of nearly realistic ex vivo mechanical simulation of the natural human eye. Amongst others such ex vivo mechanical eye models are used to verify the optical quality of new intraocular lenses. Measurements of modulation transfer function (MTF) performed by an ex vivo mechanical eye model and numerical analysis of saggital and tangential MTF are presented.

Keywords: Mechanical eye model, Numerical optical analysis, Intraocular lens, Image quality, MTF

1. INTRODUCTION

The mathematical and numerical characterization of the optical and physiological properties of the human eye has a more than hundred years old history. An overview of different publications separated by multiplicity levels of complexity was given by different authors [Atchison (2005); de Almeida and Cavalho (2007); Navarro (2009)].

In the nineties ex vivo mechanical eye models were developed to measure optical quality criteria after ophthalmic surgeries and to predict the quality of implanted intraocular lenses [Norrby et al. (2007); Drauschke et al. (2013); Díaz and Celestino (2014)]. First modern mechanical eye models are oriented to the ISO 11979–2 standard [International Organization for Standardization ISO Central Secretariat (2003)] for measuring intraocular lens (IOL) quality. The definitions of the ISO eye model are not adaptive for all cases of application. On the one hand new advanced models do not fulfill the requirement of this standard, e.g. using more physiological aspherical cornea lenses [Drauschke et al. (2013)]. On the other hand Norrby had pointed out, that the ISO eye model cannot be adapted to test of aspherical lenses [Norrby (2008)]. Due to this mismatch, the development of non ISO eye models has been strongly motivated.

The quality measurement and test instructions for IOL are defined in the ISO 11979–2 [International Organization for Standardization ISO Central Secretariat (2003)]. The quality definition is based on the measurement of the optical resolution and the MTF in a well defined measurement set–up. However, since new optical design strategies allow the design of aberration free aspherical IOL additional optical quality parameters are used to find applicable mechanical eye models and better accordance between patients physiological image quality feeling and physical image quality [Pieh et al. (2009); Applegate et al. (2003); Drauschke et al. (2013)].

2. MATERIALS AND METHODS

2.1 Numerical eye models

The investigation of the human eye starts with explanation of the optical basics of imaging by Gauss in 1841. As a result many theoretical eye models were developed to characterize physiological aspects based on measured optical properties of the human in vivo eye.

A reduced eye model was presented by Emsley in 1952 [Emsley (1952)] as shown in table 1. Advanced eye models use three spherical interfaces as presented by Helmholtz & Laurance (1909), Gullstrand (1911) and Le Grand & El Hage (1980) [Alpern (1978); Southall (1924); Le Grand and El Hage (1980)]. Optical properties of this eye models are shown in table 2. Schematic eye models with four spherical interfaces were presented by Gullstrand (1911) and Le Grand & El Hage (1980) [Le Grand and El Hage

Table 1. Reduced eye model with 1 spherical surface

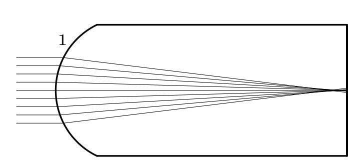
Physical parameters			
Surface	**Radius in [mm]**	**Thickness in [mm]**	**Refractive index**
[Emsley (1952)]			
			
1	5.55	22.22	1.3333

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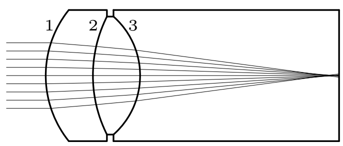
Table 2. Reduced eye model with 3 spherical surfaces

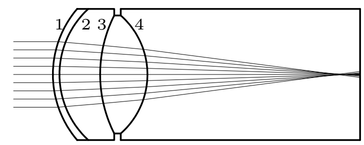
Physical parameters			
Surface	**Radius in [mm]**	**Thickness in [mm]**	**Refractive index**
Helmholtz & Laurance (1909) (in [Alpern (1978)])			



1	8.00	3.60	1.3330
2	10.00	3.60	1.4500
3	-6.00	15.18	1.3330
Gullstrand (1911) (in [Southall (1924)])			
1	7.80	3.60	1.3360
2	10.00	3.60	1.4130
3	-6.00	16.97	1.3360
[Le Grand and El Hage (1980)]			
1	7.8	3.60	1.3330
2	10.20	3.60	1.4160
3	-6.00	16.70	1.3330

Table 3. Eye model with 4 spherical surfaces

Physical parameters			
Surface	**Radius in [mm]**	**Thickness in [mm]**	**Refractive index**
Gullstrand (1911) (in [Le Grand and El Hage (1980)]			



1	7.70	0.50	1.3760
1	6.80	3.10	1.3360
2	10.00	3.6	1.4085
3	-6.00	16.97	1.3360
[Le Grand and El Hage (1980)]			
1	7.80	0.55	1.3771
2	6.50	3.05	1.3374
3	10.20	4.00	1.4200
4	-6.00	12.45	3.3360

(1980)]. The parameters of that schematic eyes are listet in table 3. Most sophisticated schamatic eye models use aspherical interfaces, the grated index structure of the eye lens and include the dispersion of tissue material as presented by Schwiegerling(1995), Liou & Brennan (1997) and Escudero & Navarro (1999) [Schwiegerling (1995); Liou and Brennan (1997); Escudero-Sanz and Navarro (1999)]. Optical parameters of that schematic eye models are listet in table 4.

2.2 The numerical and mechanical eye model set–up

The ex vivo mechanical eye model used in this paper is not conform to the ISO eye model. A numerical and a mechanical eye model based on the measurements of optical properties of the human eye performed by Liou and Brennan was used [Liou and Brennan (1997); Drauschke et al. (2012, 2013)]. The small differences between the mechanical eye model and the eye model by Liou and Brennan are explained in the following. The numerical set–up is performed within ZEMAX©[Radiant Zemax Corporate Offices & Research Center (2013)].

Both models, numerical and mechanical, were built up with aspherical cornea lenses. The numerical eye model consists of homogeneous material with refractive index of 1.376 and Abbe V–number of 61.2 according to Liou & Brennan [Liou and Brennan (1997); Atchison (2005)]. The anterior surface has a spherical radius of $R = 7.77$ mm and an asphericity of $Q = -0.18$. The posterior surface has a radius of $R = 6.4$ mm and an asphericity of $Q = -0.6$. The cornea has a center thickness of $d = 0.5$ mm.

In the mechanical eye model an aspherical meniscus lens is used too. The anterior and posterior surfaces are defined by

$$z = \frac{\frac{r^2}{R}}{1 + \sqrt{1 - (1+Q)\left(\frac{r}{R}\right)^2}}. \quad (1)$$

Concerning manufacturing constrains and the use of material with different refractive index (Polymethyl methacrylate: PMMA) a lens with same focal distance but different shapes is used as cornea lens. In equation 1, the parameters are defined as follows; $R = 7.77$ mm the spherical radius, $0\,\text{mm} \leq r \leq 6\,\text{mm}$ the radial coordinate and $Q = -0.194053$ the asphericity of the anterior lens surface and $R = 7.186631$ mm the spherical radius, $0\,\text{mm} \leq r \leq 6\,\text{mm}$ the radial coordinate and $Q = -0.019958$ the asphericity of the posterior lens surface, respectively. The center thickness of the lens is $d = 0.7$ mm. A small shift of the principal planes of the cornea lens is compensated within the set–up. The spherical aberration is somewhat smaller than that for the natural cornea lens.

A natural (double) gradient–index (GRIN) eye lens, a spherical IOL, or an aspherical IOL is used in the numerical eye model according to simulations of Drauschke et al [Drauschke et al. (2013)]. The gradient function of the (double) GRIN lens is taken according to Liou & Brennan [Liou and Brennan (1997)]. Within the mechanical eye model a spherical Artisan Aphakia 5/8.5 IOL with 24dpt is used. It consists of PMMA. The IOL can be shifted and tilted for alignment in reference to the optical axis which is defined by the center points of the cornea and the pupil aperture.