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OPTICAL MODELLING FOR UNCORRECTED AND CORRECTED MYOPIA USING RAY TRACING TECHNIQUE

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OPTICAL MODELLING FOR UNCORRECTED AND CORRECTED MYOPIA USING RAY TRACING TECHNIQUE

By

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Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

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Faculty : Science

Current trend shows that the eye modelling is based on the emmetropic eye taken its ocular optical components value from the population-based studies. However, no studies have been done to study the effect of aberration of myopic refractive error by modelling the eye using the parameters from ocular biometrics and ray tracing method. The objective of the present study was to assess the aberrations quality of myopic refractive error using eye modelling and ray tracing technique. Five eye models had been successfully modelled in Zemax software, namely, Emsley's Reduced Eye, Gullstrand-Emsley, emmetropic Liou and Brennan, myopic Liou and Brennan, corrected myopic Liou and Brennan. The optical performance of the eye models were tested using the merit functions in Zemax, namely, modulation transfer function (MTF), spot diagram (SPD), ray fan plot, point spread function (PSF), and diffraction image analysis. From the MTF analysis at 100 cycles/mm, the tangential and sagittal rays of Liou and Brennan had the highest optical performance from sharpness ability and contrast behaviour among the emmetropic models. In contrast, the Emsley produced the lowest optical performance for both components. As the MTF value indicates the threshold of the image contrast of sinusoidal pattern, the higher the value will enable higher image recognition. On further analysis, the MTF value for myopic Liou and Brennan eye was the lowest compared to the other emmetropic models. Also, it was found out that the MTF value of the corrected myopic Liou and Brennan model was higher compared to the previous uncorrected myopic model. Furthermore, in comparison with the emmetropic models, the MTF values for corrected myopic Liou and Brennan was also higher compared to both emmetropic Emsley and Gullstrand-Emsley models. However, the corrected myopic model produced lower MTF values for both tangential and sagittal MTF compared with the emmetropic model of Liou and Brennan. For the SPD, the emmetropic Liou and Brennan model had the lowest root mean square (RMS) value and Airy disc diameters among the three emmetropic models as this model had collective aberration corrections from the multiple ocular optical components. In contrast, the emmetropic Emsley model had the highest RMS

value as its single refracting surface produced higher diffraction effect. On further analysis, the ray distribution from the analysis of SPD of myopic Liou and Brennan eye was larger compared to the emmetropic model. In comparison with the emmetropic Liou and Brennan model, for the blue wavelength, the RMS spot radius for the corrected version was increased. However, the RMS values were decreased for green and red wavelengths. The large difference at longer wavelength specifically at green and red were due to chromatic aberration of the lens medium. For the corrected myopic version of Liou and Brennan, in comparison with its emmetropic model, the Airy disc diameter increased with the increment of wavelengths. Although the corrective lenses had been used to correct the myopia, the refractive correction is not at the optimum state. This was because the corrective lens power was calculated in the spherical equivalent refraction (SER) forms that sums up the spherical and cylindrical components. For the ray fan plot, as the chromatic aberration is highly dependent on light wavelength, this had caused the myopic Liou and Brennan model to contain more spherical aberration effect in comparison to emmetropic eye models. Furthermore, in comparison with the emmetropic Liou and Brennan model, the corrected version of myopic Liou and Brennan model had more diffraction-limited effect, thus the marginal rays were less aberrated. The green wavelength had almost no aberration as the corrective lenses refractive index was calculated at the wavelength closer to the green wavelength itself. For the PSF, the Strehl ratio for all the three wavelengths for the Liou and Brennan model were the highest among the emmetropic models. Whereas, in comparison with emmetropic eye models, the Strehl ratio value of myopic Liou and Brennan was much lower, thus did not producing a diffraction-limited system. On further analysis, in comparing with the emmetropic model, it was found out that the Strehl ratio values for all wavelengths of corrected myopic Liou and Brennan were much higher except for the blue wavelength. Finally, for the diffraction image analysis, the image quality from Liou and Brennan model was at the upmost quality among the emmetropic models. On the other hand, the image quality of the myopic Liou and Brennan model was at the lowest quality. On further analysis, in comparison with the emmetropic Liou and Brennan model, the image quality of the corrected myopic version was slightly lower. In this study, the accuracy of the merit functions for the myopia correction and emmetropia using the Liou and Brennan (1997) model were calculated. It was found that the accuracy of the MTF value at tangential and sagittal rays was lower. In contrast, for the Airy disc diameter, the accuracy were higher for the blue, green and red wavelengths. Although the accuracy values were in a positive sign, for Airy disc diameter, the smaller value indicates a diffraction-limited condition. Finally, for the Strehl ratio, the accuracy for the blue wavelength was lower. On the other hand, the green and red wavelengths had higher accuracy.

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MODEL OPTIK BAGI MIOPIA TANPA DAN DENGAN PEMBETULAN MENGGUNAKAN TEKNIK PENYURIHAN SINAR

Oleh

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Kecenderungan terkini menunjukkan bahawa permodelan mata adalah menggunakan mata emetropia dengan mengambil nilai komponen-komponen optikal okular dari hasil kajian populasi. Objektif kajian ini adalah bertujuan untuk menilai aberasi pada kualiti imej miopia dengan menggunakan teknik penyurihan sinar pada model mata. Lima model mata telah dibangunkan dengan menggunakan perisian Zemax, iaitu Emsley's *Reduced Eye*, Gullstrand-Emsley, mata emetropia Liou dan Brennan, mata miopia Liou dan Brennan, dan mata pembetulan miopia Liou dan Brennan. Prestasi optikal model mata tersebut telah diuji dengan menggunakan fungsi merit dalam perisian Zemax, iaitu fungsi hantaran modulasi (MTF), gambarajah bintik (SPD), plot sinar kipas, fungsi serakan titik (PSF), dan analisis imej belauan. Melalui analisis MTF pada 100 kitar/mm, sinar tangen dan sagital bagi model mata Liou dan Brennan mempunyai prestasi optik tertinggi dari segi ketajaman dan kontras antara model-model mata emetropia yang dikaji. Manakala model mata Emsley mempunyai prestasi optik yang lemah untuk kedua-dua ciri ketajaman dan kontras. Oleh kerana nilai MTF merupakan indikasi kepada nilai ambang bagi kontras imej pada corak bentuk sinus, nilai MTF yang semakin tinggi membolehkan pengecaman imej yang lebih jelas. Seterusnya, nilai MTF bagi model mata miopia Liou dan Brennan adalah yang paling rendah berbanding model mata emetropia yang lain. Kajian ini juga mendapati bahawa nilai MTF bagi model mata pembetulan miopia Liou dan Brennan adalah lebih tinggi berbanding model mata miopia sebelumnya. Selanjutnya, berbanding dengan model-model mata emetropia yang lain, nilai MTF bagi model mata pembetulan miopia Liou dan Brennan juga adalah lebih tinggi. Walau bagaimanapun, model mata pembetulan miopia tersebut menunjukkan nilai MTF yang lebih rendah bagi kedua-dua tangen dan sagital berbanding model mata emetropia Liou dan Brennan. Untuk nilai SPD, model mata emetropia Liou dan Brennan mempunyai nilai punca min kuasa dua (RMS) dan diameter diska Airy yang paling rendah antara ketiga-tiga model emetropia, di mana model tersebut telah mengambilkira

pembetulan jumlah aberasi dari pelbagai komponen optik okularnya secara kolektif. Manakala model mata emetropia Emsley menunjukkan nilai RMS tertinggi disebabkan model mata tersebut hanya mempunyai satu permukaan refraksi yang mengakibatkan kesan belauan yang tinggi. Analisis SPD seterusnya mendapati bahawa taburan sinar bagi model mata miopia Liou dan Brennan adalah lebih luas berbanding model matanya yang emetropia. Jika dibandingkan dengan model mata emetropia Liou dan Brennan, bagi jarak gelombang biru, nilai jejari bintik RMS bagi model mata dengan pembetulan miopia adalah meningkat. Walau bagaimanapun, nilai RMS bagi mata dengan pembetulan miopia adalah berkurang masing-masing bagi jarak gelombang hijau dan merah. Perbezaan yang besar pada jarak gelombang panjang, iaitu hijau dan merah ini adalah disebabkan oleh aberasi kromat pada medium kanta pembetulan yang digunakan. Bagi model mata versi pembetulan miopia Liou dan Brennan, jika dibandingkan dengan model emetropianya, diameter diska Airy meningkat sejajar dengan peningkatan jarak gelombang. Meskipun kanta pembetulan telah digunakan bagi membetulkan ralat refraksi miopia tersebut, pembetulan ralat refraksi tersebut tidak mencapai tahap optimum. Ini adalah kerana kuasa kanta pembetulan dikira dalam refraksi sfera setara (SER) yang menjumlahkan komponen-komponen sfera dan silinder secara sekali gus. Bagi keputusan plot sinar, oleh kerana aberasi kromat amat bergantung kepada jarak gelombang cahaya, ini menyebabkan model mata Liou dan Brennan mempunyai lebih kesan aberasi sfera berbanding dengan model mata emetropia yang lain. Disamping itu, dibandingkan dengan model mata emetropia Liou dan Brennan, versi model mata pembetulan miopia pula mempunyai kesan had-belauan yang tinggi, seterusnya kurang aberasi terjadi pada sinar marginal. Manakala hampir tiadanya aberasi pada jarak gelombang hijau kerana kuasa kanta pembetulan dikira menggunakan jarak gelombang yang menghampiri jarak gelombang hijau itu sendiri. Bagi keputusan PSF pula, nisbah Strehl bagi ketiga-tiga jarak gelombang untuk model mata Liou dan Brennan adalah yang tertinggi antara semua model mata emetropia. Manakala berbanding dengan semua model emetropia, nilai nisbah Strehl bagi model miopia Liou dan Brennan adalah lebih rendah, menyebabkan tiada berlakunya sistem had-belauan. Analisis seterusnya, iaitu membandingkan dengan model mata emetropia, didapati bahawa nilai nisbah Strehl bagi pembetulan miopia Liou dan Brennan adalah lebih tinggi kecuali pada jarak gelombang biru. Akhir sekali, bagi analisis imej belauan, didapati kualiti imej dari model mata Liou dan Brennan lebih berkualiti tinggi antara semua model mata emetropia. Manakala kualiti imej model mata miopia Liou dan Brennan adalah yang paling rendah. Analisis seterusnya menunjukkan imej kualiti model mata pembetulan miopia Liou dan Brennan adalah lebih rendah berbanding dengan model matanya yang emetropia. Dalam kajian ini, pengiraan kejituaan untuk fungsi merit bagi pembetulan miopia dan emetropia menggunakan model Liou dan Brennan telah dijalankan. Didapati bahawa nilai kejituan bagi nilai MTF pada sinar tangen dan sagital adalah rendah. Manakala bagi diameter diska Airy, nilai kejituan adalah tinggi bagi semua jarak gelombang biru, hijau dan merah. Meskipun nilai kejituan adalah bertanda positif bagi diameter diska Airy, nilai yang semakin mengecil menunjukkan keadaan yang menghampiri had-belauan. Akhir sekali, utuk nisbah Strehl, nilai kejituaan untuk jarak gelombang biru adalah rendah. Manakala jarak gelombang hijau dan merah pula mempunyai nilai kejituan yang tinggi.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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LIST OF ABBREVIATIONS AND SYMBOLS

Abbreviations

ACD	Anterior chamber depth
AL	Axial length
BSCVA	Best spectacle-corrected visual acuity
BHVI	Brien Holden Vision Institute
BVS	Best vision sphere
CCD	Charged couple device
CLC	Circle of least confusion
CR	Corneal radius
D	Dioptre
EPD	Effective pupil diameter
GAT	Goldmann applanation tonometry
GRIN	Gradient-index
IOP	Intraocular pressure
JCC	Jackson cross-cylinder
JOM	Juvenile-onset myopia
LED	Light-emitting diode
LOM	Late-onset myopia
LT	Lens thickness
M	Modulation
MTF	Modulation transfer function
OTF	Optical transfer function
PI	First Purkinje image
PIII	Third Purkinje image

PIV	Fourth Purkinje image
PSF	Point spread function
RMS	Root mean square
SD	Standard deviation
SER	Spherical equivalent refraction
SLE	Slit-lamp examination
SPD	Spot diagram
UPM	Universiti Putra Malaysia
VA	Visual acuity
VCD	Vitreous chamber depth

Symbols

c	Surface curvature
d	Effective pupil diameter
D	Airy disc diameter
E	Strehl intensity ratio
e	Position of first principal point
e'	Position of second principal point
f'	Second focal length
f_E	First equivalent focal length
f'_E	Second equivalent focal length
F (D)	Refractive power
F	First principal focus
F'	Second principal focus
F_E	Equivalent power
Hx	History
I_{max}	Maximum intensity
I_{min}	Minimum intensity
n	Refractive index of the first medium
n'	Refractive index of the second medium
N	First nodal point
N'	Second nodal point
P	First principal point
P'	Second principal point
Q	Conic constant
r	Radius of curvature

$\bar{t}$	Reduced thickness
λ	Light wavelength
~	Approximately equal to
%	Percentage

CHAPTER 1

INTRODUCTION

This chapter introduces an overview of schematic eye models. It covers the summary of research background, issues and key challenges faced in eye models development. The significance and contribution of this study towards a better understanding of eye modelling and its mechanism are highlighted. In addition, the research objectives and scopes are defined. In the final part, the organisation of the thesis is described.

1.1 Research Background

1.1.1 Overview of Human Ocular Anatomy and Visual System

The eye sits in a protective bony socket called the orbit. Six extraocular muscles in the orbit are attached to the eye (Bowling, 2016). These muscles move the eye up and down and side to side, and allows for eyeballs rotation. The extraocular muscles are attached to the white part of the eye called the sclera. This is a strong layer of tissue that covers nearly the entire surface of the eyeball. The most anterior surface of the exposed eye and the inner surface of the eyelids are covered with a transparent membrane layer called the conjunctiva. Tears lubricate the eye and the tear film is made up of three layers. The eye's lacrimal gland is located under the outside edge of the eyebrow in the orbit. This gland produces the aqueous part of the tears. Another gland, i.e., the meibomian gland produces the oil that becomes another part of the tear film. Tears drain from the eye through the tear duct that connects into the nose cavity.

Light is impinging and focus into the eye through the clear, dome-shaped front portion of the eye called the cornea (Goss & West, 2002; Rapuano, 2019). Behind the cornea is a fluid-filled space called the anterior chamber. The fluid is called aqueous humour. The eye is always producing aqueous humour. To maintain a constant eye pressure, aqueous humour also drains from the eye into an area called the drainage angle. Behind the anterior chamber is the eye's iris and the dark aperture in the middle called the pupil. Muscles in the iris dilate or constrict the pupil to control the amount of light reaching the back of the eye. Directly behind the pupil sits the crystalline lens. The crystalline lens focuses light towards the back of the eye. The crystalline lens changes shape to help the eye focus on objects up close known as accomodation. Small fibres called zonules are attached to the capsule holding the crystalline lens, suspending it from the eye wall. The vitreous cavity lies between the crystalline lens and the posterior of the eye. A jellylike substance called vitreous humour fills the cavity, nourishing the retina and helping the eye to hold its shape.

Light that is focused into the eye by the cornea and crystalline lens passes through the vitreous onto the retina; the light-sensitive tissue lining the back of the eye (Schwartz, 2013; Tunnacliffe & Hirst, 1996). A tiny but much specialised area of the retina called the macula lutea is responsible for providing detailed, central vision. The other part of the retina, i.e., the peripheral retina, provides the peripheral vision. The retina has special cells called photoreceptors. These cells change light into energy that is transmitted to the brain. There are two types of photoreceptors, namely, rods and cones. Rods perceive black and white stimulus, and enable scotopic vision. Whereas cones perceive colour, and provide photopic vision. The retina sends light as electrical impulses through the optic nerve to the brain. The optic nerve is made up of millions of nerve fibres that transmit these impulses to the visual cortex; the part of the brain that is responsible for vision (Remington, 2012).

1.1.2 Myopia

The incidence of myopia has been escalating globally, especially in East Asia, during the past 60 years (Dolgin, 2015; Yotsukura et al., 2019). The incidence of high myopia, which can be vision intimidating in later life, is also increasing worldwide (Holden et al., 2016). It is envisaged that the population with myopia will be approximately 5 billion in 2050 (Holden et al., 2016). Myopia is a common condition found in many populations, especially in Asian countries. In Singapore, Hong Kong and Taiwan, the prevalence of high myopia, which is defined as a refractive error of at least -6.00 D, is escalating (Fan et al., 2004; Lin et al., 1999; Pan, Dirani, Cheng, Wong, & Saw, 2015; Saw et al., 1996; Wong et al., 2000). In Malaysia, the prevalence of myopia has been recorded to be between 8 to 50 percent (Chung et al., 1996; Garner et al., 1987; Goh et al., 2005; Hashemi et al., 2018; Saadah et al., 2000). In myopic eyes, light from the object impinging into the eye via pupil will focus its image in front of the retina, which results to an inferior image quality (Freeman & Hull, 2003). Myopia is a potentially blinding condition owing to its association with ocular disease such as glaucoma, cataract, retinal detachment, posterior staphyloma, and degenerative macular neovascularisation (Ludwig et al., 2018; Saw et al., 2005; Saw, Matsumura, & Hoang, 2019). The conventional measurement of eye power, e.g., myopic refractive error are carried out using clinical refraction technique (Benjamin, 2006; Carlson & Kurtz, 2016; Elliot, 2014). In point of fact, the light impinging to the eye undergoes refraction that takes place in the refracting surfaces and ocular media in the visual system. The visual system consists of the following structures and media, namely, the cornea, aqueous humour, natural crystalline lens and vitreous humour, and finally the image is formed inside the eye (Artal, 2017; Rabbetts, 2007).

In myopic eyes, the globe is enlarged with an increase in axial length (AL) (Curtin, 1985). The stretching of the retina beyond normal dimensions may result in thinning of the retina (Luo et al., 2006). Retinal changes that occur in highly myopic subjects include the following, namely, peripheral lattice degeneration, peripapillary atrophy, inclined or malinsertion of the optic disc, posterior staphyloma, breaks in Bruch’s membrane, and myopic macula degeneration (Curtin, 1985; Fan et al., 2004; Ikuno, 2017; Wong, Phua, Lee, Wong, & Cheung, 2017). Some highly myopic subjects experience several complications that impair visual acuity purely as a result of the increased AL or the formation of posterior staphyloma (Curtin, 1985; Tideman et al., 2016). High myopes also tend to have chorioretinal atrophy at the posterior pole (Curtin, 1985; Tokoro, 2012), choroidal neovascularisation at the macular area (Ohno-Matsui et al., 2003; Ohno-Matsui, Jonas & Spaide, 2016), and a macular hole at the posterior pole (Kobayashi et al., 2002; Wu, Kung, Chang, & Chang, 2018).

1.1.3 Optical Models of Human Eye

Because the optics of real eyes are very complex, eye model (schematic) that is simpler than the real eye has been designed (Thibos & Bradley, 1999; Zapata-Diaz, Radhakrishnan, Charman, & Lopez-Gil, 2019). Eye models are available with a range of complexity, but at minimum, they include numerical values for radii of curvature, distance between refracting surfaces, and indices of refraction.

To best of our knowledge, not many eyes were modelled as affected by refractive state. Atchison (2006) had modelled an anatomical and optical performance measurements of young adult myopic eyes. In the study, the author incorporated measured parameters into refraction dependent eye models. However, it was stated by him that it must be appreciated that there are considerable variations between people, and often the correlations between a parameter and refraction are low even when the variation of the parameter is significantly related to the latter. The models can be modified to account for such variations where additional knowledge is available. Having developed the models, he determined their predictions of on-axis and off-axis aberrations against experimental findings.

1.2 Motivation

Previous myopia studies have proven that myopic refractive error is associated with eyeball elongation, in particular, the vitreous chamber depth increment (Gwiazda et al., 2002; Jiang & Woessner, 1996; Sun et al., 2015). In contrary, there is reduced in choroidal thickness along the increment of myopia (Matri et al., 2012; Nishida et al., 2012). This type of myopia is classified as the axial myopia. In routine optometric examination, clinical refraction has been regarded as the conventional way of obtaining myopic refractive error. These clinical refraction techniques, namely, autorefraction, skiascopy (retinoscopy) and subjective refraction have been regarded as the standard procedures (Carlson & Kurtz, 2016; Elliot, 2014). Nevertheless, only few studies (Hiraoka, Kotsuka, Kakita, Okamoto, & Oshika, 2017; Liu & Wang, 2019) have been done to study the effect of aberration of myopic refractive error by modelling the eye using the parameters from the ocular biometrics and ray tracing method. At present, the eye modelling is based on emmetropic eye. Therefore, a question arises if we can develop a computer modelling of eye that can verify the axial type of myopia from the clinical refraction findings, using the numerical values of the parameters of ocular optical components and the fixed refractive indices of media from the existing chosen eye model. Also, the value of spectacle refractive error is used to correct the myopic eye model, and analyse its optical performance using the merit functions in Zemax.

1.3 Problem Statements

As stated in Section 1.2 on page 5, myopia has been proven to be associated with elongation of the globe, in particular the increase of the vitreous chamber (Gwiazda et al., 2002; Jiang & Woessner, 1996). Also, this myopia is categorised as axial myopia type. Different methods of clinical refraction of obtaining myopic refractive error, i.e., autorefraction, retinoscopy and subjective refraction have been used as a routine procedures during part of the optometric examination.

The investigation on obtaining myopic refractive error via clinical technique as stated above has been extensively conducted since decades. Nevertheless, from the available literature and as stated in Section 1.2 on page 5, no studies have been done to determine the optical performance of myopic refractive error by modelling the eye using the parameters from ocular biometrics and ray tracing method. At present, the eye modelling is based on emmetropic eye. Therefore, a question comes if we can develop a computer modelling of eye that can verify the axial type of myopia from the clinical refraction finding, using the numerical values of the parameters of ocular optical parts and the established refractive indices of ocular media using the chosen eye models studied previously.

Therefore, the new methods of identifying the optical performance of the myopic eye and validating the refractive correction were carried out using the available software.

In order to conduct this study, due to lack of previous data and studies, the following hypotheses were deduced. Firstly is the validating of emmetropic eye using computer model utilising clinical ocular parameter. Secondly, the commonly used optical performance will be used in the validation process and lastly a simple comparison will be proposed to make the validation process would be easily to be utilised in real application of correcting myopic problem.

1.4 Research Objectives

1.4.1 General Objective

This study aims to assess the aberrations of the image quality of myopia using a ray tracing technique of an eye model. The image quality gathered from the study will be discriminated and later a conclusion comparison of the proposed myopic eye can be deduces.

1.4.2 Specific Objectives

The specific objectives of the study are as follows:

1. To determine the ocular biometry parameters of the myopic eye.
2. To compare the merit functions of the established emmetropic eyes based on their parameters of ocular optical components in optical design software.
3. To develop the myopic eye and corrected myopic eye model in the optical design software based on the parameters of ocular optical components taken from the results of ocular biometry and clinical refraction.
4. To determine the optical performance of eye models using a simulation software.
5. To assess the accuracy of the merit functions for the myopia correction.

1.5 Research Scopes

In order to achieve the above-mentioned research objectives, several scopes of works have been drawn. It has been determined that the study of myopia estimation in this thesis is limited to the eye modeling and the results from the ocular biometry and the clinical refraction were used to model the eye. Three established eye models are used and being incorporated in Zemax as follows:

a) Emsley reduced eye
b) Gullstrand-Emsley schematic eye
c) Liou & Brennan model eye

Then, the best model eye were selected based on the simulation results that produced better image quality via merit functions analysis in Zemax which was used to model the myopic eye. The parameters for modelling the myopic eye were using the data taken from ocular biometry measurements of real human subjects.

The myopic refractive error of the model eye was estimated using the corrective lenses designed in Zemax. The power of the lenses was taken from the value obtained via clinical refraction. The lens parameters were constructed and designed to ensure that the same power was used in the modelling.

1.6 Thesis Organisation

The thesis is divided into six main chapters. Chapter 1 presents the preface of the thesis. It covers the summary of research background, issues and key challenges faced in the model eye development. The research objectives and scopes are also described. Chapter 2 comprises a review on development of human model eyes. It covers the historical evolution of model eyes, development of model eyes and analysis on roles of various model eyes reported in previous studies. Detailed aspects of components and curvatures of model eyes structure from studies using aberration and ray tracing technique are thoroughly reviewed. A detailed description of the eye models that are chosen for the computer modelling in Zemax are also described. The theory of the optical performance of the eye, theoretical models related to aberration assessment, i.e., the modulation transfer function (MTF), spot diagram (SPD), ray fan plot, point spread function (PSF), and diffraction image analysis are described. The theory of merit function that is applied in Zemax and principles of the image quality calculation that involve points and patterns are also elaborated. Chapter 3 outlines the modelling process using the established schematic eyes. The methods of obtaining data from human subjects via clinical measurements are elaborated. Chapter 4 is divided into seven sections, i.e., five sections to present the results and discussion on Zemax merit functions of model eyes simulation, one section on data analysis from the clinical measurement, and one section for the overall discussion of the results. In each model eye section, the 2-D layout of the respective model eye is presented. The merit functions from Zemax, i.e., MTF, SPD, ray fan plot, PSF and diffraction image analysis are also presented. In addition, in the clinical results section, the descriptive analysis of the data from the clinical measurement are also presented and discussed. The analysis of model eyes are compared in terms of their aberration and ray tracing. In addition, the results of the optical performance from the modelling are also compared with the previous studies. Chapter 5 concludes the general outcomes from arguments presented in preceding chapters. For future work, limitations on current studies and recommendations for future research are highlighted.

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