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Optical models for human myopic eyes

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Abstract

Data from the author's investigations and other studies are used to construct refractive dependent models. These models include a gradient index lens and aspheric corneal, lens and retinal surfaces. Elements that alter with refraction are anterior corneal radius, vitreous length and retinal shape (vertex radius of curvature and asphericity) and decentration. Two versions of the models are produced, one with centred and symmetrical optical elements, and one with tilts of the lens and decentrations and tilts of the retina. The centred model predicts increase in spherical aberration in myopia. It predicts the relative change in mean sphere in the periphery between the horizontal and vertical meridians that has been observed in a recent experimental study. It overestimates peripheral astigmatism by about 50%. The decentred version has limited success in predicting changes in peripheral refraction of average eyes.

Keywords: Aberration; Astigmatism; Myopia; Optics of the human eye; Peripheral refraction; Refractive error; Schematic eye

1. Introduction

Several optical models of the human eye, often called schematic eyes, have appeared over the last 150 years. These have been of different levels of complexity, ranging from reduced eyes (one refracting surface), three refracting surfaces (single surfaced cornea and a two surfaced lens), four refracting surfaces (two corneal surfaces and two lens surfaces), and models that allow for variation in refractive index within the lens. The first of the last type was the Gullstrand No. 1 (exact) eye (Gullstrand, 1909), in which the gradient index was modelled by a two shell lens in which the inner shell (nucleus or core) had higher refractive index and more curved surfaces than the outer shell (cortex). Others have used more elaborate shell structures (Atchison & Smith, 1995; Mutti, Zadnik, & Adams, 1995; Pomerantzeff, Rankratov, Wang, & Dufault, 1984). With the advent of more knowledge about the gradient index structure and advances in the ability to trace through gradient index media, a shell structure can be replaced by two surfaces and a gradient index media as has been done in recent models (Blaker, 1991; Liou & Brennan, 1997; Smith, Pierscionek, & Atchison, 1991).

Most early eye models such as Emsley's reduced eye, Gullstrand–Emsley simplified eye, the Le Grand exact eye and Gullstrand's No. 1 eye, can be described as paraxial models. This means that they are useful only for small aperture sizes and small field angles, but there are found wanting in predicting on-axis aberrations (particularly spherical aberration) and off-axis aberrations (Atchison & Smith, 2000). Since the 1970s, "finite" eye models have appeared which attempt to give reasonable estimates of at least some of the aberrations of the eye. The abilities of the Lotmar (1971), Drasdo and Fowler (1974), Kooijman (1983), Navarro, Santamaría, and Bescós (1985) and Liou and Brennan (1997) finite model eyes to predict on- and off-axis aberrations have been discussed by Atchison and Smith (2000). Some models allow predictions of chromatic aberrations by including media exhibiting chromatic dispersion e.g., Le Grand's exact eye, Navarro's finite eye, Thibos et al.'s "Indiana" eye (Thibos, Ye, Zhang, & Bradley, 1992), and Liou and Brennan's finite eye.

Most model eyes have been emmetropic, although the Gullstrand No. 1, Gullstrand–Emsley, and Le Grand full

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Optical models for human myopic eyes

人类近视眼的光学模型

None

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Abstract

Data from the author's investigations and other studies are used to construct refractive dependent models. These models include a gradient index lens and aspheric corneal, lens and retinal surfaces. Elements that alter with refraction are anterior corneal radius, vitreous length and retinal shape (vertex radius of curvature and asphericity) and decentration. Two versions of the models are produced, one with centred and symmetrical optical elements, and one with tilts of the lens and decentrations and tilts of the retina. The centred model predicts increase in spherical aberration in myopia. It predicts the relative change in mean sphere in the periphery between the horizontal and vertical meridians that has been observed in a recent experimental study. It overestimates peripheral astigmatism by about 50%. The decentred version has limited success in predicting changes in peripheral refraction of average eyes.

摘要

作者的调查数据和其他研究数据被用来构建折射率依赖模型。这些模型包括梯度折射率透镜和非球面角膜、晶状体和视网膜表面。随着折射率的变化而改变的元素包括前表面角膜半径、玻璃体长度和视网膜形状（顶点曲率半径和非球度）以及偏心率。制作了两个版本的模型，一个带有中心对称的光学元件，另一个带有透镜倾斜、视网膜偏心和倾斜。中心模型预测近视的球形像差会增加。它预测了最近实验性研究中在水平和垂直子午线之间观察到的周边平均球的相对变化。它把周围的散光高估了约50%。偏心版本在预测普通眼的周边屈光度变化方面有限的成功。

None.

Keywords

Aberration; Astigmatism; Myopia; Optics of the human eye; Peripheral refraction; Refractive error; Schematic eye

关键词

畸变；散光；近视；人眼光学；周边屈光不正；屈光错误；示意眼（None）

1. Introduction Several optical models of the human eye, often called schematic eyes, have appeared over the last 150 years. These have been of different levels of complexity, ranging from reduced eyes (one refracting surface), three refracting surfaces (single surfaced cornea and a two surfaced lens), four refracting surfaces (two corneal surfaces and two lens surfaces), and models that allow for variation in refractive index within the lens. The first of the last type was the Gullstrand No. 1 (exact) eye (Gullstrand, 1909), in which the gradient index was modelled by a two shell lens in which the inner shell (nucleus or core) had higher refractive index and more curved surfaces than the outer shell (cortex). Others have used more elaborate shell structures (Atchison & Smith, 1995; Mutti, Zadnik, & Adams, 1995; Pomerafft, Rankratov, Wang, & Dufault, 1984). With the advent of more knowledge about the gradient index structure and advances in the ability to trace through gradient index media, a shell structure can be replaced by two surfaces and a gradient index media as has been done in recent models (Blaker, 1991; Liou & Brennan, 1997; Smith, Pierscionek, & Atchison, 1991).

2. 简介 过去150年中，人眼的几种光学模型，通常被称为示意眼，已经出现。这些模型的复杂程度有所不同，从简化的眼（一个折射面），到三个折射面（单面角膜和双面晶状体），四个折射面（两个角膜表面和两个晶状体表面），以及允许晶状体内屈光度变化的模型。最后一种模型的第一个是Gullstrand No.1（精确）眼睛（Gullstrand，1909），其中梯度折射率是由一个双壳晶状体模拟的，其中内壳（核或核心）具有比外壳（皮层）更高的折射率和更弯曲的表面。其他人使用了更复杂的壳结构（Atchison&Smith，1995；Mutti，Zadnik和Adams，1995；Pomerafft，Rankratov，Wang和Dufault，1984）。随着对梯度折射率结构的了解越来越多以及追踪梯度折射率介质的能力的进步，壳结构可以被两个表面和一个梯度折射率介质所取代，就像最近的模型一样（Blaker，1991；Liou&Brennan，1997；Smith，Pierscionek&Atchison，1991）。

Most early eye models such as Emsley's reduced eye, Gullstrand–Emsley simplified eye, the Le Grand exact eye and Gullstrand's No. 1 eye, can

be described as paraxial models. This means that they are useful only for small aperture sizes and small field angles, but there are found wanting in predicting on-axis aberrations (particularly spherical aberration) and off-axis aberrations (Atchison & Smith, 2000). Since the 1970s, ''finite'' eye models have appeared which attempt to give reasonable estimates of at least some of the aberrations of the eye. The abilities of the Lotmar (1971), Drasdo and Fowler (1974), Kooijman (1983), Navarro, Santamarı´a, and Besco´s (1985) and Liou and Brennan (1997) finite model eyes to predict on- and off-axis aberrations have been discussed by Atchison and Smith (2000). Some models allow predictions of chromatic aberrations by including media exhibiting chromatic dispersion e.g., Le Grand's exact eye, Navarro's finite eye, Thibos et al.'s ''Indiana'' eye (Thibos, Ye, Zhang, & Bradley, 1992), and Liou and Brennan's finite eye.

大多数早期的眼睛模型，如艾姆斯利减少眼睛、古尔斯特兰-艾姆斯利简化眼睛、勒格朗精确眼睛和古尔斯特兰1号眼睛，都可以描述为副轴模型。这意味着它们只适用于小孔径大小和小视场角，并且在预测轴向像差（特别是球形像差）和离轴像差方面存在缺陷（阿奇森和史密斯，2000年）。自20世纪70年代以来，出现了"有限"眼睛模型，试图提供至少一些眼睛的像差的合理估计。阿奇森和史密斯（2000年）讨论了Lotmar（1971年）、Drasdo和Fowler（1974年）、Kooijman（1983年）、Navarro、Santamarı´a和Besco´s（1985年）以及Liou和Brennan（1997年）有限模型眼睛预测轴向和离轴像差的能力。有些模型通过包括具有色散的介质来允许预测色差像差，例如勒格朗的精确眼睛、纳瓦罗的有限眼睛、Thibos等人的"印度纳州"眼睛（Thibos，Ye，Zhang和Bradley，1992）以及Liou和Brennan的有限眼睛。

Most model eyes have been emmetropic, although the Gullstrand No. 1, Gullstrand–Emsley, and Le Grand full.

大多数模型眼睛都是正视力，尽管有Gullstrand No.1、Gullstrand-Emsley和Le Grand Full。None

schematic eyes are available in fully accommodated forms, and the Navarro model eye is "adaptive" in that its lens parameters and the anterior chamber and vitreous depths change continuously with accommodation. With increase in age, the lens becomes thicker, more curved in its unaccommodated state and its refractive index distribution changes, and this has been considered in recent models of adult eyes (Atchison & Smith, 2000; Blaker, 1991; Norrby, 2005; Rabbetts, 1998; Smith, Atchison, & Pierscionek, 1992). Zadnik et al. (2003) have recently described age related changes in emmetropic children, but this has not yet been incorporated into a formal eye model.

There does not appear to have been any modelling of eyes as affected by refractive state in adult eyes. Recently in conjunction with colleagues, I have made many anatomical and optical performance measurements of young adult myopic eyes. In this paper I incorporate these into refraction dependent eye models. 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, I determine their predictions of on-axis and off-axis aberrations against experimental findings.

2. Methods

2.1. Subjects and measurements

The research followed the tenets of the Declaration of Helsinki, with the research approved by both the QUT University Human Research Ethics Committee and the Prince Charles Hospital Human Research Ethics Committee and with informed consent obtained from all participants. The study cohort comprised 121 emmetropic and myopic participants aged 25 ± 5 years (age range 18–36 years). Non cycloplegic monocular sphero-cylinder subjective refraction was performed on both eyes using a Jackson crossed cylinder in a phoroptor. Maximum plus and binocular balance to ± 0.25 D were administered. The range of spectacle mean spherical refraction (SR) was +0.75 D to −12.38 D. This was assumed to be at 12 mm vertex distance. Participants with >0.50 D of astigmatism as measured by subjective refraction or with a corrected visual acuity poorer than 6/6 in the test eye were excluded. Participants were also excluded if they had any ocular disease in either eye, previous ocular surgery, or had ocular tension >21 mm Hg. Right eyes were measured in 94% of cases. The left eye was used where it met the inclusion criteria and the refraction of the right eye was outside spherical or astigmatic limits (9 cases). As applicable, signs of left eye parameters are changed to match right eyes.

Videokeratographic images were taken of anterior corneas of all 121 participants with the Medmont E300 instrument. This generates various data files. The data are centred relative to the keratometric axis, which pass to the fixation point normal to the cornea. One of the data files generated by the instrument indicates the position of the entrance pupil centre relative to the keratometric axis, and this was used with the height data fit in a least squares fitting procedure to determine the best fitting vertex radius of curvature (R) and corneal conicoid asphericity (Q) for a 6 mm diameter cornea using the formula:

$$(X^2 + Y^2) + (1 + Q)Z^2 - 2ZR = 0,$$

where the Z-axis passes through the line of sight. Measurements were taken with undilated pupils. Mean pupil diameter was 4.4 ± 0.8 mm with a range of 2.7–6.0 mm. Poor approximation of the pupillary outline (and hence centre) was found when the pupil is covered by the reflection of the rings of the Placido disk or for some subjects with dark irides. In these cases, the pupil centre and size were manually estimated.

A-scan ultrasound biometry measurements made on 119 participants were taken on an eye while the contralateral eye fixated a distance (6 m) target. One drop of topical anaesthetic, benoxinate hydrochloride 0.4% (Minims, Chauvin Pharmaceuticals Ltd), was instilled in the test eye approximately 1 min before ultrasound measurement. Special care was taken in aligning the transducer beam probe along the optical axis and to exert minimal corneal pressure. Ten measures with variability of less than 0.08 mm were averaged.

Magnetic resonance imaging (MRI) measurements were made on 87 participants (Atchison et al., 2004).

There was a female bias, with 63% of the total group and 60% of the MRI participants being female. The mean refractions of males and females were -2.2 ± 2.6 and -2.8 ± 2.9 D, respectively. Attention will be drawn to differences between males and females.

All measurements were taken without the use of cycloplegic drugs. Although it was intended that the measurements and hence modelling apply for the unaccommodated state, it is possible that there may have been some degree of accommodation for some subjects. This would have the effect of decreasing anterior chamber and increasing lenticular thickness measurements slightly.

2.2. Statistical analysis

Linear regressions of different parameters were performed using mean spherical refraction (SR) as the independent variable. Where significant correlations were not found, means were compared with zero using one sample t tests. Males and females were compared using independent sample t tests with equal variances assumed. The level of significance used for all tests was 5%. The statistical package SPSS was used for analyses.

2.3. Modelling

The modelling is based on previous models of unaccommodated emmetropic eyes (Liou & Brennan, 1997; Navarro et al., 1985), corneal and lens shapes reported using Scheimpflug photography by Dubbelman and colleagues (Dubbelman & Van der Heijde, 2001; Dubbelman, Van der Heijde, & Weeber, 2001; Dubbelman, Weeber, van der Heijde, & Volker-Dieben, 2002) in vitro lens refractive index measurements (Jones, Atchison, Meder, & Pope, 2005), previously reported MRI measurements (Atchison et al., 2004; Atchison et al., 2005), chromatic dispersion modelling (Atchison & Smith, 2005) and previously unreported anterior corneal topography and ultrasound intraocular distance measurements. Where age related data are used, I used my group mean age of 25 years. The selected values are compared with other literature values. Table 1 has the model parameters.

Apart from taking into account variation in parameters caused by refraction, two models are used. The surfaces of the centred Model 1 are co-axial, but the surfaces of Model 2 incorporate lens and retinal tilts and decentrations. The models are considered to be right eyes.

2.3.1. Anterior cornea (C1)

2.3.1.1. Vertex radius of curvature. The vertex radius of curvature is significantly correlated with refraction (Fig. 1). For the models, the obtained regression equation for the anterior cornea is rounded to

$$R_{C1}\ (\text{mm}) = 7.77 + 0.022SR \quad (1)$$

with a maximum error <0.003. This is slightly higher than that of the Navarro model eye (7.72 mm). Several other studies have reported either significant decrease in anterior radius of curvature with increase in myopia, or significant differences between emmetropic and myopic groups,

Schematic Eyes

立体感眼睛

Component	Function
Cornea	Refracts light onto lens
Lens	Focuses light onto retina
Retina	Converts light into neural signals
Optic nerve	Transmits neural signals to brain

Schematic eyes are available in fully accommodated forms, and the Navarro model eye is ‘‘adaptive’’ in that its lens parameters and the anterior chamber and vitreous depths change continuously with accommodation. With increase in age, the lens becomes thicker, more curved in its unaccommodated state and its refractive index distribution changes, and this has been considered in recent models of adult eyes (Atchison & Smith, 2000; Blaker, 1991; Norrby, 2005; Rabbetts, 1998; Smith, Atchison, & Pierscionek, 1992). Zadnik et al. (2003) have recently described age related changes in emmetropic children, but this has not yet been incorporated into a formal eye model.

支架眼睛可以以完全的适应形式提供，Navarro模型眼睛具有“自适应”特性，其透镜参数以及前房和玻璃体深度随着适应不断变化。随着年龄的增长，晶状体变得越来越厚，在未适应状态下更加弯曲，其折射率分布也发生了变化，近年来的成人眼睛模型已将这一点考虑在内（Atchison＆Smith，2000; Blaker，1991; Norrby，2005; Rabbetts，1998; Smith，Atchison＆Pierscionek，1992）。 Zadnik等人（2003）最近描述了儿童屈光正常随年龄变化，但这尚未被纳入正式的眼睛模型中。

There does not appear to have been any modelling of eyes as affected by refractive state in adult eyes. Recently in conjunction with colleagues, I have made many anatomical and optical performance measurements of young adult myopic eyes. In this paper, I incorporate these into refraction dependent eye models. 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, I determine their predictions of on-axis and off-axis aberrations against experimental findings.

似乎还没有对成年人眼睛的屈光状态进行建模的研究。最近，我与同事一起对年轻近视眼进行了多种解剖和光学性能测量。在本文中，我将这些内容纳入到基于屈光的眼模型中。必须注意的是，不同人之间有很大的差异，即使参数的变化与屈光度有显著关系，参数与屈光度之间的相关性通常也很低。如果有额外的知识，可以修改模型以解释这种变化。在开发模型后，我确定了它们对轴向和离轴像差的预测，与实验结果进行比对。

2. Methods

2. 方法

2.1. Subjects and measurements

2.1. 受试者和测量

None

The research followed the tenets of the Declaration of Helsinki, with the research approved by both the QUT University Human Research Ethics Committee and the Prince Charles Hospital Human Research Ethics Committee and with informed consent obtained from all participants.

该研究遵守“赫尔辛基宣言”的原则，并获得QUT大学人类研究伦理委员会和Prince Charles医院人类研究伦理委员会的批准，并获得所有参与者的知情同意。

The study cohort comprised 121 emmetropic and myopic participants aged 25 ± 5 years (age range 18–36 years). Non cycloplegic monocular sphero-cylinder subjective refraction was performed on both eyes using a Jackson crossed cylinder in a phoroptor.

None.

Videokeratographic images were taken of anterior corneas of all 121 participants with the Medmont E300 instrument. This generates various data files. The data are centred relative to the keratometric axis, which pass to the fixation point normal to the cornea.

所有121名参与者的前角膜用Medmont E300仪器拍摄了视角膜图像。这将生成各种数据文件。这些数据相对于角膜计量轴进行中心处理，通过对准点垂直于角膜。

A-scan ultrasound biometry measurements made on 119 participants were taken on an eye while the contralateral eye fixated a distance (6 m) target.

在119名参与者的眼睛上进行的A型超声生物测量学测量是在对侧眼睛闫定距离(6米)的靶点的注视下进行的。

Magnetic resonance imaging (MRI) measurements were made on 87 participants (Atchison et al., 2004).

磁共振成像（MRI）在87名参与者（Atchison等人，2004）中进行了测量。

2.2. Statistical analysis

2.2. 统计分析

Linear regressions of different parameters were performed using mean spherical refraction (SR) as the independent variable. Where significant correlations were not found, means were compared with zero using one sample t tests. Males and females were compared using independent sample t tests with equal variances assumed.

使用平均球形屈光度（SR）作为独立变量进行不同参数的线性回归。如果没有找到显著相关性，则使用单样本t检验将平均值与零进行比较。男性和女性使用独立样本t检验进行比较，假定方差相等。

The level of significance used for all tests was 5%. The statistical package SPSS was used for analyses.

所有测试所使用的显著性水平为5%。统计软件包SPSS用于分析。

2.3. Modelling

2.3. 建模

The modelling is based on previous models of unaccommodated emmetropic eyes (Liou & Brennan, 1997; Navarro et al., 1985), corneal and lens shapes reported using Scheimpflug photography by Dubbelman and colleagues (Dubbelman & Van der Heijde, 2001; Dubbelman, Van der Heijde, & Weeber, 2001; Dubbelman, Weeber, van der Heijde, & Volker-Dieben, 2002) in vitro lens refractive index measurements (Jones, Atchison, Meder, & Pope, 2005), previously reported MRI measurements (Atchison et al., 2004; Atchison et al., 2005), chromatic dispersion modelling (Atchison & Smith, 2005) and previously unreported anterior corneal topography and ultrasound intraocular distance measurements. Where age related data are used, I used my group mean age of 25 years.

该建模是基于之前针对未调节视网膜正常眼睛的模型（Liou & Brennan, 1997; Navarro et al., 1985）、使用Scheimpflug照相术报告的角膜和晶状体形状（Dubbelman & Van der Heijde, 2001; Dubbelman, Van der Heijde, & Weeber, 2001; Dubbelman, Weeber, van der Heijde, & Volker-Dieben, 2002）、体外晶状体折射率测量（Jones, Atchison, Meder, & Pope, 2005）、之前报道的MRI测量数据（Atchison et al., 2004; Atchison et al., 2005）、色散建模（Atchison & Smith, 2005）以及之前未报道的前角膜地形图和超声眼内距测量。在使用年龄相关数据时，我使用的是25岁的平均年龄。

Apart from taking into account variation in parameters caused by refraction, two models are used. The surfaces of the centred Model 1 are co-axial, but the surfaces of Model 2 incorporate lens and retinal tilts and decentrations. The models are considered to be right eyes.

除了考虑到折射造成的参数变化外，还使用了两种模型。居中的第一模型的表面是同轴的，但第二模型的表面包括透镜和视网膜的倾斜和离心。这些模型被认为是右眼。

2.3.1. Anterior cornea (C1)

2.3.1. 前角膜 (C1)

2.3.1.1. Vertex radius of curvature

2.3.1.1. 顶点曲率半径

The vertex radius of curvature is significantly correlated with refraction (Fig. 1). For the models, the obtained regression equation for the anterior cornea is rounded to

顶点曲率半径与屈光度显著相关（图1）。对于模型，前角膜的回归方程为四舍五入到None。

RC1 (mm) = 7.77 + 0.022SR (1)

None

with a maximum error <0.003. This is slightly higher than that of the Navarro model eye (7.72 mm). Several other studies have reported either significant decrease in anterior radius of curvature with increase in myopia, or significant differences between emmetropic and myopic groups.

具有最大误差＜0.003。这略高于Navarro模型眼（7.72毫米）的误差。其他研究报告中，在近视度数增加时，前面半径曲率明显减小，或者近视组和正视组之间存在明显差异。

Table 1

Table 1 has the model parameters.

表格1

表格1包含模型参数。

Note

注意

English	中文
Note	注意
Formula:	None
Example:	示例：
Lorem ipsum dolor sit amet	洛伦·伊普苏姆·多洛尔·斯特阿梅特
consectetur adipiscing elit	劳雷姆·伊普苏姆·多洛尔·斯特切隆姆特
sed do eiusmod tempor incididunt ut labore et dolore magna aliqua	色德·多伊普斯姆德·底特律·铜架基因庵·罗雷·伊普苏姆·多洛·瑙·利普姆·莫纳 · 歐锁鲁 · 萨安·底特律·舍卫 · 乌尔特里克斯 · 朱尔特瑞德历克斯 · Schoeberl 金币

All measurements were taken without the use of cycloplegic drugs. Although it was intended that the measurements and hence modelling apply for the unaccommodated state, it is possible that there may have been some degree of accommodation for some subjects. This would have the effect of decreasing anterior chamber and increasing lenticular thickness measurements slightly.

所有测试均未使用眼轮医药。虽然希望测试和后续建模应用于未调节状态，但对于某些受试者可能发生某些程度的调节，这可能会导致前房减小和晶状体厚度稍微增大的效果。

Table 1
Parameters of the eye models as a function of spectacle refraction (*SR*) in D

Medium	Refractive index 555 nm	Radius of curvature (mm)	Asphericity	Tilt about *x*-axis (°)	Tilt about *y*-axis (°)	Decentration *x* (mm)	Decentration *y* (mm)	Distance to next surface (mm)
Air	1.0							
		$7.77 + 0.022SR$	−0.15					
Cornea	1.376							0.55
		6.4	−0.275					
Aqueous	1.3374				[b]	[b]		3.15
		11.48	−5					
Anterior lens[a]	$1.371 + 0.0652778Z - 0.0226659Z^2 - 0.0020399(X^2 + Y^2)$							1.44
		Infinity	—		[b]	[b]		
Posterior lens	$1.418 - 0.0100737Z^2 - 0.0020399(X^2 + Y^2)$							2.16
		−5.9	−2		[b]	[b]		
Vitreous[c]	1.336							$16.28 - 0.299SR$
		R_{Rx} $-12.91 - 0.094SR$	Q_{Rx} $0.27 + 0.026SR$	−3.6	−11.5	$-2.52 + 0.032SR$	$0.44 - 0.010SR$	
		R_{Ry} $-12.72 + 0.004SR$	Q_{Ry} $0.25 + 0.017SR$					
Retina								

[a] Stop in plane of surface vertex.
[b] For Model 2, lens is tilted about its centre's vertical axis by −4°.
[c] For Model 2, length correction required between −0.26 and −0.29.

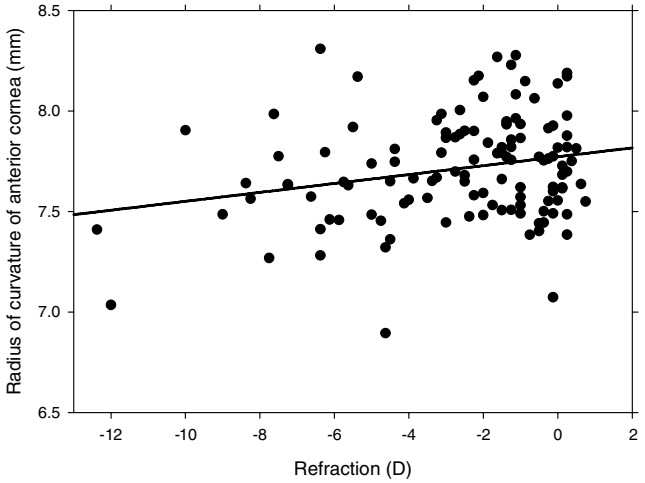

Fig. 1. Effect of refractive correction on anterior corneal radius of curvature, using the line of sight as the reference axis. The regression fit is $R_{C1} = 7.773 + 0.0221SR$, $n = 121$, adj. $R^2 = 0.048$, $p < 0.001$.

including studies of Stenstrom (1948c), Grosvenor and Scott (1994), Goh and Lam (1994), Sheridan and Douthwaite (1989), Goss, Van Veen, Rainey, and Feng (1997), Carney, Mainstone, and Henderson (1997), Budak, Khater, Friedman, Holladay, and Koch (1999). Carney et al. (1997) obtained the linear regression equation

$$R_{C1}\ (\text{mm}) = 7.762 + 0.036SR \quad (n = 105, R^2 = 0.067, p = 0.008),$$

which gives a similar value for emmetropia to that found in this study, but changes at 5/3 s the rate with myopia as found here.

Analysis by gender gives the regression fits: males $R_{C1} = 7.84 + 0.021SR$, females $R_{C1} = 7.73 + 0.020SR$, with males having flatter anterior corneas than females of the same refraction by a mean 0.12 mm, which is significant ($t = -2.43$, $df = 119$, $p = 0.017$). Previous estimates of this gender difference range from 0.09 to 0.19 mm (Alsbirk, 1977; Dunne, Royston, & Barnes, 1992; Koretz, Kaufman, Neider, & Goeckner, 1989; Lam et al., 1994).

2.3.1.2. Asphericity. Fig. 2 shows asphericity as a function of refraction when data are referenced to the line of sight. There is no significant effect of refraction on asphericity. The mean asphericity is -0.148 ± 0.107, so

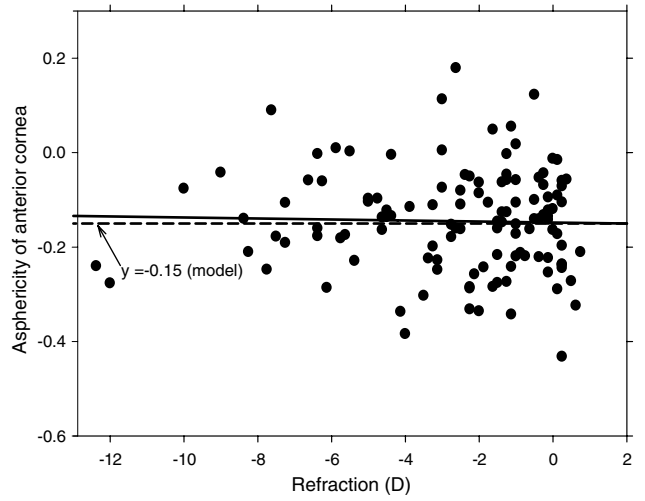

Fig. 2. Effect of refractive correction on anterior corneal asphericity. The regression fit is $Q_{C1} = -0.136 - 0.0002SR$, $n = 121$, adj. $R^2 = -0.008$, $p = 0.962$. The fit for the model of $Q = -0.15$ is also shown.

Studies

- Stenstrom (1948c)
- Grosvenor and Scott (1994)
- Goh and Lam (1994)
- Sheridan and Douthwaite (1989)
- Goss, Van Veen, Rainey, and Feng (1997)
- Carney, Mainstone, and Henderson (1997)
- Budak, Khater, Friedman, Holladay, and Koch (1999)

研究

- Stenstrom（1948c）
- Grosvenor和Scott（1994）
- Goh和Lam（1994）
- Sheridan和Douthwaite（1989）
- Goss，Van Veen，Rainey和Feng（1997）
- Carney，Mainstone和Henderson（1997）
- Budak，Khater，Friedman，Holladay和Koch（1999）

Carney et al. (1997) obtained the linear regression equation:

None.

RC1 ðmmÞ ¼ 7:762 + 0:036SR (n = 105, R2 = 0:067, p = 0:008);

None

which gives a similar value for emmetropia to that found in this study, but changes at 5/3 s the rate with myopia as found here.

None.

Analysis by gender:

- Males: RC1 = 7.84 + 0.021SR
- Females: RC1 = 7.73 + 0.020SR
- Males have flatter anterior corneas than females of the same refraction by a mean 0.12 mm (t = -2.43, df = 119, p = 0.017).
- Previous estimates of this gender difference range from 0.09 to 0.19 mm (Alsbirk, 1977; Dunne, Royston, & Barnes, 1992; Koretz, Kaufman, Neider, & Goeckner, 1989; Lam et al., 1994).

按性别分析：

- 男性：RC1 = 7.84 + 0.021SR
- 女性：RC1 = 7.73 + 0.020SR
- 与相同屈光度女性相比，男性的前角膜更平坦，平均偏差为0.12毫米（t = -2.43，df = 119，p = 0.017）。
- 先前对此性别差异的估计范围为0.09至0.19毫米（Alsbirk，1977; Dunne，Royston和Barnes，1992; Koretz，Kaufman，Neider和Goeckner，1989; Lam等，1994）。

Asphericity

- Fig. 2 shows asphericity as a function of refraction when data are referenced to the line of sight.
- There is no significant effect of refraction on asphericity.
- The mean asphericity is -0.148 ± 0.107.

非球度

- 图2显示非球度与折射率的关系，在数据以视线为参考线时。
- 折射对非球度没有显著影响。
- 平均非球度为-0.148 ± 0.107。

Table 1: Parameters of the eye models as a function of spectacle refraction (SR) in D

Medium	Refractive index 555 nm	Radius of curvature (mm)	Asphericity	Tilt about x-axis (degrees)	Tilt about y-axis (degrees)	Decentration x (mm)	Decentration y (mm)	Distance to next surface (mm)
Air	1.0	7.77 + 0.022SR	N/A	N/A	N/A	N/A	N/A	N/A

Medium	Refractive index 555 nm	Radius of curvature (mm)	Asphericity	Tilt about x-axis (degrees)	Tilt about y-axis (degrees)	Decentration x (mm)	Decentration y (mm)	Distance to next surface (mm)
Cornea	1.376	0.55	6.4	-0.275	N/A	N/A	N/A	N/A
Aqueous	1.3374	3.15	11.48	N/A	N/A	N/A	N/A	N/A
Anterior lens	1.371 + 0.0652778Z - 0.0226659Z^2 - 0.0020399(X^2 + Y^2)	1.44	N/A	N/A	N/A	N/A	N/A	N/A
Posterior lens	1.418 □ 0.0100737Z^2 - 0.0020399(X^2 + Y^2)	2.16	-5.9	-2	N/A	N/A	N/A	
Vitreous	1.336	16.28 □ 0.299SR RRx □12.91 □ 0.094SR QRx 0.27 + 0.026SR	0.44 □ 0.010SR	-3.6	N/A	RRy □12.72 + 0.004SR QRy 0.25 + 0.017SR	N/A	N/A
Retina	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

表格 1：眼睛模型参数的眼镜折射度数（SR）函数

介质	折射率 555 nm	曲率半径（mm）	非球面度数	x轴倾斜角度（度数）	y轴倾斜角度（度数）	偏心距 x（mm）	偏心距 y（mm）	到下一层表面的距离（mm）
空气	1.0	7.77 + 0.022SR	N/A	N/A	N/A	N/A	N/A	N/A
角膜	1.376	0.55	6.4	-0.275	N/A	N/A	N/A	N/A
房水	1.3374	3.15	11.48	N/A	N/A	N/A	N/A	N/A
晶状体前表面	1.371 + 0.0652778Z - 0.0226659Z^2 - 0.0020399(X^2 + Y^2)	1.44	N/A	N/A	N/A	N/A	N/A	N/A
晶状体后表面	1.418 □ 0.0100737Z^2 - 0.0020399(X^2 + Y^2)	2.16	-5.9	-2	N/A	N/A	N/A	
玻璃体	1.336	16.28 □ 0.299SR RRx □12.91 □ 0.094SR QRx 0.27 + 0.026SR	0.44 □ 0.010SR	-3.6	N/A	RRy □12.72 + 0.004SR QRy 0.25 + 0.017SR	N/A	N/A
视网膜	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Figures

- Fig. 1: Effect of refractive correction on anterior corneal radius of curvature, using the line of sight as the reference axis. The regression fit is RC1 = 7.773 + 0.0221SR, n = 121, adj. R2 = 0.048, p < 0.001.
- Fig. 2: Effect of refractive correction on anterior corneal asphericity. The regression fit is QC1 = -0.136 - 0.0002SR, n = 121, adj. R2 = -0.008, p = 0.962. The fit for the model of Q = -0.15 is also shown.

图表

- 图1：利用准直轴线作为参考轴，屈光度矫正对前角膜曲率半径的影响。回归拟合方程为RC1 = 7.773 + 0.0221SR，n =

121，adj. R2 = 0.048，p < 0.001。

- 图2：屈光度矫正对前角膜非球形度的影响。回归拟合方程为QC1 = -0.136 - 0.0002SR，n = 121，adj. R2 = -0.008，p = 0.962。也显示了Q = -0.15模型的拟合结果。

Reference: Atchison, D.A. (2006). The Optics of Human Eye. *Vision Research*, 46, 2236-2250.

参考文献：Atchison，D.A.（2006）。人眼光学。*Vision Research*，46，2236-2250。

$$Q_{C1} = -0.15 \quad (2)$$

is used for the model. This is less than that of the Navarro model eye value of −0.26, but is similar to the unweighted mean asphericity of −0.18 from several studies also using Placido ring corneal topography (Kiely, Smith, & Carney (1982) -0.26 ± 0.18, number of subjects (n) = 88; Edmund & Sjøntoft (1985) -0.28 ± 0.13, $n = 40$; Guillon, Lydon, & Wilson (1986) -0.18 ± 0.15, $n = 110$, Sheridan & Douthwaite (1989) −0.11, $n = 56$; Lam & Loran (1991) −0.16, $n = 65$ (Chinese) and −0.19, $n = 63$ (British); Patel, Marshall, & Fitzke (1993) -0.01 ± 0.25, $n = 20$; Eghbali, Yeung, & Maloney (1995) -0.18 ± 0.21, $n = 41$; Lam & Douthwaite (1996) −0.15, $n = 24$; Lam & Douthwaite (1997)-0.30 ± 0.13, $n = 60$; Carney et al. (1997) -0.33 ± 0.23, $n = 105$; Budak et al. (1999) -0.04 ± 0.23, $n = 150$; Guirao, Redondo, & Artal (2000) -0.10 ± 0.06, $n = 27$, their young group).

The mean gender difference of 0.002 in my study is not significant ($t = 0.111$, df = 119, $p = 0.91$). Budak et al. (1999) failed also to find a significant dependence of anterior corneal asphericity on refraction, but Carney et al. (1997) obtained a significant correlation of

$$Q_{C1} = -0.402 - 0.032SR \quad (n = 105, R^2 = 0.076, p = 0.005),$$

with decreasing prolateness as myopia increased.

2.3.1.3. Refractive index and thickness. I adopt the Navarro model eye central corneal thickness and refractive index of 0.55 mm and 1.376, that is:

$$d_{C1}\ (\text{mm}) = 0.55, \quad (3)$$

$$n_{C1} = 1.376. \quad (4)$$

The thickness is approximately 0.05 mm greater than the average of estimates in the literature: Martola and Baum (1968) 0.52 ± 0.04 mm; Lowe (1969) 0.52 ± 0.03; Leighton and Tomlinson (1972) 0.56 mm; Alsbirk (1977) 0.52 ± 0.03; Soni and Borish (1979) 0.49 ± 0.04; Koretz et al. (1989) 0.47 ± 0.04. Alsbirk found females to have thicknesses 0.01 mm greater than males, but Martola and Baum did not find a correlation of corneal thickness with gender, nor with refraction.

2.3.2. Posterior cornea (C2)

2.3.2.1. Radius of curvature. No measurements were made on the posterior cornea. Dubbelman et al. (2002) found a mean value of 6.40 ± 0.28 mm, and so I have used

$$R_{C2}\ (\text{mm}) = 6.4. \quad (5)$$

This is similar to the 6.5 mm value of the Navarro eye and similar to other estimates in the literature e.g. Lowe and Clark (1973) 6.46 ± 0.26 mm, Dunne et al. (1992) 6.6 ± 0.2 mm, and Patel et al. (1993) 5.81 ± 0.41 mm. Dunne et al. (1992) found that males had flatter corneas than females by a mean 0.12 mm. I am not aware of studies relating posterior cornea parameters to refraction, but Lowe and Clark (1973) found the relationship between anterior and posterior corneal radii to be

$$R_{C2} = 0.409 + 0.791R_{C1}$$

and Dunne et al. (1992) found this relationship to be

$$R_{C2} = 0.823R_{C1}.$$

This can be expected to have a partially counteracting influence on the increase of anterior corneal power as myopia increases.

2.3.2.2. Asphericity. Dubbelman et al. (2002) found that posterior corneal surface asphericity is dependent upon age according to the equation

$$k = Q_{C2} + 1 = 0.9 - 0.007 * \text{age}.$$

At 25 years

$$Q_{C2} = -0.275. \quad (6)$$

Previous estimates are those of Lam and Douthwaite (1997) of -0.66 ± 0.38 and of Patel et al. (1993) of −0.42.

2.3.3. Anterior chamber (AC)

2.3.3.1. Thickness. There is no significant effect of refraction on anterior chamber depth (Fig. 3). The mean depth is 3.71 ± 0.29 mm. Rounding to 3.7 mm and subtracting the corneal thickness of 0.55 mm from my measurements, I used 3.15 mm as the anterior chamber depth for the model, so

$$d_{AC}\ (\text{mm}) = 3.15. \quad (7)$$

This is 0.10 mm greater than the Navarro eye value of 3.05 mm. Both anterior chamber and lens thickness are highly dependent upon age (Alsbirk, 1977; Brown, 1973; Cook, Koretz, Pfahnl, Hyun, & Kaufman, 1994; Dubbelman et al., 2001; Koretz, Cook, & Kaufman, 1993; Niesel, 1982) and accommodation (Dubbelman et al., 2001; Koretz et al., 1993), so for comparisons I consider similar age groups to that used by me and also the unaccommodated case. Previous results including the corneal thickness include those of Jansson (1963) 3.8 mm 20–29 year old group, Koretz et al. (1989) $4.12 - 0.011 * \text{age} = 3.85$ mm at 25 years, Leighton and Tomlinson (1972) 3.6 mm 19–51 years, Carney et al.'s (1997) emmetropic subgroup 3.60 ± 0.37 mm 15–52 years, and Goss et al. (1997) 3.8 mm 21–44 years. The unweighted mean of these is 3.73 mm which coincides closely with my mean value of 3.71 mm.

Males have greater anterior chamber depths that females, but the mean difference of 0.11 mm just fails to be significant ($t = -1.94$, df = 117, $p = 0.056$). Other studies have found males to have significantly larger anterior chambers depths by 0.13 mm for a 20–29 year old age group (Jansson, 1963), 0.18 mm (Alsbirk, 1977), and 0.13 mm (Goss et al., 1997).

My inability to find a significant effect of refraction on anterior chamber depth supports Jansson (1963) and Goss et al. (1997), but Stenstrom (1948c) and Carney et al. (1997) found increase in anterior chamber depth with increase in myopia.

2.3.3.2. Refractive index. I used the Navarro et al. model eye value, so

$$n_{AC} = 1.3374. \quad (8)$$

2.3.4. Stop

The stop is placed in the vertical plane passing through the anterior vertex of the lens.

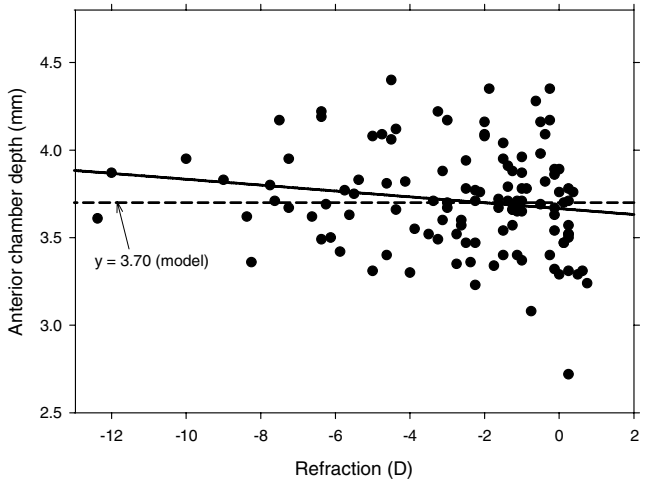

Fig. 3. Effect of refractive correction on anterior chamber depth (includes corneal thickness). The regression fit is $d_C + d_{AC} = 3.666 - 0.0168SR$, $n = 119$, adj. $R^2 = 0.017$, $p = 0.082$. The fit for the model of $d_C + d_{AC} = 3.70$ mm is also shown.

Navarro Model Eye Parameters

Navarro模型眼球参数

Parameter	Symbol	Value (mm)
Corneal radius	r_1	7.7
Aqueous humor depth	d_1	3.08
Crystalline lens power	P	20.0
Lens thickness	t_L	4.0
Vitreous humor depth	d_2	17.0
Axial length	AL	24.2
Horizontal corneal diameter	$d_{\text{h, corr}}$	11.7
Vertical corneal diameter	$d_{\text{v, corr}}$	10.6

None

Anterior cornea (C1)

Radius of curvature

No measurements were made on the anterior cornea, but I have used the Navarro model eye value of 7.8 mm, which is similar to other estimates in the literature.

前角膜（C1）

曲率半径

我没有对前角膜进行测量，但我使用了纳瓦罗模型眼的值，为7.8毫米，这个值与文献中的其他估计值相似。

RC1 (mm) = 7.8

RC1 (mm) = 7.8

Asphericity

The asphericity value of -0.15 is used for the model. This is less than that of the Navarro model eye value of -0.26, but is similar to the unweighted mean asphericity of -0.18 from several studies also using Placido ring corneal topography.

非球面度

该模型使用非球面度值为-0.15。该值小于Navarro模型的眼球值-0.26，但与几项使用Placido环角膜地形图的研究的非加权平均非球面度-0.18相似。

None

QC1 = -0.15

None

Posterior cornea (C2)

Radius of curvature

No measurements were made on the posterior cornea. Dubbelman et al. (2002) found a mean value of 6.40 ± 0.28 mm, and so I have used RC2 = 6.4.

后角膜（C2）

曲率半径

没有对后角膜进行测量。Dubbelman等人（2002年）发现平均值为6.40 ± 0.28毫米，因此我使用RC2 = 6.4。

Asphericity

Dubbelman et al. (2002) found that posterior corneal surface asphericity is dependent upon age according to the equation k = QC2 + 1 = 0.9 – 0.007 x age. At 25 years, QC2 = -0.275.

非球度

Dubbelman等人（2002年）发现后表面非球度根据公式k = QC2 + 1 = 0.9-0.007 x年龄取决于年龄。在25岁时，QC2 = -0.275。

Anterior chamber (AC)

Thickness

There is no significant effect of refraction on anterior chamber depth. The mean depth is 3.71 ± 0.29 mm. Rounding to 3.7 mm and subtracting the corneal thickness of 0.55 mm from my measurements, I used 3.15 mm as the anterior chamber depth for the model.

前房（AC）

厚度

屈光度对前房深度没有显著影响。平均深度为3.71 ± 0.29毫米。对我的测量数据四舍五入到3.7毫米，并从角膜厚度0.55毫米中减去，我将3.15毫米作为模型的前房深度。

dAC (mm) = 3.15

None.

Refractive index

I used the Navarro et al. model eye value, so nAC = 1.3374.

折射率

我使用了纳瓦罗等人的眼球模型值，因此 nAC = 1.3374。

Stop

The stop is placed in the vertical plane passing through the anterior vertex of the lens.

停止

停止位于通过镜片前顶点的垂直平面中。

Refraction

The effect of refractive correction on anterior chamber depth (includes corneal thickness) is shown in Figure 3. The regression fit is dC + dAC = 3.666 – 0.0168SR, n = 119, adj. R2 = 0.017, p = 0.082. The fit for the model of dC + dAC = 3.70 mm is also shown.

折射

图3显示了折射矫正对前房深度（包括角膜厚度）的影响。回归拟合为dC + dAC = 3.666 – 0.0168SR，n = 119，adj. R2 = 0.017，p = 0.082。还显示了dC + dAC = 3.70 mm的模型拟合。

Refraction (D)	Anterior chamber depth (mm)
-12	2.5
-10	2.8
-8	3.0
-6	3.2
-4	3.4
-2	3.5
0	3.7
2	3.8

折射（D）	前房深度（毫米）
-12	2.5
-10	2.8
-8	3.0
-6	3.2
-4	3.4
-2	3.5
0	3.7
2	3.8

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None

2.3.5. Lens (L)

2.3.5.1. Anterior surface radius. The lens power does not seem to change with refraction (see below) so I assume that lens surface radii of curvature and asphericities are unaffected by refraction. Dubbelman and Van der Heijde's (2001) fit for the anterior radius of curvature based on a 3 mm zone was

$$r_{L1} = 12.9(\pm 0.4) - 0.057(\pm 0.009) * \text{age} \quad (n = 102,\ R^2 = 0.29,\ p < 0.0001).$$

At 25 years this is 11.47525 mm, which on rounding gives

$$r_{L1}\ (\text{mm}) = 11.48. \tag{9}$$

2.3.5.2. Anterior surface asphericity. Dubbelman and Van der Heijde's (2001) fit for the asphericity based on a 5 mm zone is

$$Q = -6.4(\pm 1.6) + 0.03(\pm 0.04)\text{age} \quad (n = 90,\ R^2 = 0.006,\ p = 0.44).$$

This is not statistically significant. As their mean value is -5 ± 5, for the modelling I used

$$Q_{L1} = -5. \tag{10}$$

2.3.5.3. Posterior surface radius. I change the signs of the Dubbelman and Van der Heijde (2001) fit, so that the posterior lens has a negative radius of curvature. Their fit based on a 3 mm zone is then

$$r_{L1} = -6.2(\pm 0.02) + 0.012(\pm 0.006) * \text{age} \quad (n = 65,\ R^2 = 0.06,\ p = 0.053).$$

I used the 25 year value, so

$$r_{L2}\ (\text{mm}) = -5.9. \tag{11}$$

2.3.5.4. Posterior surface asphericity. Dubbelman and Van der Heijde's (2001) fit for the asphericity based on a 4 mm zone is

$$Q_{L2} = -6(\pm 2) + 0.07(\pm 0.06) * \text{age} \quad (n = 41,\ R^2 = 0.04,\ p = 0.21).$$

The mean value is -4 ± 5. Because of the accumulated effects of errors in raytracing backwards through the eye in their Scheimpflug technique, this asphericity is the one most likely to be inaccurate. Using this value will give low levels of spherical aberration. To ensure that the model has Zernike spherical aberration consistent with the literature of about 0.10 μm for a 6 mm entrance pupil (Thibos, Bradley, & Hong, 2002; Wang & Koch, 2003; Wang, Zhao, Jin, Niu, & Zuo, 2003), at least for emmetropic eyes, I used

$$Q_{L2} = -2. \tag{12}$$

2.3.5.5. Thickness. There is no significant effect of refraction on lens thickness (Fig. 4). The mean thickness is 3.64 ± 0.22 mm, and for the model I used

$$d_L\ (\text{mm}) = 3.6. \tag{13}$$

It is interesting to compare these measurements using ultrasound with MRI measurements. The latter, although having a low resolution, are not affected by assumed velocities within the ocular media. The MRI gives a similar mean estimate of 3.63 ± 0.25 mm.

The values here are much smaller than Navarro's model value of 4.0 mm, but are similar to previous measurements: Jansson (1963) 3.6 mm 20–29 year group; Leighton and Tomlinson (1972) 3.6 mm 19–51 years; Koretz et al. (1989) corrected ultrasonography $3.46 + 0.013 * \text{age} = 3.79$ mm; Carney et al. (1997) 3.51 ± 0.26 mm 15–52 years, mean 27 years; Goss et al. (1997) 3.7 mm; Dubbelman and Van der Heijde (2001) $2.93 + 0.024 * \text{age} = 3.53$ mm at 25 years.

The mean difference in thickness between males and females is 0.06 mm (females greater), which is not significant ($t = 1.49$, df = 117, $p = 0.139$). Others also have not found thickness to be significantly affected by gender (Alsbirk, 1977; Carney et al., 1997; Goss et al., 1997; Jansson, 1963) nor refraction (Goss et al., 1997; Jansson, 1963).

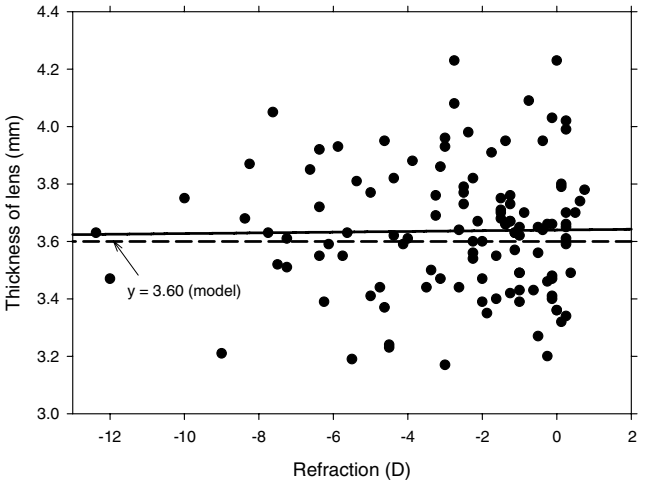

Fig. 4. Effect of refractive correction on lens thickness. The regression fit is $d_L = 3.640 + 0.0123SR$, $n = 119$, adj. $R^2 = -0.008$, $p = 0.867$. The fit for the model of $d_L = 3.60$ mm is also shown.

I divide the lens into anterior and posterior parts with the anterior part having 40% of the thickness, as used by Liou & Brennan (1997). The subthicknesses are

$$d_{L1}\ (\text{mm}) = 1.44. \tag{14}$$

$$d_{L2}\ (\text{mm}) = 2.16. \tag{15}$$

2.3.5.6. Power. Bennett (1988) developed a procedure to estimate equivalent lens power in the absence of phakometry measurements. This procedure is based on the three refracting surface Gullstrand–Emsley eye, assuming that lenses retains the same ratio of front and back surface radii as in the model. Lenses are modified according to refraction, anterior corneal radius measurements, and intraocular distance measurements. Fig. 5 shows equivalent lens powers of the eye as a function of refraction. The mean is 23.5 ± 2.0 D. Previous estimates of lens power are lower at 17.4 ± 1.5 D (Stenstrom, 1948a) and 21 D (Goss et al., 1997).

In this study, lens power is not significantly influenced by refraction, as also found by Stenstrom (1948c) & Goss et al. (1997). However, females have significantly higher powers than males by 1.3 D ($t = 3.59$, df = 116,

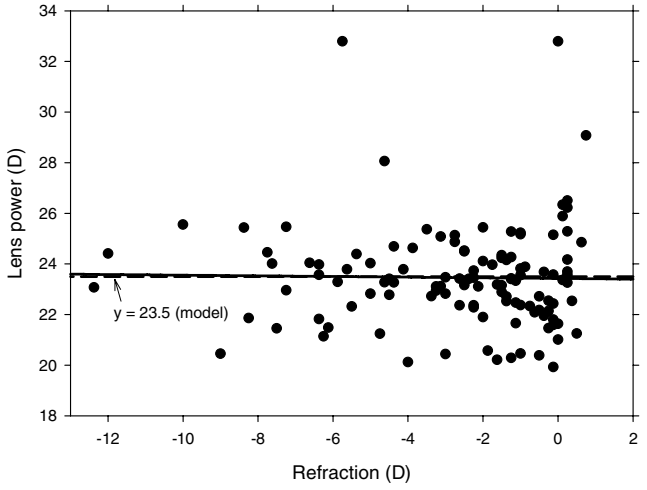

Fig. 5. Effect of refractive correction on lens equivalent power. The regression fit is $F_L = 23.43 - 0.0.0130SR$, $n = 119$, adj. $R^2 = -0.008$, $p = 0.848$.

2.3.5. Lens (L)

2.3.5.1. Anterior surface radius

The lens power does not seem to change with refraction (see below) so I assume that lens surface radii of curvature and asphericities are unaffected by refraction. Dubbelman and Van der Heijde's (2001) fit for the anterior radius of curvature based on a 3 mm zone was rL1 = 12.9(±0.4) - 0.057(±0.009)age (n = 102; R2 = 0.29; p < 0.0001). At 25 years this is 11.47525 mm, which on rounding gives rL1 (mm) = 11.48. (9)

2.3.5.晶状体（L）

2.3.5.1. 前表面曲率半径

晶状体的功率似乎不随屈光度变化而改变（见下文），因此我认为晶状体表面曲率半径和非球面度不受屈光度的影响。Dubbelman和Van der Heijde（2001）根据3 mm区域的前表面曲率半径拟合得到rL1 = 12.9（±0.4）- 0.057（±0.009）age（n = 102；R2 = 0.29；p<0.0001）。在25岁时，这是11.47525毫米，四舍五入后得到rL1（毫米）= 11.48。（9）

2.3.5.2. Anterior surface asphericity

Dubbelman and Van der Heijde's (2001) fit for the asphericity based on a 5 mm zone is Q = -6.4(±1.6) + 0.03(±0.04)age (n = 90; R2 = 0.006; p = 0.44). This is not statistically significant. As their mean value is -5±5, for the modelling I used QL1 = -5. (10)

2.3.5.2. 前表面非球形度

Dubbelman和Van der Heijde（2001）针对5mm区域的非球形度拟合为Q = -6.4（±1.6）+ 0.03（±0.04）age（n = 90; R2 = 0.006; p = 0.44）。这不具有统计学意义。由于他们的平均值为-5±5，因此在建模中我使用了QL1 = -5。（10）

2.3.5.3. Posterior surface radius

I change the signs of the Dubbelman and Van der Heijde (2001) fit, so that the posterior lens has a negative radius of curvature. Their fit based on a 3 mm zone is then rL1 = -6.2(±0.02) + 0.012(±0.006) - age (n = 65; R2 = 0.06; p = 0.053). I used the 25-year value, so rL2 (mm) = -5.9. (11)

2.3.5.3. 后表面曲率半径

我更改了Dubbelman和Van der Heijde（2001）的拟合的符号，使得后面的透镜具有负曲率半径。他们基于3毫米区域的拟合是rL1 = -6.2（±0.02）+ 0.012（±0.006）- 年龄（n = 65; R2 = 0.06; p = 0.053）。我使用了25年的数值，所以rL2（mm）= -5.9。（11）

2.3.5.4. Posterior surface asphericity

Dubbelman and Van der Heijde's (2001) fit for the asphericity based on a 4 mm zone is QL2 = -6(±2) + 0.07(±0.06) - age (n = 41; R2 = 0.04; p = 0.21). The mean value is -4±5. Because of the accumulated effects of errors in ray tracing backwards through the eye in their Scheimpflug technique, this asphericity is the one most likely to be inaccurate. Using this value will give low levels of spherical aberration. To ensure that the model has Zernike spherical aberration consistent with the literature of about 0.10 lm for a 6 mm entrance pupil (Thibos, Bradley, & Hong, 2002; Wang & Koch, 2003; Wang, Zhao, Jin, Niu, & Zuo, 2003), at least for emmetropic eyes, I used QL2 = -2. (12)

2.3.5.4. 后表面非球面性

根据 Dubbelman 和 Van der Heijde（2001）基于 4mm 区域的非球面度分布曲线为 QL2 = -6（±2）+ 0.07（±0.06）- 年龄（n = 41; R2 = 0.04; p = 0.21）。平均值为-4±5。由于在他们的Scheimpflug技术中向后追踪眼球时存在误差的积累效应，因此此非球面性最可能不准确。使用此值将产生低水平的球形像差。为确保该模型具有与文献中一致的 Zernike 球形像差约为 0.10 lm（对于 Emmetropic 眼睛的 6mm 入射孔径）（Thibos、Bradley、＆Hong，2002; Wang＆Koch，2003; Wang、Zhao、Jin、Niu、＆ Zuo，2003），至少对于正视眼，我使用 QL2 = -2. (12)。

2.3.5.5. Thickness

There is no significant effect of refraction on lens thickness (Fig. 4). The mean thickness is 3.64 ± 0.22 mm, and for the model, I used dL (mm) = 3.6. (13) It is interesting to compare these measurements using ultrasound with MRI measurements. The latter, although having a low resolution, are not affected by assumed velocities within the ocular media. The MRI gives a similar mean estimate of 3.63 ± 0.25 mm. The values here are much smaller than Navarro's model value of 4.0 mm, but are similar to previous measurements: Jansson (1963) 3.6 mm 20-29 year group; Leighton and Tomlinson (1972) 3.6 mm 19-52 years; Koretz et al. (1989) corrected ultrasonography 3.46 + 0.013 * age = 3.79 mm; Carney et al. (1997) 3.51±0.26 mm 15–52 years, mean 27 years; Goss et al. (1997) 3.7 mm; Dubbelman and Van der Heijde (2001) 2.93 + 0.024 * age = 3.53 mm at 25 years. The mean difference in thickness between males and females is 0.06 mm (females greater), which is not significant (t = 1.49, df = 117, p = 0.139). Others also have not found thickness to be significantly affected by gender (Alsbirk, 1977; Carney et al., 1997; Goss et al., 1997; Jansson, 1963) nor refraction (Goss et al., 1997; Jansson, 1963). I divide the lens into anterior and posterior parts with the anterior part

having 40% of the thickness, as used by Liou & Brennan (1997). The sub-thicknesses are: - dL1 (mm) = 1.44. (14) - dL2 (mm) = 2.16. (15)

2.3.5.5. 厚度

玻璃体折射对晶状体厚度没有显著影响（图4）。平均厚度为3.64 ± 0.22毫米，对于模型，我使用dL（mm）= 3.6。 （13）有趣的是使用超声波和MRI测量这些测量值进行比较。尽管MRI分辨率低，但不受眼内介质假定速度的影响。 MRI给出了相似的平均估计值为3.63 ± 0.25毫米。这里的值比Navarro的模型值4.0毫米小得多，但与先前的测量值相似：Jansson（1963）20-29岁群体3.6毫米; Leighton和Tomlinson（1972）19-52岁3.6毫米; Koretz等人。 （1989）纠正的超声检查3.46 + 0.013 *年龄= 3.79毫米; Carney等人。 （1997）15-52岁，平均27岁，3.51±0.26毫米; Goss等人。 （1997年）3.7毫米; Dubbelman和Van der Heijde（2001）2.93 + 0.024* 年龄= 25岁时的3.53毫米。男性和女性之间的厚度平均差为0.06毫米（女性更大），这不是显着的（t = 1.49，df = 117，p = 0.139）。其他人也未发现厚度受性别（Alsbirk，1977; Carney等，1997; Goss等，1997; Jansson，1963）或折射（Goss等，1997; Jansson，1963）的显著影响。我将晶状体分为前部和后部，前部占厚度的40％，如Liou＆Brennan（1997）所用。子厚度为： - dL1（mm）= 1.44。 （14） - dL2（mm）= 2.16。 （15）

2.3.5.6. Power

Bennett (1988) developed a procedure to estimate equivalent lens power in the absence of phakometry measurements. This procedure is based on the three refracting surface Gullstrand-Emsley eye, assuming that lenses retain the same ratio of front and back surface radii as in the model. Lenses are modified according to refraction, anterior corneal radius measurements, and intraocular distance measurements. Fig. 5 shows equivalent lens powers of the eye as a function of refraction. The mean is 23.5 ± 2.0 D. Previous estimates of lens power are lower at 17.4 ± 1.5 D (Stenstrom, 1948a) and 21 D (Goss et al., 1997). In this study, lens power is not significantly influenced by refraction, as also found by Stenstrom (1948c) & Goss et al. (1997). However, females have significantly higher powers than males by 1.3 D (t = 3.59, df = 116, p < 0.001).

2.3.5.6. 功率

Bennett（1988）开发了一种估算等效镜头功率的方法，可以在无晶体度数测试的情况下进行。该方法基于三个折射面的Gullstrand-Emsley眼模型，假设透镜前后表面半径的比例与该模型相同。根据屈光度、角膜前半径测量和眼内距离测量来修改透镜。图5显示了眼睛的等效镜头功率与屈光度的函数关系。平均值为23.5±2.0 D。之前的透镜功率估计值较低为17.4±1.5 D（Stenstrom，1948a）和21 D（Goss等人，1997）。在这项研究中，透镜功率并未受屈光度显著影响，这也是Stenstrom（1948c）和Goss等人（1997）的发现。然而，女性的透镜功率比男性高1.3 D（t = 3.59，df = 116，p <0.001）。 None

$p < 0.001$). A significant gender difference was not found by Goss et al. (1997), although they did find females to have significantly steeper posterior corneas than males.

2.3.5.7. Gradient index and components of lens power. Jones et al. (2005) found that the refractive index of the lens varies from 1.371 at the edge to 1.418 in the middle, with little dependence on age. Consistent with Liou & Brennan (1997), I used a parabolic equation to describe refractive index $n(\rho)$ of the form

$$n(\rho) = c_0 + c_1\rho^2.$$

Here, ρ is the relative distance from the centre of the lens to the edge and c_0 and c_1 are co-efficients. c_0 is the refractive index in the centre of the lens (1.418) and $c_0 + c_1$ is the refractive index at the edge of the lens (1.371). Better knowledge of the refractive index gradient might result in a more sophisticated equation that would aid the accurate prediction of aberrations of the lens. However, the Jones et al. (2005) data were obtained from unrestrained lenses which would have been in accommodated states and so I cannot be confident about the exact equation in the unaccommodated state.

For raytracing purposes, this equation can be converted into $N(X, Y, Z)$ co-efficients where

$$N(X,Y,Z) = N_0(Z) + N_1(Z)(X^2+Y^2) + N_2(Z)(X^2+Y^2)^2 + \cdots$$

and $N_{i,j}$ co-efficients are given by:

$$N_0(Z) = N_{0,0} + N_{0,1}Z + N_{0,2}Z^2 + \cdots,$$

$$N_1(Z) = N_{1,0} + N_{1,1}Z + N_{1,2}Z^2 + \cdots,$$

$$N_2(Z) = N_{2,0} + N_{2,1}Z + N_{2,2}Z^2 + \cdots.$$

For the parabolic model, $N_{i,j}$ co-efficients for the front half of the lens are given by (Smith et al., 1991):

$$N_{0,0} = c_0 + c_1,$$

$$N_{0,1} = -2c_1/d_{\mathrm{L1}},$$

$$N_{0,2} = c_1/d_{\mathrm{L1}}^2,$$

$$N_{1,0} = c_1/b^2,$$

and co-efficients for the back half of the lens are given by:

$$N_{0,0} = c_0,$$

$$N_{0,2} = c_1/d_{\mathrm{L2}}^2,$$

$$N_{1,0} = c_1/b^2,$$

with all other co-efficients being zero. Here b is the semi-diameter of the lens and is set to 4.8 mm to give an equivalent lens power of 23.2 D, close to the experimental mean of 23.5 D. The value of 4.8 mm for b is not anatomically accurate as mean lens diameter is 9.06 ± 0.41 mm (see below). However, in this context b can be regarded as a paraxial quantity. The corresponding $N_{i,j}$ co-efficients for the front half of the lens are $N_{0,0} = 1.371$, $N_{0,1} = 0.0652778$, $N_{0,2} = -0.0226659$ and $N_{1,0} = -0.0020399$. For the back half, $N_{0,0} = 1.418$, $N_{0,2} = -0.0100737$ and $N_{1,0} = -0.0020399$. These can be written as:

$$n_{\mathrm{L1}} = 1.371 + 0.0652778Z - 0.0226659Z^2 - 0.0020399(X^2+Y^2), \quad (16)$$

$$n_{\mathrm{L2}} = 1.418 - 0.0100737Z^2 - 0.0020399(X^2+Y^2). \quad (17)$$

Equivalent lens power is a combination of the surface contributions and the gradient index contributions. The anterior and posterior surface powers are 2.93 and 5.69 D, respectively. The gradient index, combined with small effects due to the displacement of its principal planes away from the surface vertices, contributes 63% of the lens power.

2.3.5.8. Tilt. Lenses of eyes are considerably tilted about the vertical axis, with their axes usually being directly temporally into object space. Using MRI images, Atchison et al. (2005) found that tilt was not significantly affected by refraction, and that the horizontal component of the mean tilt was significantly different from zero at $4.0 \pm 2.4°$. Hence, I used a tilt about the vertical axis where

$$\theta_{y\mathrm{L}}\,(^\circ) = -4. \quad (18)$$

The negative sign is used to match the convention used by the optical design program (Zemax), and means that the axis is directly temporally into object space.

The method of MRI measurement, in which the orientation of the lens was important in determining the alignment of the eye (Atchison et al., 2004) meant that no estimate of the lens tilt about the horizontal axis could be made, and hence I have set this to zero.

2.3.5.9. Decentration. Having no information about this, I assume that the lens centre coincides with the line of sight. This requires horizontal decentration of the anterior and posterior surfaces of equal amounts but in opposite directions by $1.8\cos(4°) = 0.125562$ mm, with the front surface temporal decentration having a positive sign to match the convention of the optical design program.

2.3.5.10. Diameter. Lens diameters were measured in the axial transverse section for 84 subjects with MRI images. There is no significant trend for the group, with the regression equation being

$$D_{\mathrm{L}}\ (\mathrm{mm}) = 9.012 - 0.030SR \quad (t = -1.57,\ \mathrm{adj.}R^2 = 0.017,\ p = 0.114).$$

The mean diameter for all subjects is 9.08 ± 0.41 mm, with a range of 7.8–9.9 mm. Males have greater diameters (9.18 ± 0.42 mm) than females (9.01 ± 0.38 mm), but the difference is not quite significant ($t = -1.902$, $\mathrm{df} = 82$, $p = 0.061$). Although not used in my raytracing, a useful diameter to use for modelling the unaccommodated lens is

$$D_{\mathrm{L}}\ (\mathrm{mm}) = 9.1.$$

The results for my group are slightly smaller, but not significantly so, than the 9.18 ± 0.30 mm (range 8.6–9.9 mm) obtained by Strenk et al. (1999) in a group of 25 subjects across the age range 22–83 years. They found that lens diameter did not change significantly with age for unaccommodated eyes.

2.3.6. Length of eye

Ultrasound measurements of total length are shown in Fig. 6. In accordance with many previous studies (Carney et al., 1997; Chau, Fung, Pak, & Yap, 2004; Grosvenor & Scott, 1991; Stenstrom, 1948b, 1948c) there is a strong significant dependence upon refraction. The regression equations for males and females are $L = 24.04 - 0.314SR$ (adj. $R^2 = 0.632$) and

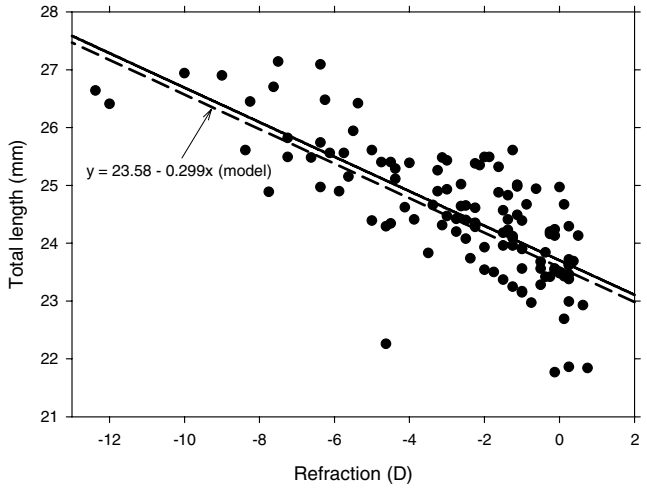

Fig. 6. Effect of refractive correction on ocular length. The regression fit is $d_{\mathrm{total}} = 23.70 - 0.298SR$, $n = 119$, adj. $R^2 = 0.570$, $p < 0.001$. The fit for the model of $d = 23.58 - 0.299SR$ is also shown.

Ocular Anatomy

眼部解剖学

Structure	Chinese Name
Sclera	巩膜
Cornea	角膜
Iris	虹膜
Pupil	瞳孔
Lens	晶状体
Retina	视网膜
Optic Nerve	视神经
Choroid	脉络膜
Conjunctiva	结膜
Tear Gland	泪腺
Eyelid	眼睑
Eyelashes	睫毛

None

Corneas

- Females have significantly steeper posterior corneas than males (Goss et al., 1997).
- Meniconi et al. (1998) found that corneal thickness increases with increased myopia.

角膜

- 女性后表面角膜比男性更陡峭 (Goss et al., 1997)。
- Meniconi等人(1998)发现随近视度数的增加，角膜厚度也增加。

Gradient index and components of lens power

- Jones et al. (2005) found that the refractive index of the lens varies from 1.371 at the edge to 1.418 in the middle, with little dependent on age.
- The equation used to describe refractive index is n(q) = c0 + c1q2, where q is the relative distance from the centre of the lens to the edge and c0 and c1 are co-efficients.
- For raytracing purposes, the equation can be converted into N(X, Y, Z) co-efficients where Ni,j co-efficients are given by: N 0(Z) = N 0,0 + N 0,1Z + N 0,2Z2, N 1(Z) = N 1,0 + N 1,1Z + N 1,2Z2, and N 2(Z) = N 2,0 + N 2,1Z + N 2,2Z2.
- The anterior and posterior surface powers of the lens are 2.93D and 5.69 D, respectively, and the gradient index contributes 63% of the lens power.

透镜梯度折射率和组份

- Jones等人（2005）发现透镜的折射率从边缘的1.371变化到中心的1.418，与年龄关系不大。
- 描述折射率所用的方程式为n（q）= c0 + c1q2，其中q是相对于透镜中央到边缘的距离，而c0和c1是系数。
- 为了进行光线追踪，可以将该方程式转换为N（X，Y，Z）系数，其中Ni，j系数由以下进行给定：N 0（Z）= N 0,0 + N 0,1Z + N 0,2Z2，N 1（Z）= N 1,0 + N 1,1Z + N 1,2Z2，以及N 2（Z）= N 2,0 + N 2,1Z + N 2,2Z2。
- 透镜的前后表面力分别为2.93D和5.69D，其中梯度折射率贡献的透镜力为总透镜力的63%。

Tilt

- Lens axes are usually directly temporally into object space and MRI images show that tilt is not significantly affected by refraction (Atchison et al., 2005).
- The tilt about the vertical axis is given by hyL (theta) = -4.

倾斜

- 透镜轴通常直接暂时进入物体空间，MRI图像显示，倾斜不受折射的显著影响（Atchison等，2005）。
- 垂直轴的倾斜由hyL（theta）=-4给出。

Decentration

- The lens centre is assumed to coincide with the line of sight and the anterior and posterior surfaces have equal but opposite horizontal decentration by 1.8cos(4°) = 0.125562 mm.

偏心

- 假设镜片中心与视线重合，前表面和后表面的水平偏心相等但方向相反，为1.8cos(4°) = 0.125562毫米。

Diameter

- Lens diameters were measured in the axial transverse section for 84 subjects with MRI images.
- The mean diameter for all subjects is 9.08 ± 0.41 mm, with males having greater diameters than females.
- Strenk et al. (1999) found a mean lens diameter of 9.18 ± 0.30 mm in a group of 25 subjects across the age range 22–83 years.
- Lens diameter does not change significantly with age for unaccommodated eyes.

直径

- 通过MRI图像，对84名受试者的镜头直径进行了轴向横截面测量。
- 所有受试者的平均直径为9.08±0.41毫米，男性的直径比女性大。
- Strenk等人（1999）在一个25名受试者年龄范围为22-83岁的群体中发现平均镜头直径为9.18±0.30毫米。
- 未调节眼睛的镜头直径随年龄的变化不明显。

Length of eye

- There is a significant dependence of total length on refraction (Carney et al., 1997; Chau, Fung, Pak, & Yap, 2004; Grosvenor & Scott, 1991; Stenstrom, 1948b, 1948c).
- The regression equations for males and females are L = 24.04 - 0.314SR and L = 23.70 - 0.298SR, respectively.

眼睛长度

- 总长度与屈光度有显著关联（Carney等人，1997; Chau，Fung，Pak和Yap，2004; Grosvenor & Scott，1991; Stenstrom，1948b，1948c）。
- 男性和女性的回归方程分别为L = 24.04 - 0.314SR和L = 23.70 - 0.298SR。

$L = 23.46 - 0.303SR$ (adj. $R^2 = 0.618$), respectively, so male eyes are 0.6 mm longer than female eyes of similar refractions, and the change in length with refraction is similar to those in the above studies. The male-female difference has been noted several times with axial length differences estimates of 0.16 ± 0.08 mm (Stenstrom, 1948a), 0.86 mm (Jansson, 1963), 0.71 mm (Alsbirk, 1977), 0.02 mm (Yu, Kao, & Change, 1979), and 0.65 mm (emmetropes) (Koretz et al., 1989), so my difference fits well within these. Estimates of emmetropic males in these studies are close to 24.0 mm, which again well fits with my results.

I did not use the regression fit to determine axial length, but used the previously described parameters to determine lengths corresponding to paraxial imagery. The corresponding linear fit is

$$d_{\text{total}}\ (\text{mm}) = 23.58 - 0.299SR, \tag{19}$$

with absolute errors $\leqslant 0.013$ mm between 0 and -10 D refraction. The length of the model is 0.12–0.11 mm smaller than the regression fitted to the data (Fig. 6). The correction is due to accumulated errors in the previous parameters, of which I suspect that the Bennett computing scheme and the subsequent lens gradient index distribution are important contributors.

2.3.7. Vitreous chamber (V)

The vitreous lengths are 7.3 mm less than the total length and so are described by

$$d_{\text{V}}\ (\text{mm}) = 16.28 - 0.299SR. \tag{20}$$

This gives the paraxial distance and can be manipulated to improve image quality as a user sees fit.

2.3.7.1. Refractive index.

I used the Navarro values, so

$$n_{\text{v}} = 1.336. \tag{21}$$

2.3.8. Retina (R)

2.3.8.1. Radius of curvature.

Atchison et al. (2005) described retinal shapes retina by non-rotationally symmetrical ellipsoids. The ellipsoids had semi-diameters given by:

$$R_x = 11.455 - 0.043SR, \tag{22}$$

$$R_y = 11.365 - 0.090SR, \tag{23}$$

$$R_z = 10.148 - 0.163SR. \tag{24}$$

The vertex radii of curvature of the retina along the X–Z and Y–Z planes are given by:

$$R_{\text{R}x} = -R_x^2/R_z,$$

$$R_{\text{R}y} = -R_y^2/R_z.$$

Based on the semi-diameters and using steps of 1 D between refractions of 0 and -12 D, linear regression equations of the vertex radii and asphericities, used for the model, are:

$$R_{\text{R}x} = -12.91 - 0.094SR\ (\text{max absolute error} < 0.03), \tag{25}$$

$$R_{\text{R}y} = -12.72 + 0.004SR\ (\text{maximum absolute error} < 0.02). \tag{26}$$

2.3.8.2. Asphericity.

The asphericities in the X–Y and Y–Z planes of the retinal ellipsoids are given by:

$$Q_{\text{R}x} = (R_x/R_z)^2 - 1,$$

$$Q_{\text{R}y} = (R_y/R_z)^2 - 1.$$

Based on the semi-diameters and using steps of 1 D between refractions of 0 and -12 D, linear regression equations of the vertex radii and asphericities are:

$$Q_{\text{R}x} = 0.27 + 0.026SR\ (\text{maximum absolute error} < 0.01), \tag{27}$$

$$Q_{\text{R}y} = 0.25 + 0.017SR\ (\text{maximum absolute error} < 0.01). \tag{28}$$

2.3.8.3. Decentration of retinal ellipsoidal centre.

The centres of the ellipsoids are decentred 0.5 mm nasal and 0.2 mm below the line of sight, so, adopting the convention used by Zemax

$$\text{Dec}_{\text{REC}x}\ (\text{mm}) = -0.5, \tag{29}$$

$$\text{Dec}_{\text{REC}y}\ (\text{mm}) = -0.2. \tag{30}$$

2.3.8.4. Tilt.

The ellipsoids are tilted horizontal 11.5° temporally in object space and 3.6° downwards in object space, so, adopting the conventions used by Zemax

$$\theta_{y\text{R}}\ (^\circ) = -11.5, \tag{31}$$

$$\theta_{x\text{R}}\ (^\circ) = -3.6. \tag{32}$$

2.3.8.5. Decentration.

Combining Eqs. (24), (29) and (31), the decentration of the retina in the horizontal direction is

$$\begin{aligned}\text{Dec}_{\text{CR}x}\ (\text{mm}) &= -0.5 - \sin(11.5^\circ)(10.148 - 0.163SR)\\ &= -2.52 + 0.032SR.\end{aligned} \tag{33}$$

Similarly, combining Eqs. (24), (30) and (32), the decentration of the retina in the vertical direction is

$$\begin{aligned}\text{Dec}_{\text{CR}y}\ (\text{mm}) &= -0.2 + \sin(3.6^\circ)(10.148 - 0.163SR)\\ &= 0.44 - 0.010SR.\end{aligned} \tag{34}$$

Note that retinal vertices are on the opposite side of the axis in the Y-direction to that of the ellipsoid centres.

2.3.9. Chromatic dispersion

No chromatic aberration investigation is described in this paper, but I provided chromatic dispersions for the models. I followed Atchison & Smith (2005) who determined chromatic dispersion for all media using 4-term Cauchy's equations

$$n(\lambda) = A + B/\lambda^2 + C/\lambda^4 + D/\lambda^6. \tag{35}$$

Coefficients for A, B, C, and D for the cornea, aqueous, lens, and vitreous are given in Table 2. Those for the cornea and vitreous are taken from Atchison and Smith's Table 5. The lens refractive index distribution and the refractive index for the aqueous are different for this model eye than those given by Atchison and Smith, and to convert from their co-efficients to new co-efficients I have used the scaling recommended by them:

$$n(\lambda)_{\text{H}} = n(\lambda)_{\text{A}}[n(\overline{\lambda})_{\text{H}}/n(\overline{\lambda})_{\text{A}}], \tag{36}$$

Table 2
Chromatic dispersion co-efficients A, B, C, and D in Eq. (35) for the media of model eyes

Medium	A	B	C	D
Cornea	1.361594	6.009687×10^3	-6.760760×10^8	5.908450×10^{13}
Aqueous	1.323016	6.077158×10^3	-7.069706×10^8	6.154303×10^{13}
Lens—centre	1.401105	6.576875×10^3	-6.162814×10^8	5.958617×10^{13}
Lens—edge	1.354665	6.358883×10^3	-5.958546×10^8	5.761117×10^{13}
Vitreous	1.322357	5.560240×10^3	-5.817391×10^8	5.036810×10^{13}

Model Eye Parameters

模型眼参数

Parameter	Description	Range
Pupil Diameter	Diameter of the pupil	2.0 - 8.0 mm
Corneal Curvature	Curvature of the cornea	7.0 - 10.0 mm
Axial Length	Length of the eye from cornea to retina	22.0 - 26.0 mm
Refractive Error: Spherical	Spherical refractive error of the eye	-10.00 to +10.00 dpt
Refractive Error: Cylindrical	Cylindrical refractive error of the eye	0 to 6.00 dpt
Refractive Error: Axis	Axis of cylindrical refractive error	0 to 180 degrees

None

Axial length (AL)

None

The axial length is described by:

None

d_{total} (mm) = 23.46 ± 0.303SR (adj. R2 = 0.618)

None.

Male eyes are 0.6 mm longer than female eyes of similar refractions, and the change in length with refraction is similar to those in the above studies.

男性眼睛比视力相似的女性眼睛长0.6毫米，并且随着视力的变化，眼睛长度的变化类似于上述研究。

Vitreous chamber (V)

玻璃体室（V）

The vitreous lengths are 7.3 mm less than the total length and so are described by:

None

dV (mm) = 16.28 ± 0.299SR.

None.

This gives the paraxial distance and can be manipulated to improve image quality as a user sees fit.

这会给出近轴距离，并可以根据使用者的需要进行调整以改善图像质量。

Refractive index

折射率

The refractive index is:

折射率为：None

nv = 1.336.

None

Retina (R)

视网膜（R）

None

Radius of curvature

曲率半径

Retinal shapes are described by non-rotationally symmetrical ellipsoids. The ellipsoids had semi-diameters given by:

视网膜的形状由非旋转对称的椭球描述。椭球的半径如下所示：

Rx = 11.455 ± 0.043SR;
Ry = 11.365 ± 0.090SR; Rz = 10.148 ± 0.163SR.

None

The vertex radii of curvature of the retina along the X–Z and Y–Z planes are given by:

None.

RRx = $-R^2x/Rz$;
RRy = $-R^2y/Rz$.

None

Asphericity

非球度

The asphericities in the X–Y and Y–Z planes of the retinal ellipsoids are given by:

视网膜椭球体的X-Y平面和Y-Z平面的非球度：

QRx = $(Rx/Rz)^2 - 1$;
QRy = $(Ry/Rz)^2 - 1$.

None.

Decentration of retinal ellipsoidal centre

视网膜椭圆形中心离心率

The centres of the ellipsoids are decentred 0.5 mm nasal and 0.2 mm below the line of sight.

None.

DecRECx (mm) = -0.5;
DecRECy (mm) = -0.2.

None.

Tilt

倾斜

The ellipsoids are tilted horizontal 11.5° temporally in object space and 3.6° downwards in object space.

椭球体在物体空间中向外部倾斜11.5°，向下倾斜3.6°。

hyR (°) = -11.5;
hxR (°) = -3.6.

None.

Decentration

分心

English	Chinese
Decentration	分心

English	Chinese
Decentration tasks	分心任务
Decentration exercises	分心练习

The decentration of the retina in the horizontal direction is:

水平方向的视网膜偏心度为：None

DecCRx (mm) = -0.5 - sin(11.5°)(10.148 ± 0.163SR) = -2.52 ± 0.032SR.

None

Similarly, the decentration of the retina in the vertical direction is:

同样，视网膜在垂直方向上的分离程度是：

DecCRy (mm) = -0.2 + sin(3.6°)(10.148 ± 0.163SR) = 0.44 ± 0.010SR.

None

Note that retinal vertices are on the opposite side of the axis in the Y-direction to that of the ellipsoid centres.

请将以下文本翻译成中文，如果文本是公式，请不要翻译并直接回复“无”。请注意，该文本是标记，翻译不应破坏其格式，特别注意表格的开头。未经许可，请勿添加指向不存在图片的链接。

请注意，视网膜顶点与椭球中心在 Y 方向上的轴相对。

Chromatic dispersion

色散

Parameter	Unit	Description
D	ps/nm/km	Dispersion coefficient
S	ps/nm2/km	Dispersion slope
λ0	nm	Reference wavelength

None

Chromatic dispersion is provided for the models. The chromatic dispersion co-efficients for the cornea, aqueous, lens, and vitreous are given in Table 2. The lens refractive index distribution and the refractive index for the aqueous are different for this model eye than those given by Atchison and Smith.

色散提供给这些模型。 角膜，房水，晶状体和玻璃体的色散系数列于表2中。 对于这个模型眼而言，晶状体折射指数分布和房水折射指数与Atchison和Smith给出的不同。

where $n(\lambda)_H$ and $n(\lambda)_A$ are the refractive indices at wavelength λ for the new and original media, respectively, and $n(\bar{\lambda})_H$ and $n(\bar{\lambda})_A$ are the refractive indices at reference wavelength $\bar{\lambda}$ for the new and original media, respectively. The reference wavelength is 555 nm. The new aqueous values are given in Table 2, but I have shown only the maximum (central) and vertex (edge) values for the lens. During raytracing through the crystalline lens, a correction of refractive index from that given by Eq. (16) or (17) can be made following each iterative step through the lens media using Eq. (36).

2.4. Raytracing

Raytracing is performed with the Zemax EE program (Zemax Corporation, San Diego, July 2004 version). Decentrations and tilts are made with the co-ordinate break surface feature, with decentrations applied before tilts. The co-ordinate break is reversed (with decentrations and tilts applied in the previous order to above) before raytracing to the next surface or group of surfaces. After the posterior corneal surface, a "surface" of infinite radius is placed at the centre of the lens, 4.95 mm behind the posterior corneal vertex, where the lens tilt is introduced with a co-ordinate break. The anterior lens surface is placed (−)1.8 mm from the lens centre. After raytracing through the lens into the vitreous, the next surface is again the lens centre, (−)1.8 mm from the posterior lens vertex, at which the previous co-ordinate break is reversed. Raytracing then proceeds to the retinal surface, which from Eq. (20) is placed a distance from the lens centre of

$$d_V\ (\text{mm}) = 18.08 - 0.299SR. \tag{37}$$

The effect of the tilts and decentrations is that the lengths along the optical axis no longer coincide with the values given by Eq. (19). To correct for this, a ray is traced along the optical axis, its Z co-ordinate relative to the anterior cornea is determined, and a modification of between −0.26 (emmetropia) and −0.29 mm (10 D myopia) is made to the constant in Eq. (37).

For raytracing purposes, the lens is treated as having anterior and posterior sections with gradient refractive index distributions given by Eqs. (16) and (17), respectively. The posterior section 1.44 mm from the anterior lens vertex starts with a "surface" of infinite radius of curvature.

To determine peripheral refractions, thin lenses are placed next to the cornea aligned along the chief ray. An optimization routine is used to vary the principal curvatures and meridians of the front surface of the thin lenses, for an entrance pupil diameter of 0.1 mm, so as to bring the light from infinity to a focus at the retina. These powers are converted into dioptres of surface powers F_x and F_y along the horizontal and vertical meridians (ignoring surface rotation θ). The mean sphere, 90–180° astigmatism J_{180} and 45–135° astigmatism J_{45} are then obtained from:

$$M = (F_x + F_y)/2,$$

$$J_{180} = (F_x - F_y)\cos(2\theta)/2,$$

$$J_{45} = (F_x - F_y)\sin(2\theta)/2.$$

Here, M, J_{180}, and J_{45} are related to conventional sphero-cylindrical form $S/C \times \theta$, with a negative cylinder, by

$$M = S + C/2,$$

$$J_{180} = -C\cos(2\theta)/2,$$

$$J_{45} = -C\sin(2\theta)/2.$$

2.5. Models

Results are presented for the two eye models, Model 1 with centred surfaces and Model 2 with a tilted lens about its centre (Eq. (18)), a tilted and decentred retina (Eqs. (31)–(34)) and with the modification to vitreous length as described in Section 2.4. As mentioned earlier, details of the models are provided in Table 1. Fig. 7 shows the models for emmetropia and 10 D myopia and in both horizontal and vertical sections.

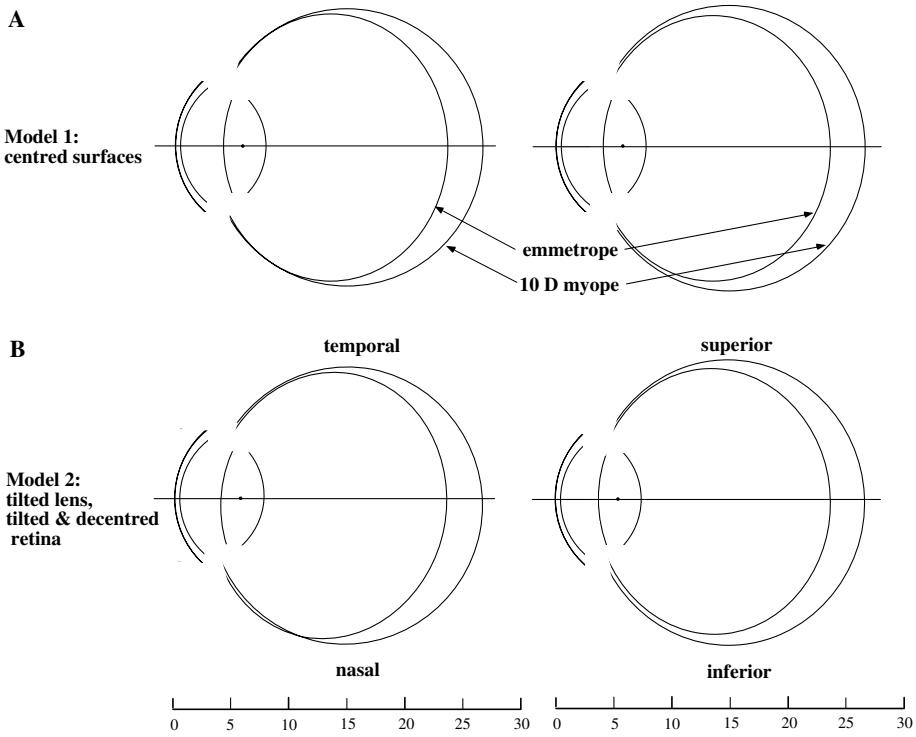

Fig. 7. Centred Model 1 (A) and decentred Model 2 (B) for emmetropia and 10 D myopia, and in both horizontal (left) and vertical sections (right). The lens surfaces are not shown as aspherised, and differences between the anterior corneal surfaces for emmetropia and 10 D myopia cannot be distinguished.

Refractive indices

折射率

Material	Index
Air	1.000293
Vacuum	1.0
Water	1.333
Alcohol	1.36
Glass	1.52
Diamond	2.42

Where n(k)H and n(k)A are the refractive indices at wavelength k for the new and original media, respectively, and n(k)H and n(k)A are the refractive indices at reference wavelength k for the new and original media, respectively. The reference wavelength is 555 nm. The new aqueous values are given in Table 2, but I have shown only the maximum (central) and vertex (edge) values for the lens. During raytracing through the crystalline lens, a correction of refractive index from that given by Eq. (16) or (17) can be made following each iterative step through the lens media using Eq. (36).

其中 n(k)H 和 n(k)A 分别为新的和原始介质在波长 k 处的折射率，n(k)H 和 n(k)A 分别为新的和原始介质在参考波长 k 处的折射率。参考波长为 555 nm。新的水溶性价值见表2，但我仅显示了晶体镜的最大（中心）和顶点（边缘）值。在晶状体透镜内进行光线追踪时，可以使用方程式（36）在通过透镜介质的每个迭代步之后对折射率进行修正，该方程式不使用方程式（16）或（17）给出的值。

Raytracing

光线追踪

Raytracing is performed with the Zemax EE program (Zemax Corporation, San Diego, July 2004 version). Decentrations and tilts are made with the co-ordinate break surface feature, with decentrations applied before tilts. The co-ordinate break is reversed (with decentrations and tilts applied in the previous order to above) before raytracing to the next surface or group of surfaces. After the posterior corneal surface, a ‘‘surface’’ of infinite radius is placed at the centre of the lens, 4.95 mm behind the posterior corneal vertex, where the lens tilt is introduced with a co-ordinate break. The anterior lens surface is placed (□)1.8 mm from the lens centre. After raytracing through the lens into the vitreous, the next surface is again the lens centre, (□)1.8 mm from the posterior lens vertex, at which the previous co-ordinate break is reversed. Raytracing then proceeds to the retinal surface, which from Eq. (20) is placed a distance from the lens centre of dV ðmmÞ ¼ 18:08 □ 0:299SR. The effect of the tilts and decentrations is that the lengths along the optical axis no longer coincide with the values given by Eq. (19). To correct for this, a ray is traced along the optical axis, its Z co-ordinate relative to the anterior cornea is determined, and a modification of between □0.26 (emmetropia) and □0.29 mm (10 D myopia) is made to the constant in Eq. (37).

使用Zemax EE程序（Zemax Corporation，圣地亚哥，2004年7月版）执行光线追踪。使用坐标破裂表面功能进行偏离和倾斜，偏置应先于倾斜进行。在进行下一表面或表面组之前，破裂坐标会反转（先应用偏心和倾斜）。在后角膜表面之后，在透镜中心处放置一个无限半径的“表面”，距离后角膜顶点4.95 mm，并引入透镜倾斜。前透镜面距离透镜中心（□）1.8 mm。在经过透镜进入玻璃体后，下一个表面再次是透镜中心，距离后透镜顶点（□）1.8 mm，在此处反转前一个坐标破裂。然后，光线追踪到视网膜表面，根据公式（20），该距离透镜中心的距离为dV ðmmÞ ¼ 18:08 □ 0:299SR。倾斜和偏心的影响是光轴沿着的长度不再与公式（19）中给出的值重合。为了纠正这个问题，沿着光轴追踪光线，确定其相对于前面的角膜的Z坐标，并对公式（37）中常量进行修改，范围在□0.26（屈光正常）和□0.29 mm（10度近视）之间。

For raytracing purposes, the lens is treated as having anterior and posterior sections with gradient refractive index distributions given by Eqs. (16) and (17), respectively. The posterior section 1.44 mm from the anterior lens vertex starts with a ‘‘surface’’ of infinite radius of curvature.

为了光线追踪的目的，该镜头被视为具有前后部分，其梯度折射率分布分别由方程 (16) 和 (17) 给出。距前面透镜顶点 1.44 毫米的后面部分以曲率半径无限大的“表面”开始。None

To determine peripheral refractions, thin lenses are placed next to the cornea aligned along the chief ray. An optimization routine is used to vary the principal curvatures and meridians of the front surface of the thin lenses, for an entrance pupil diameter of 0.1 mm, so as to bring the light from infinity to a focus at the retina. These powers are converted into dioptres of surface powers Fx and Fy along the horizontal and vertical meridians (ignoring surface rotation h). The mean sphere, 90–180□ astigmatism J180 and 45–135□ astigmatism J45 are then obtained from: M = (Fx + Fy)/2, J180 = (Fx − Fy) cos(2h)/2, J45 = (Fx − Fy) sin(2h)/2. Here, M, J180, and J45 are related to conventional sphero-cylindrical form S/C · h, with a negative cylinder, by M = S + C/2, J180 = −C cos(2h)/2, J45 = −C sin(2h)/2.

使用薄透镜沿主光路与角膜相邻，优化算法可调整薄透镜前表面的主曲率和子午线，使从无穷远处发出的光能够在视网膜上聚焦（入射孔径直径为0.1毫米），并将这些主曲率和子午线转换为水平和竖直子午线上的面强度dioptres Fx和Fy（忽略表面旋转 h) 从中得出平均球面度数、90-180度散光角 J180 和 45-135度散光角 J45，分别为：M=(Fx+Fy)/2,J180=(Fx-Fy)cos(2h)/2,J45=

(Fx-Fy)sin(2h)/2。这里， M、J180和J45与常规球柱形式的 S/C·h（具有负柱）有关，其中M = S + C/2, J180 = -C cos(2h)/2， J45 = -C sin(2h)/2。

Models

模型

Results are presented for the two eye models, Model 1 with centred surfaces and Model 2 with a tilted lens about its centre (Eq. (18)), a tilted and decentred retina (Eqs. (31)–(34)) and with the modification to vitreous length as described in Section 2.4. As mentioned earlier, details of the models are provided in Table 1. Fig. 7 shows the models for emmetropia and 10 D myopia and in both horizontal and vertical sections.

以下是两个眼模型的结果，模型1具有中心表面，模型2具有围绕其中心倾斜的镜头（公式（18））， 倾斜和偏心的视网膜（公式（31）-（34））以及根据第2.4节所述修改玻璃体长度。如前所述，模型的细节在表1中提供。图7显示了等距和10 D近视的模型，以及水平和垂直剖面。

Model 1: centred surfaces Model 2: tilted lens, tilted & decentred retina

表格如下：

模型	描述
Model 1	居中表面
Model 2	倾斜镜头，倾斜和偏心的视网膜

Source: D.A. Atchison / Vision Research 46 (2006) 2236–2250

源自：D.A. Atchison / 视觉研究 46（2006）2236-2250

物质	折射率
眼房水	1.336
晶状体核	1.406
晶状体皮质	1.386
眼玻璃体	1.336

None

3. Results

3.1. Model 1 (centred)

3.1.1. Powers

The equivalent power of model eyes can be described by the equation

$$P_{eq} = 61.50 - 0.128SR$$

thus showing a small rate of increase in power as myopia increases.

3.1.2. On-axis spherical aberration (6 mm pupil)

Fig. 8 shows the central spherical aberrations of Model 1 as a function of refraction. This is done using *into-the-eye* raytracing from infinity, where the sampled rays are spread evenly across a 6 mm diameter entrance pupil. The whole eye aberration plots give the co-efficient for the emmetropic eye as 0.09 μm, which is only slightly smaller than the estimate of the average of 0.10 μm given by Atchison (2005). Spherical aberration is highly dependent on refraction, changing at a rate of approximately 0.007 μm per dioptre of myopia. This is in contradiction to experimental findings of no increase in spherical aberration with increase in myopia (Carkeet, Luo, Tong, Saw, & Tan, 2002; Cheng, Bradley, Hong, & Thibos, 2003; Porter, Guirao, Cox, & Williams, 2001; Zadok et al., 2005).

The anterior corneas have much higher aberrations than those of the total eye, but their aberrations change more slowly with increase in myopia. The corneas increase slowly in vertex curvature (Eq. (1)) and do not change at all in asphericity (Eq. (2)) as myopia increases, leaving the increase in spherical aberration of the eyes to be explained by increases in axial length (Atchison & Charman, 2005).

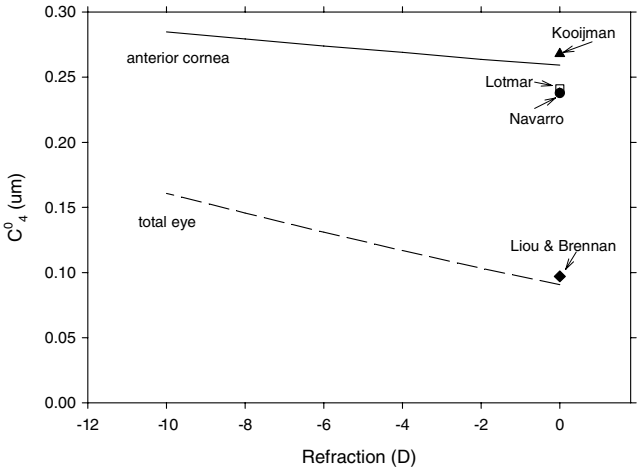

Fig. 8. Zernike aberration co-efficient c_4^0 (μm) of Model 1 as a function of myopia for a 6 mm diameter entrance pupil, for total eye and anterior cornea. Also shown are the co-efficients for the emmetropic model eyes of Lotmar (1971), Kooijman (1983), Navarro et al. (1985) and Liou and Brennan (1997).

Results for other, emmetropic model eyes are also shown in Fig. 8. My model gives similar spherical aberration to the Liou and Brennan model, but only about a one-third of those of Lotmar (1971), Kooijman (1983) & Navarro et al. (1985) model eyes.

Estimates of aberrations of eyes can be influenced by the direction of raytracing (e.g., *into-the-eye* or *out-of-the-eye*) and the reference surface used for the stop (iris, corneal plane, entrance pupil plane), and whether the eyes are corrected or not (Atchison & Charman, 2005). In the case of these models, correcting the eye while ensuring that the stop size (rather than the entrance pupil size) is constant gives similar results to those in Fig. 8. An *out-of-the-eye* raytrace (as applied in Hartmann-Shack instruments) also gives similar results to those presented in Fig. 8.

3.1.3. Peripheral refraction

Because I am showing results only for the horizontal and vertical meridians and there is no tilt or decentration of the elements in front of the retina, there is no J_{45} astigmatism for Model 1. Fig. 9 shows the peripheral refractions for the emmetropic model eye along the horizontal and vertical meridians out to 40° visual field angle. For comparison, results are shown for other model eyes along the horizontal meridian. My model eye shows similar results along horizontal and vertical meridians for the mean sphere M with myopic shifts amounting to approximately −0.9 D by 40° (Fig. 9A). The myopic shift is in agreement with experimental studies for the horizontal meridian (Atchison, Pritchard, & Schmid, 2006; Atchison, Pritchard, White, & Griffiths, 2005; Gustafsson, Terenius, Buchheister, & Unsbo, 2001; Millodot, 1981; Seidemann, Schaeffel, Guirao, Lopez-Gil, & Artal, 2002) and for the vertical meridian (Atchison et al., 2006). Three other model eyes, those of Lotmar (1971), Kooijman (1983), Escudero-Sanz & Navarro (1999) & Navarro et al. (1985) predict hypermetropic shifts into the periphery. Liou & Brennan's (1997) model eye does not have a defined retinal shape, but with a −12 mm radius of curvature it has a slight myopic shift as shown in the figure. With a −12.4 mm radius of curvature, this shift becomes similar to that shown by my model eye.

My model eye shows similar results along horizontal and vertical meridians for 90–180° astigmatism J_{180}, except that the signs are opposite (Fig. 9B). The Liou & Brennan (1997) model eye has similar astigmatism (note that this is relatively insensitive to the retinal radius of curvature). The other three model eyes have smaller amounts of astigmatism. The rates of change of astigmatism with angle-squared for the model eyes are, ignoring sign, 0.0010 D/degrees^2 for the Lotmar eye, 0.0012 D/degrees^2 (Kooijman and Navarro eyes), and 0.0016 D/degrees^2 (Liou and Brennan eye and my model eye). The recent experimental study by Atchison et al. (2006) has slopes of 0.0010–0.0011 D/degrees^2. This indicates that my model and that of Liou & Brennan (1997) overestimate the mean astigmatism by about 50%, whereas the

3. Results

3.1. Model 1 (centred)

3.1.1. Powers

The equivalent power of model eyes can be described by the equation P eq ¼ 61:50 □ 0:128SR thus showing a small rate of increase in power as myopia increases.

3.1.2. On-axis spherical aberration (6 mm pupil)

Fig. 8 shows the central spherical aberrations of Model 1 as a function of refraction. This is done using into-the-eye raytracing from infinity, where the sampled rays are spread evenly across a 6 mm diameter entrance pupil. The whole eye aberration plots give the co-efficient for the emmetropic eye as 0.09 lm, which is only slightly smaller than the estimate of the average of 0.10 lm given by Atchison (2005). Spherical aberration is highly dependent on refraction, changing at a rate of approximately 0.007 lm per dioptre of myopia. This is in contradiction to experimental findings of no increase in spherical aberration with increase in myopia (Carkeet, Luo, Tong, Saw, & Tan, 2002; Cheng, Bradley, Hong, & Thibos, 2003; Porter, Guirao, Cox, & Williams, 2001; Zadok et al., 2005). The anterior corneas have much higher aberrations than those of the total eye, but their aberrations change more slowly with increase in myopia. The corneas increase slowly in vertex curvature (Eq. (1)) and do not change at all in asphericity (Eq. (2)) as myopia increases, leaving the increase in spherical aberration of the eyes to be explained by increases in axial length (Atchison & Charman, 2005). Results for other, emmetropic model eyes are also shown in Fig. 8. My model gives similar spherical aberra-tion to the Liou and Brennan model, but only about a one-third of those of Lotmar (1971), Kooijman (1983) & Navarro et al. (1985) model eyes. Estimates of aberrations of eyes can be influenced by the direction of raytracing (e.g., into-the-eye or out-of-the-eye) and the reference surface used for the stop (iris, corneal plane, entrance pupil plane), and whether the eyes are cor-rected or not (Atchison & Charman, 2005). In the case of these models, correcting the eye while ensuring that the stop size (rather than the entrance pupil size) is constant gives similar results to those in Fig. 8. An out-of-the-eye raytrace (as applied in Hartmann-Shack instruments) also gives similar results to those presented in Fig. 8.

3.1.3. Peripheral refraction

Because I am showing results only for the horizontal and vertical meridians and there is no tilt or decentration of the elements in front of the retina, there is no J45 astigmatism for Model 1. Fig. 9 shows the peripheral refrac-tions for the emmetropic model eye along the horizontal and vertical meridians out to 40□ visual field angle. For comparison, results are shown for other model eyes along the horizontal meridian. My model eye shows similar results along horizontal and vertical meridians for the mean sphere M with myopic shifts amounting to approx-imately □0.9 D by 40□ (Fig. 9A). The myopic shift is in agreement with experimental studies for the horizontal meridian (Atchison, Pritchard, & Schmid, 2006; Atchison, Pritchard, White, & Griffiths, 2005; Gustafsson, Terenius, Buchheister, & Unsbo, 2001; Millodot, 1981; Seidemann, Schaeffel, Guirao, Lopez-Gil, & Artal, 2002) and for the vertical meridian (Atchison et al., 2006). Three other model eyes, those of Lotmar (1971), Kooijman (1983), Escudero-Sanz & Navarro (1999) & Navarro et al. (1985) predict hypermetropic shifts into the periphery. Liou & Brennan's (1997) model eye does not have a defined retinal shape, but with a □12 mm radius of curva-ture it has a slight myopic shift as shown in the figure. With a □12.4 mm radius of curvature, this shift becomes similar to that shown by my model eye. My model eye shows similar results along horizontal and vertical meridians for 90–180□ astigmatism J180, except that the signs are opposite (Fig. 9B). The Liou & Brennan (1997) model eye has similar astigmatism (note that this is relatively insensitive to the retinal radius of curvature). The other three model eyes have smaller amounts of astigmatism. The rates of change of astigma-tism with angle-squared for the model eyes are, ignoring sign, 0.0010 D/degrees2 for the Lotmar eye, 0.0012 D/degrees2 (Kooijman and Navarro eyes), and 0.0016 D/degrees2 (Liou and Brennan eye and my model eye). The recent experimental study by Atchison et al. (2006) has slopes of 0.0010–0.0011 D/degrees2. This indicates that my model and that of Liou & Brennan (1997) over-estimate the mean astigmatism by about 50%, whereas the Refraction (D) graph (not shown) from the study properly estimates the mean amount of astigmatism.

Fig. 8:

Zernike aberration co-efficient c0 4 (lm) of Model 1 as a function of myopia for a 6 mm diameter entrance pupil, for total eye and anterior cornea. Also shown are the co-efficients for the emmetropic model eyes of Lotmar (1971), Kooijman (1983), Navarro et al. (1985) and Liou and Brennan (1997).

Fig. 9:

Peripheral refractions for the emmetropic model eye along the horizontal and vertical meridians out to 40□ visual field angle. Comparison is made with other model eyes along the horizontal meridian. A) Mean sphere M shows that my model eye has similar results along horizontal and vertical meridians with myopic shifts amounting to approximately □0.9 D by 40□. B) 90-180□ astigmatism J180 shows that my model eye has similar results along horizontal and vertical meridians with signs that are opposite.

3. 结果

3.1. 模型1 (中心)

3.1.1. 功率

模型眼睛的等效功率可以用方程P eq ¼ 61:50 □ 0:128SR来描述，因此随近视度数的增加功率略微增加。

3.1.2. 中心球面像差 (6毫米瞳孔)

图8显示了模型1的中心球面像差随屈光度变化的变化情况。这是通过从无穷远点入射的光线追踪获得的，其中采样的光线均匀地分布在6毫米的入射瞳孔上。整体眼球像差图给出了正视眼的系数为0.09lm，略小于Atchison (2005)给出的0.10 lm的平均估计值。球面像差高度依赖于屈光度，每度近视变化约为0.007 lm。这与实验结果相矛盾，实验结果表明像差随着近视的增加没有增加（Carkeet、Luo、Tong、Saw和Tan，2002；Cheng、Bradley、Hong和Thibos，2003；Porter、Guirao、Cox和Williams，2001；Zadok等，2005）。前角膜的像差要比整个眼睛的像差高得多，但它们的像差随着近视的增加变化更慢。角膜的顶点曲率（方程（1））缓慢增加，不会改变畸变度（方程（2）），随着近视的增加留下的是眼球球面畸变的增加（Atchison和Charman，2005年）。图8还显示了其他正视眼模型的结果。我的模型与Liou和Brennan模型的球面畸变相似，但仅为Lotmar（1971年）、Koojman（1983年）和Navarro等人（1985年）模型眼睛的三分之一。眼睛的像差估计受到光线追踪方向（例如，进入眼睛或离开眼睛）、用于光圈（虹膜、角膜平面、入瞳孔平面）的参考面以及眼睛是否纠正（Atchison和Charman，2005年）的影响。在这些模型的情况下，纠正眼睛并确保光圈大小（而不是入瞳孔大小）恒定会给出与图8中类似的结果。用哈特曼-夏克仪器进行的离开眼标记追踪（与图8中呈现的结果相似）。

3.1.3. 周边屈光度

因为我只显示水平和垂直子午线的结果，并且视网膜前元素没有倾斜或离中，所以模型1没有J45散光。图9显示了水平和垂直子午线上至40度视野角的正常模型眼的周边屈光度。为了比较，还显示了其他模型眼沿水平子午线的结果。我的模型眼在水平和垂直子午线上显示出类似的结果，平均球体M的近视偏移量约为40度时为-0.9 D。这个近视偏移量与水平子午线（Atchison、Pritchard和Schmid，2006；Atchison、Pritchard、White和Griffiths，2005；Gustafsson、Terenius、Buchheister和Unsbo，2001；Millodot，1981；Seidemann、Schaeffel、Guirao、Lopez-Gil和Artal，2002）和垂直子午线（Atchison等人，2006）的实验研究相一致。在周边，Lotmar（1971年）、Koojman（1983年）和Escudero-Sanz& Navarro（1999年）和Navarro等人（1985年）的三个模型眼预测球形近视偏移。Liou和Brennan（1997）的模型眼没有定义的视网膜形状，但半径为-12毫米，则呈现轻微近视移位。将半径改为-12.4毫米后，偏移量变得与我的模型眼类似。我的模型眼在水平和垂直子午线方向上显示出类似的90-180°散光J180的结果，唯一不同的是符号相反（图9B）。Liou和Brennan（1997）的模型眼具有类似的散光（请注意，这相对于视网膜曲率半径来说相对不敏感）。其他三个模型眼的散光量更小。模型眼随角度平方的散光变化速率，忽略符号，为Lotmar眼0.0010D/度2，Koojman和Navarro眼0.0012D/度2，Liou和Brennan眼和我的模型眼0.0016D/度2。Atchison等人（2006年）的最近一项实验研究具有0.0010-0.0011 D/degrees2的斜率。这表明我的模型和Liou& Brennan（1997）的模型高估了平均散光约50%，而来自该研究的屈光度（D）图（未显示）正确估计了散光的平均量。

图8：

对于6毫米口径入射瞳孔，Model 1的Zernike像差系数c0 4（lm）随近视度数的变化情况，包括整个眼球和角膜前表面。还显示了Lotmar（1971年）、Koojman（1983年）、Navarro等人（1985年）和Liou和Brennan（1997）正视眼模型的系数。

图9：

正常模型眼在水平和垂直子午线上至40度视野角的周边屈光度。将结果与其他模型眼在水平子午线方向上进行比较。A）平均球体M表明，我的模型眼在水平和垂直子午线方向上显示出类似的结果，40度时近视偏移量约为-0.9D。B）90-180°散光J180表明，我模型眼在水平和垂直子午线方向上显示出类似的结果，符号相反。

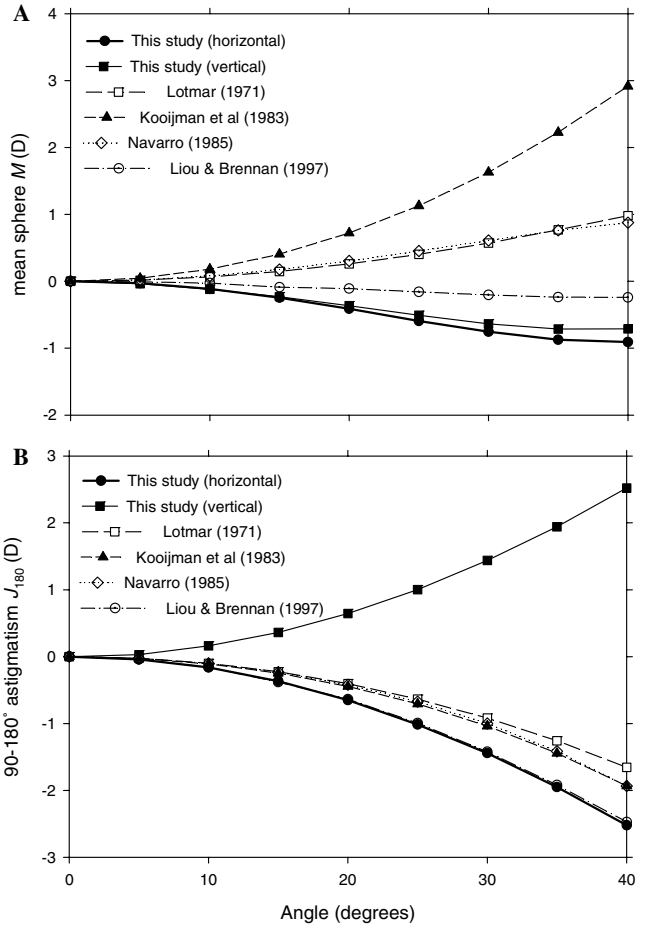

Fig. 9. Peripheral refraction of Model 1 as a function of peripheral angle for emmetropia. Both horizontal and vertical visual field results are shown. (A) Mean refraction M, (B) 0–180° astigmatism J_{180}. For the horizontal meridian, results are also shown for the model eyes of Lotmar (1971), Kooijman (1983), Navarro et al. (1985) and Liou and Brennan (1997). The Lotmar eye has a spherical retina with a radius of curvature of −12.3 mm, the Kooijman eye has two retina possibilities and I used the spherical retina with a radius of curvature of −10.8 mm, the Navarro eye has a spherical retina with a radius of curvature of −12.0 mm, and the Liou and Brennan eye has no retina shape but was given a spherical retina with a radius of curvature of −12.0 mm.

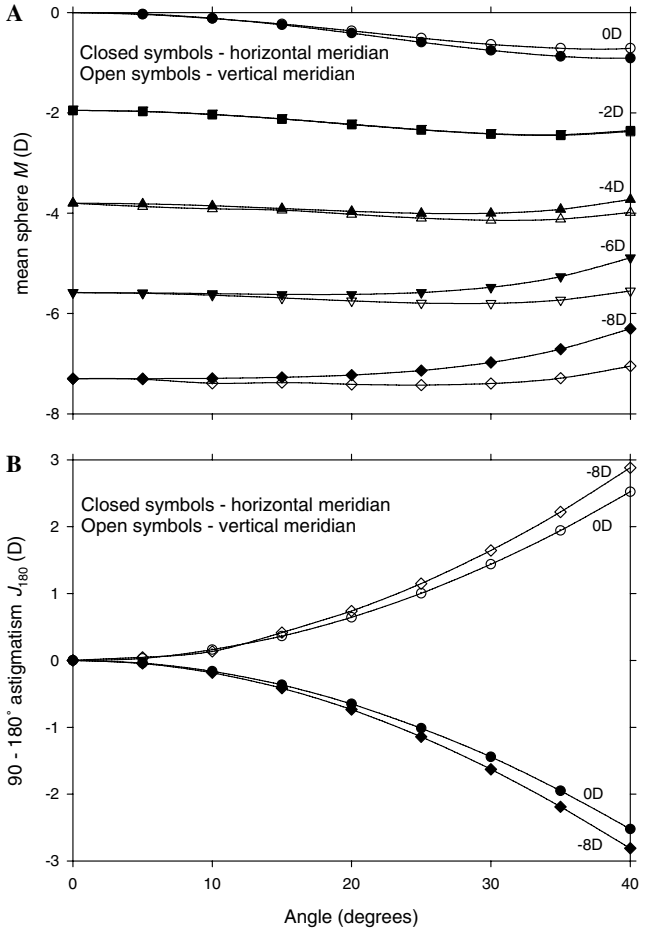

Fig. 10. Peripheral refraction of Model 1 as a function of peripheral angle for emmetropia and 2 D, 4 D, 6 D and 8 D myopia. Both horizontal (closed symbols) and vertical (open symbols) visual field results are shown. (A) Mean refraction M, (B) 0–180° astigmatism J_{180}. Note that M at fixation is slightly different from the labelled myopia, because the former is the correction at the front of the eye rather than at the spectacle plane.

other models predict astigmatism well. To the contrary, the first two models (in particular my model) give much better predictions of M than the latter model eyes.

Fig. 10 shows the peripheral refractions for my model eye along the horizontal and vertical meridians out to 40° visual field angle as a function of refraction. Fig. 10A shows mean sphere M for 0, −2, −4, −6, and −8 D myopic corrections. As myopia increases, there is a reduction in the relative peripheral myopia and eventually a relative peripheral hypermetropia occurs. The rate of change of this is much greater along the horizontal meridian than along the vertical meridian, with the change to relative hypermetropia occurring at approximately −4 D and −6 D, respectively. This difference is because of the different rates of flattening of the retina in the meridians as myopia increases (Eqs. (27) and (28)). For −8 D at 40° visual field, the horizontal meridian has 1 D relative hypermetropia. The relative hypermetropic shift for the horizontal meridian is less than that of the mean data of Atchison et al. (2006) for which the relative hypermetropic shift begins at about 2 D myopia. Although the model predicts a slow change in this direction in the case of vertical meridian, the mean experimental results do not change. Fig. 10B shows results for 90–180° astigmatism J_{180}. The model predicts a slight increase with increase in myopic correction to −8 D, but this is small (0.3 D at 40°). By contrast, Atchison et al.'s (2006) study determined that there was a small reduction in astigmatism of about 0.3 D along the horizontal, but not the vertical, meridian.

3.1.4. Peripheral refraction with ophthalmic correction

If relative hypermetropic shifts into the periphery in corrected myopic eyes might stimulate further eye growth (Wallman & Winawer, 2004), it is of considerable interest to know how variations in design of ophthalmic lenses might affect this shift. To investigate this, I have corrected a 4 D myopic eye with spectacle and contact lenses. The spectacle lenses are fitted 12 mm in front of the eye and have

Peripheral Refraction in Myopic Eyes

近视眼的周边屈光不正

None

Other models predict astigmatism well. To the contrary, the first two models (in particular my model) give much better predictions of M than the latter model eyes. Fig. 10 shows the peripheral refractions for my model eye along the horizontal and vertical meridians out to 40□ visual field angle as a function of refraction.

其他模型可以较好地预测散光。相反的是，前两个模型（尤其是我的模型）比后一个模型给出了更好的M的预测。图10显示了我的模型眼的周边屈光度沿水平和垂直子午线延伸到40□的视野角度的曲线。

Fig. 10A shows mean sphere M for 0, □2, □4, □6, and □8 D myopic corrections. As myopia increases, there is a reduction in the relative peripheral myopia and eventually a relative periph- eral hypermetropia occurs. The rate of change of this is much greater along the horizontal meridian than along the vertical meridian, with the change to relative hyperme- tropia occurring at approximately □4 D and □6 D, respectively. This difference is because of the different rates of flattening of the retina in the meridians as myopia increases (Eqs. (27) and (28)). For □8 D at 40□ visual field, the horizontal meridian has 1 D relative hypermetropia. The relative hypermetropic shift for the horizontal meridian is less than that of the mean data of Atchison et al. (2006) for which the relative hypermetropic shift begins at about 2 D myopia. Although the model predicts a slow change in this direction in the case of vertical meridian, the mean experimental results do not change.

图10A显示0、-2、-4、-6和-8 D近视矫正的平均球M。随着近视的增加，相对外周的近视程度减少，最终相对外周的远视程度增加。这种变化随着水平子午线而不是垂直子午线发生，相对远视的变化分别在大约-4 D和-6 D时发生。这种差异是因为随着近视的增加，子午线的视网膜变平的速度不同（方程（27）和（28））。在40°的视野下，-8 D的水平子午线有1 D的相对远视状态。水平子午线的相对远视移位小于Atchison等人（2006）的平均数据的相对远视移位开始于大约2 D的近视。尽管模型预测在垂直子午线方向上这种变化是缓慢的，但平均实验结果不会改变。

Fig. 10B shows results for 90–180□ astigmatism J180. The model predicts a slight increase with increase in myopic correction to □8 D, but this is small (0.3 D at 40□). By contrast, Atchison et al.'s (2006) study determined that there was a small reduction in astigmatism of about 0.3 D along the horizontal, but not the vertical, meridian.

Fig.10B显示了90–180°的星形J180成像结果。该模型预测眼球度数在-8D范围内矫正后有轻微的增加，但是增加量很小（40°时为0.3D）。相比之下，Atchison等人在2006年的研究中发现，沿着水平子午线会有约0.3D的小幅度近视治疗后的近视度数减少，而沿着垂直子午线没有改善。None

Peripheral Refraction with Ophthalmic Correction

使用眼科矫正进行周边屈光不正测试

眼别	M矫正	J0矫正	J45矫正
右眼	None	None	None
左眼	None	None	None

If relative hypermetropic shifts into the periphery in corrected myopic eyes might stimulate further eye growth (Wallman & Winawer, 2004), it is of considerable interest to know how variations in design of ophthalmic lenses might affect this shift. To investigate this, I have corrected a 4 D myopic eye with spectacle and contact lenses. The spectacle lenses are fitted 12 mm in front of the eye and have

|如果矫正近视眼中的相对远视转移到视网膜边缘可能会刺激进一步的眼睛生长（Wallman& Winawer，2004），则了解眼科镜片设计的变化如何影响该转移是非常重要的。为了研究这一点，我用眼镜和隐形眼镜矫正了一个4D的近视眼。眼镜是放在眼睛前面12毫米的。其中：|

Type of Lens	Location of Lens
Spectacle Lens	12 mm in front of eye
Contact Lens	On eye surface

None

Mean sphere M (D)	-8	-6	-4	-2	0
Angle (degrees)	0	10	20	30	40
90-180° astigmatism J180 (D)	-3	-2	-1	0	1

平均球面 M (D)	-8	-6	-4	-2	0

平均球面 M (D)	-8	-6	-4	-2	0
角度 (度)	0	10	20	30	40
90-180°散光J180 (D)	-3	-2	-1	0	1

closed symbols represent horizontal meridian and open symbols represent vertical meridian.

闭合符号代表水平子午线，开放符号代表垂直子午线。

Fig. 9 shows peripheral refraction of Model 1 as a function of peripheral angle for emmetropia. Both horizontal (closed symbols) and vertical (open symbols) visual field results are shown. Fig. 9A also shows the results for the model eyes of Lotmar (1971), Kooijman et al. (1983), Navarro et al. (1985) and Liou and Brennan (1997). The Lotmar eye has a spherical retina with a radius of curvature of □12.3 mm, the Kooijman eye has two retina possibilities and I used the spherical retina with a radius of curvature of □10.8 mm, the Navarro eye has a spherical retina with a radius of curvature of □12.0 mm, and the Liou and Brennan eye has no retina shape but was given a spherical retina with a radius of curvature of □12.0 mm.

图9展示了模型1在视网膜正常的情况下，随着外周角度而变化的周边屈光度。同时展示了水平方向（实心符号）和垂直方向（空心符号）的视野结果。图9A还展示了Lotmar（1971）、Koojman等人（1983）、 Navarro等人（1985）和Liou和Brennan（1997）的模型眼的结果。Lotmar眼具有半径为12.3 mm的球形视网膜，Kooijman眼有两个视网膜可能性，并且我选用了具有半径为10.8 mm的球形视网膜，Navarro眼具有半径为12.0 mm的球形视网膜，而Liou和Brennan眼没有视网膜形状，但是给定了半径为12.0 mm的球形视网膜。

(A) Mean refraction M, (B) 0–180□ astigmatism J180. Note that M at fixation is slightly different from the labelled myopia, because the former is the correction at the front of the eye rather than at the spectacle plane.

(A) 平均折光度M，(B) 0-180度散光J180。请注意，在视觉注视时，M略有不同于标记的近视度数，因为前者是在眼前的校正而不是在镜片面上。 None

a 1.5 refractive index, with one lens having a flat front surface and the other having a 4 D front surface power. The contact lenses have been taken as rigid contact lenses with a refractive index of 1.492. Both have a spherical back surface with the same radius of curvature as that of the anterior cornea. One has a spherical front surface (conic asphericity $Q = 0$) and the other has a prolate (flattening) front surface ($Q = -0.25$). A thin tear film of refractive index 1.336 is placed between the cornea and the contact lenses.

Fig. 11 shows the peripheral refractions along the horizontal meridian of the 4 D myopic eye corrected with the spectacle and contact lenses. Fig. 11A shows the mean sphere M. There is virtually no change in refraction of this eye, when uncorrected, into the periphery (Fig. 10A). The plano base spectacle lens produces an (unwanted) hypermetropic shift of up to 1 D by 40°, whereas the 4 D base spectacle lens eliminates this shift and can be considered to be a more appropriate design. The spherical contact lens shows a myopic shift which is eliminated by the aspheric contact lens—the former lens might work better as a myopia inhibiting lens. As well as their influences on peripheral M, these lenses have different effects on astigmatism J_{180} (Fig. 11B). The spectacle lenses reduce the astigmatism from that obtained with the uncorrected eye, but only marginally in the case of the 4 D base lens. The spherical contact lens increases astigmatism slightly, while the aspheric lens decreases it slightly. Fig. 11 demonstrates that spectacles and contact lenses can be designed to manipulate off-axis refractions. Spectacle lenses will have minimum effects on on-axis spherical aberration, provided that spectacle magnification effects are taken into account (Atchison & Charman, 2005), but this is not the case for contact lenses. The spherical and aspheric contact lenses provide aberration co-efficients c_4^0 of +0.09 and −0.08 μm, respectively, which represents a decrease in absolute magnitude from +0.12 μm occurring for the uncorrected eye in Fig. 8 (6 mm diameter entrance pupils).

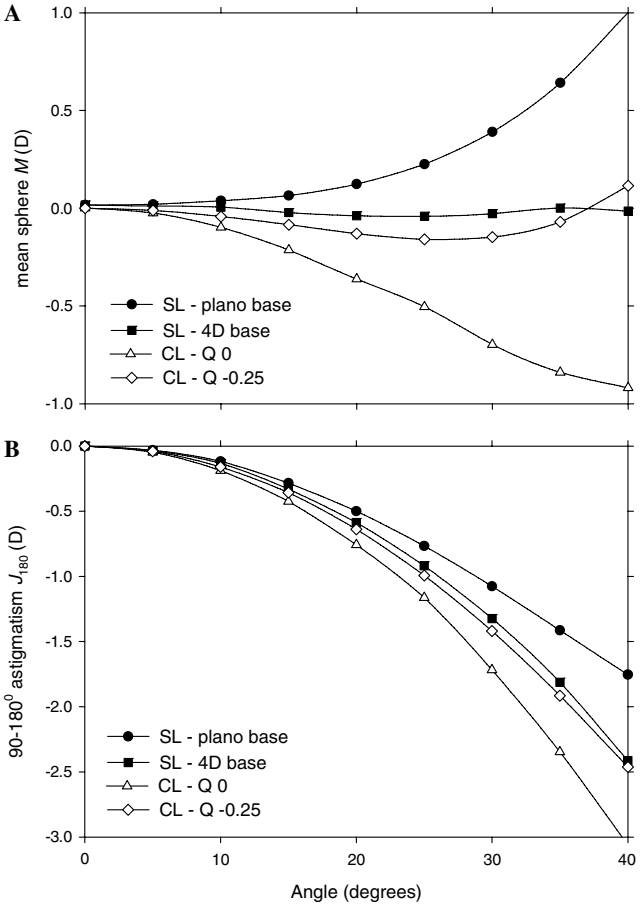

Fig. 11. Peripheral refraction of Model 1 as a function of peripheral angle for a 4 D myopia with different thin ophthalmic corrections: spectacle lens with flat front surface (SL, plano base), spectacle lens with +4 D front surface (SL, 4 D base), spherical contact lens (CL, $Q = 0$), and contact lens with aspheric front surface (CL, $Q = -0.25$). Both horizontal and vertical visual field results are shown. (A) Mean refraction M, (B) 90–180° astigmatism J_{180}.

3.2. Model 2 (tilted lens and tilted and decentred retina)

3.2.1. On-axis spherical aberration (6 mm pupil) and coma (6 mm entrance pupil)

Spherical aberrations are within 1% of those of the centred Model 1. This model now demonstrates appreciable horizontal coma, with a Zernike co-efficient c_3^1 of approximately 0.19 μm for myopia up to 10 D. Horizontal coma varies considerably between people, with a mean close to zero (Porter et al., 2001; Thibos et al., 2002; Wang & Koch, 2003; Wang et al., 2003), and with a standard deviation for 6 mm pupils of approximately 0.10 μm (Thibos et al., 2002; Wang & Koch, 2003). Thus this model tends to overestimate coma in real eyes.

3.2.2. Peripheral refraction

Fig. 12 shows the peripheral refractions along the horizontal and vertical meridians out to 40° eccentricity for emmetropic and 4 D myopic eyes. Also shown are "mean" data from the study by Atchison et al. (2006) for these levels of myopia. These mean data were determined, for each peripheral angle, from a linear regression of peripheral refraction versus myopia. In the cases of the astigmatisms, the changes relative to the fixation values, rather than the absolute values, were used. The results are similar to those obtained for emmetropic and 4 D myopic groups (Figs. 2–4) by Atchison et al. (2006), but the fluctuations in J_{45} with change in angle are reduced.

Fig. 12A shows the mean sphere M for these eyes. Both the emmetropic and myopic model eyes show symmetry for the horizontal visual field with similar changes out to the periphery as was obtained for the centred Model 1 (Fig. 10). However, there is asymmetry in the vertical visual field for these, with the emmetropic eye having a flat field inferiorly and a myopic field superiorly, and the myopic eye having a slight hypermetropic shift into the inferior field and a myopic shift into the superior field. The model eyes match the experimental results well for the horizontal meridian, but not as well as for the vertical meridian where

Model 1

模型1

This model considers a 1.5 refractive index and contact lenses with a refractive index of 1.492. The lenses have a flat front surface and a 4 D front surface power, respectively. A thin tear film of refractive index 1.336 is between the cornea and the contact lenses. Both lenses have a spherical back surface with the same radius of curvature as that of the anterior cornea. One lens has a spherical front surface (conic asphericity Q = 0), and the other has a prolate (flattening) front surface (Q = -0.25). Fig. 11 shows the peripheral refractions along the horizontal meridian of the 4 D myopic eye corrected with the spectacle and contact lenses.

该模型考虑了1.5的折射率，折射率为1.492的隐形眼镜。镜片分别具有平坦的前表面和4D前表面功率。在角膜和隐形眼镜之间有一层折射率为1.336的薄泪膜。两个镜片都具有球形背面，其曲率半径与前角膜相同。一个镜片具有球形的前表面（圆锥非光滑度Q = 0），另一个镜片具有前向短轴（扁平）的前表面（Q =-0.25）。图11显示了在水平子午线上校正4D近视眼的镜片和隐形眼镜的周边屈光度。

Fig. 11

图11

Peripheral refraction of Model 1 as a function of peripheral angle for a 4D myopia with different thin ophthalmic corrections: spectacle lens with flat front surface (SL, plano base), spectacle lens with +4 D front surface (SL, 4 D base), spherical contact lens (CL, Q = 0), and contact lens with aspheric front surface (CL, Q = -0.25). Both horizontal and vertical visual field results are shown.

视野角度 / 周边折射率	SL，平面底部	SL，+4D底部	球面接触镜	CL，Q = -0.25
水平视野	None	None	None	None
垂直视野	None	None	None	None

(A) Mean refraction M, (B) 90-180° astigmatism J180.

(A) 平均屈光度 M，(B) 90-180° 散光 J180。

The plano base spectacle lens produces an (unwanted) hypermetropic shift of up to 1 D by 40°, whereas the 4 D base spectacle lens eliminates this shift and can be considered to be a more appropriate design. The spherical contact lens shows a myopic shift that is eliminated by the aspheric contact lens- the former lens might work better as a myopia inhibiting lens. These lenses have different effects on astigmatism J180. The spectacle lenses reduce the astigmatism from that obtained with the uncorrected eye, but only marginally in the case of the 4 D base lens. The spherical contact lens increases astigmatism slightly, while the aspheric lens decreases it slightly.

plano基础眼镜镜片在40°内会产生1D的远视偏移（不希望出现），而4D基础眼镜镜片可以消除这种偏移，被认为是更合适的设计。球面隐形眼镜会产生近视偏移，而非球面隐形眼镜可以消除偏移，前者镜片可能更适合作为近视抑制镜片。这些镜片对于J180散光有不同的影响。眼镜镜片可以降低散光，但仅在4D基础镜片的情况下略微降低。球面隐形眼镜会略微增加散光，而非球面镜片会略微减小散光。

Model 2 (tilted lens and tilted and decentred retina)

模型二（倾斜透镜和倾斜偏心视网膜）

This model demonstrates appreciable horizontal coma, with a Zernike co-efficient c1 3 of approximately 0.19 lm for myopia up to 10 D. Fig. 12 shows the peripheral refractions along the horizontal and vertical meridians out to 40° eccentricity for emmetropic and 4 D myopic eyes. Also shown are "mean" data from the study by Atchison et al. (2006) for these levels of myopia. These mean data were determined, for each peripheral angle, from a linear regression of peripheral refraction versus myopia. In the cases of the astigmatisms, the changes relative to the fixation values, rather than the absolute values, were used. The results are similar to those obtained for emmetropic and 4 D myopic groups by Atchison et al. (2006), but the fluctuations in J45 with change in angle are reduced.

该模型演示了明显的水平球差，近视度数在10D以下时，第一阶泽尼克系数C1约为0.19 lm。图12展示了视网膜周边在水平和垂直子午线上，从0°到40°偏心度的屈光度对比，包括正视和4D近视眼。同时，展示了Atchison等人（2006）对这些度数的“平均”数据。对于每个周边视角，这些平均数据是通过周边屈光度与近视度数的线性回归确定的。在散光的情况下，使用相对于定位值而非绝对值的变化量。这些结果与Atchison等人（2006）对正视和4D近视组的结果相似，但旋转45度（J45）随角度变化的波动减少了。

Fig. 12

None

Peripheral refraction of Model 2 for emmetropic and 4 D myopic eyes. Both the emmetropic and myopic model eyes show symmetry for the horizontal visual field. However, there is asymmetry in the vertical visual field for these. The emmetropic eye has a flat field inferiorly and a myopic

field superiorly, and the myopic eye has a slight hypermetropic shift into the inferior field and a myopic shift into the superior field. The model eyes match the experimental results well for the horizontal meridian, but not as well as for the vertical meridian.

Model 2 的周边屈光度对正常眼及4D近视眼的影响。正常眼与近视眼在水平视野方面表现对称，但垂直视野上存在不对称性。正常眼下方视野平坦，上方视野近视，而近视眼则有轻微的远视偏移下方视野和近视偏移上方视野。模型眼在水平子午线上的效果与实验结果相符较好，但在垂直子午线上的效果略逊。

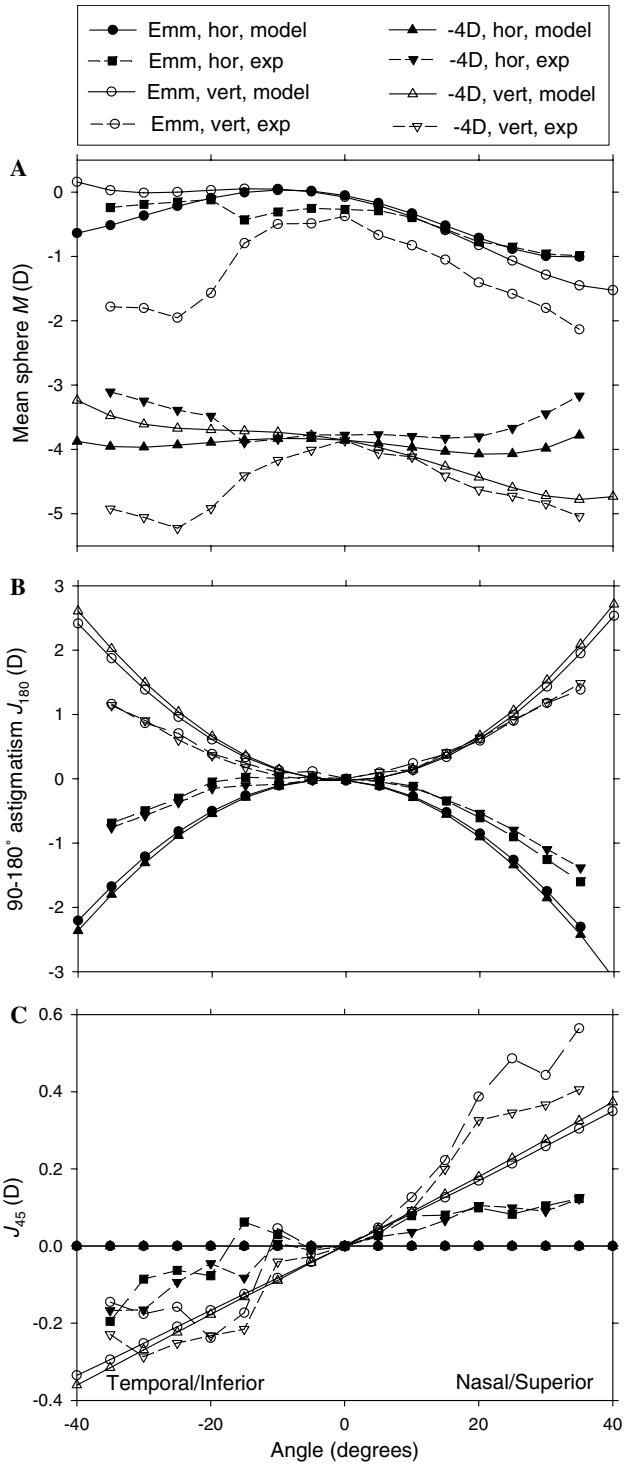

Fig. 12. Peripheral refraction of Model 2 and for average data from Atchison et al. (2006) as a function of peripheral angle for emmetropia and 4 D myopia. Both horizontal and vertical visual field results are shown. (A) Mean refraction M, (B) 90–180° astigmatism J_{180}, (C) 45–135° astigmatism J_{45}.

the experimental data shows more symmetry than the model.

Fig. 12B shows the J_{180} astigmatism for these eyes. Both emmetropic and myopic model eyes have similar magnitudes, and this is unaffected by whether measurement is along the horizontal or vertical meridian (except for change in sign). The plots are similar to those for centred Model 1 (Fig. 10B) except for shifts in the turning points of the functions to (−)2.7° temporal visual field and (−)0.3° inferior visual field. As for Model 1, the steepnesses of the plots for Model 2 are about 50% more than the experimental results. However, the shifts of the turning points from fixation are less than for the experimental eyes which are approximately −5° to −6° temporally and −2.8° to −2.5° inferiorly.

Fig. 12C shows the J_{45} astigmatism for these eyes. Because the models show neither tilt nor decentration of the elements vertically, the model predicts no astigmatism along the horizontal meridian. The prediction for the vertical meridian is a slope of 0.009 D/° for both emmetropic and 4 D myopic eyes. Experimentally, there is considerable noise but the slope from regression is about 0.004 D/° horizontally and 0.011 D/° vertically, so the model results are a reasonable prediction of the oblique astigmatism for the vertical meridian.

4. Discussion

I have designed new model eyes that include refraction related changes as derived from recent experimental data of myself and colleagues and from others. Features include a gradient index lens and horizontal lens tilt. The parameters that I have found to change with refraction are anterior corneal radius, vitreous length, retinal shape and retinal decentration. Equations dependent upon refraction are Eqs. (1), (19), (20), (22)–(28), (33) and (34). The models are capable of being "fine turned" later as more or better optical data becomes available (some of which might show that additional parameters change with refraction).

One version of the eye model has centred optical elements. This model demonstrates some reasonable prediction of changes with refraction. It gives a good prediction of the spherical aberration of real emmetropic eyes (Fig. 8), although to be fair the asphericity of the posterior lens surface was selected to achieve this purpose. The model predicts increases in spherical aberration with degree of myopia, but this has not been supported experimentally. It gives a good estimate of the observed myopic peripheral shift in mean sphere M in emmetropic eyes along both horizontal and vertical meridians of the visual field (Fig. 9). With increase in myopia, this observation changes to a relative hypermetropic shift along the horizontal meridian but not along the vertical meridian (Atchison et al., 2006). The model does a reasonable job of predicting the changes in the horizontal meridian, but it incorrectly predicts a shift, although much reduced, along the vertical meridian (Fig. 10). The model overestimates peripheral astigmatism by about 50% (Figs. 9 and 10).

This first model was used to look at the effects of altering designs of ophthalmic lenses on peripheral refraction in light of claims that relative peripheral hypermetropia might be a stimulus in eye growth. Manipulating the base curves of spectacle lenses or asphericities of contact lens surfaces

Peripheral Refraction Model and Experimental Data Comparison

Introduction

The experimental data shows more symmetry than the model. Fig. 12B shows the J180 astigmatism for these eyes. Both emmetropic and myopic model eyes have similar magnitudes, and this is unaffected by whether measurement is along the horizontal or vertical meridian (except for change in sign). The plots are similar to those for centred Model 1 (Fig. 10B) except for shifts in the turning points of the functions to (±)2.7° temporal visual field and (±)0.3° inferior visual field. As for Model 1, the steepnesses of the plots for Model 2 are about 50% more than the experimental results. However, the shifts of the turning points from fixation are less than for the experimental eyes which are approximately ±5° to ±6° temporally and ±2.8° to ±2.5° inferiorly.

视野周边屈光参考模型和实验数据对比

介绍

实验数据比模型更对称。图12B展示这些眼睛的J180散光。远视眼和近视眼模型眼的幅度相似，并且与水平或垂直子午线上的测量无关（除了符号的改变）。这些图与居中的模型1（图10B）相似，只是函数的转折点发生了位移，到(±)2.7°的视野和(±)0.3°的下视野。和模型1一样，模型2的图的陡峭度比实验结果高约50％。然而，与实验眼的转折点相比，转折点从固定点的位移要小得多，大约为±5°到±6°的时间轴和±2.8°到±2.5°的下轴。

Fig. 12C shows the J45 astigmatism for these eyes. Because the models show neither tilt nor decentration of the elements vertically, the model predicts no astigmatism along the horizontal meridian. The prediction for the vertical meridian is a slope of 0.009 D/° for both emmetropic and 4 D myopic eyes. Experimentally, there is considerable noise but the slope from regression is about 0.004 D/° horizontally and 0.011 D/° vertically, so the model results are a reasonable prediction of the oblique astigmatism for the vertical meridian.

Fig. 12C展示了这些眼睛的J45散光。由于模型在垂直方向上既没有倾斜也没有离心，模型预测沿水平子午线没有散光。对于垂直子午线的预测是等瞳孔和4D近视眼的斜率为0.009 D/°。实验数据存在相当大的噪声，但是从回归得出的斜率水平约为0.004 D/°，垂直约为0.011 D/°，因此模型结果是对于垂直子午线的斜散光的合理预测。

Discussion

I have designed new model eyes that include refraction-related changes as derived from recent experimental data of myself and colleagues and from others. Features include a gradient index lens and horizontal lens tilt. The parameters that I have found to change with refraction are anterior corneal radius, vitreous length, retinal shape, and retinal decentration. Equations dependent upon refraction are Eqs. (1), (19), (20), (22)–(28), (33) and (34). The models are capable of being "fine-tuned" later as more or better optical data becomes available (some of which might show that additional parameters change with refraction).

讨论

我已经设计了包括折射相关变化的新模型眼睛，这些变化是从我和同事以及其他人最近的实验数据中得出的。其中的特点包括梯度折射率透镜和水平透镜倾斜。我发现随着折射变化而改变的参数包括前角膜半径、玻璃体长度、视网膜形状和视网膜偏离。依赖于折射的方程式有方程（1）、（19）、（20）、（22）-（28）、（33）和（34）。这些模型能够在更多或更好的光学数据可用的情况下进行“精细调整”（其中一些可能显示其他参数随着折射的改变而改变）。

One version of the eye model has centred optical elements. This model demonstrates some reasonable prediction of changes with refraction. It gives a good prediction of the spherical aberration of real emmetropic eyes (Fig. 8), although to be fair, the asphericity of the posterior lens surface was selected to achieve this purpose. The model predicts increases in spherical aberration with the degree of myopia, but this has not been supported experimentally. It gives a good estimate of the observed myopic peripheral shift in mean sphere M in emmetropic eyes along both horizontal and vertical meridians of the visual field (Fig. 9). With an increase in myopia, this observation changes to a relative hypermetropic shift along the horizontal meridian but not along the vertical meridian (Atchison et al., 2006). The model does a reasonable job of predicting the changes in the horizontal meridian, but it incorrectly predicts a shift, although much reduced, along the vertical meridian (Fig. 10). The model overestimates peripheral astigmatism by about 50% (Figs. 9 and 10).

眼模型的一种版本具有中心的光学元件。该模型展示了一些关于折射变化的合理预测。它对实际正视眼球的球面像差有很好的预测（图8），尽管公平地说，选择了后面镜片表面的非球面度来达到此目的。该模型预测近视程度的增加会导致球面像差的增加，但这在实验上尚未得到支持。它对视野水平和垂直两个经线方向上视网膜平均球面M 的近视外周偏移有良好的估计（图9）。随着近视的增加，这种观察结果在水平经线上变成相对的远视偏移，但在垂直经线上没有变化（Atchison et al.，2006）。该模型合理地预测了水平经线的变化，但是却错误地预测了垂直的偏移，尽管偏移量大大降低（图10）。该模型高估了大约50%的外周散光（图9和10）。

This first model was used to look at the effects of altering designs of ophthalmic lenses on peripheral refraction in light of claims that relative

peripheral hypermetropia might be a stimulus in eye growth. Manipulating the base curves of spectacle lenses or asphericities of contact lens surfaces.

这个模型是用来研究改变眼科镜片设计对边缘屈光度的影响的，因为有声称相对边缘远视可能是眼睛生长的刺激。通过调整眼镜镜片的基面曲线或接触镜表面的非球面度数来操作。None

Figures	**Data**
Fig. 12A	Mean refraction M
	90-180° Astigmatism J180
	45-135° Astigmatism J45
Fig. 12B	J180 Astigmatism
Fig. 12C	J45 Astigmatism

图表	**数据**
Fig. 12A	平均屈光度 M
	90-180° 散光度 J180
	45-135° 散光度 J45
Fig. 12B	J180 散光度
Fig. 12C	J45 散光度

Atchison, D. A. (2006). Comparison of models of human eye. Vision research, 46(14), 2236-2250.

None

can make considerable changes to the mean sphere M (Fig. 11).

A second version of the model has a tilted lens and tilted and decentred retinas. This version had limited success in predicting changes in peripheral refraction of average eyes (Fig. 12). In particular, the model over-exaggerates the asymmetries in mean sphere M found in experimental results. To the contrary, the temporal and inferior shift in the turning point of astigmatism from fixation is underestimated, although the oblique component of astigmatism J_{45} is reasonably predicted for the vertical meridian.

4.1. Some shortcomings of the models

One major issue with designing model eyes is to show variation in eyes without losing generality. The next stage in sophistication here is to use a toroidal cornea.

The line of sight has been used as the reference axis, but its position is not a constant relative to other parameters. I have identified its position relative to the cornea keratometric axis, but the pupil centre is likely to be located more temporally from this as pupil size increases (Wyatt, 1995; Yang, Thompson, & Burns, 2002). Resolution is insufficient to determine the pupil centre from MRI images, and I have assumed that this passes through the centre of the lens.

Neither decentration nor tilt of the cornea has been included in the model. A better reference position for the cornea centre would have been the "apex", which is the steepest part of the cornea for a flattening cornea. Identifying the apex and measuring the cornea relative to it requires eccentric fixation relative to the fixation target of corneal topographers (Mandell, Chiang, & Klein, 1995). Future work with modelling should use the apex as the cornea reference point with the appropriate decentrations and tilts relative to the line of sight. Mandell et al. (1995) obtained a mean difference between the keratometric axes and corneal apices of 0.62 ± 0.23 mm, with the majority of keratometric axes being above the corresponding apices, a mean difference between the apex and corneal sighting centre of 0.82 ± 0.57 mm with the majority of their subjects having apices below the corneal sighting centres, and a mean difference between the keratometric axes and corneal sighting centres of 0.38 ± 0.10 mm with the majority of their subjects having keratometric axes below and nasal to corneal sighting centres. I find the mean keratometric axis to be above the mean corneal sighting centre. The equations relating the location of the keratometric axis relative to the corneal sighting centre are:

$$\mathrm{Dec}_{C1x}\,(\mathrm{mm}) = -0.176 - 0.014SR \quad (n = 119, \mathrm{adj}.R^2 = 0.054, p = 0.006), \tag{38}$$

$$\mathrm{Dec}_{C1y}\,(\mathrm{mm}) = +0.071 - 0.003SR \quad (n = 119, \mathrm{adj}.R^2 = -0.003, p = 0.432), \tag{39}$$

with the keratometric axis becoming less nasally decentred with increase in myopia. The vertical decentration is not affected significantly by refraction, but the mean of $+0.079 \pm 0.120$ mm is significantly different from zero ($t = 7.16$, $n = 119$, $p < 0.001$).

Note added in proof

The models described in this paper had a constant posterior corneal radius of curvature of 6.4 mm (Section 2.3.2.1). However, in a recent study using Scheimpflug photography, Dubbelman, Vicam, and Van der Heijde (2006) found that the posterior surface radius of curvature changed significantly at $\Delta R_{C2}\,(\mathrm{mm}) = +0.02SR$. This reduces the effect of the steepening of the anterior corneal surface with increase in myopia. Although this change should be included in future optical models of myopia, I found that it had only small effects of dependent model parameters and optical performance.

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Title: Optical models and eye morphology

标题：光学模型与眼睛形态

Structure	Description	Function
Cornea	Transparent outermost layer	Refract light into the eye
Iris	Colored ring-shaped muscle	Regulate amount of light entering the eye
Lens	Clear, flexible structure	Focus light onto the retina
Retina	Light-sensitive layer	Convert light into neural signals
Optic nerve	Bundle of nerves	Transmit neural signals to the brain

结构 | 描述 | 功能 | --- | --- | --- | | 角膜 | 透明的最外层 | 折射光线进入眼睛 | | 虹膜 | 有色的环形肌肉 | 调节进入眼睛的光量 | | 晶状体 | 清晰、柔软的结构 | 将光线聚焦到视网膜上 | | 视网膜 | 敏感于光的层 | 将光线转化为神经信号 | | 视神经 | 神经束 | 将神经信号传输到大脑 |

There are two versions of the eye model discussed in this paper. The first version shows a mean sphere M, which can cause considerable changes (Fig. 11). The second version has a tilted lens and decentred retinas which had limited success in predicting changes in peripheral refraction (Fig. 12). However, this model has some shortcomings. For example, it over-exaggerates asymmetries in mean sphere M, although it reasonably predicts the oblique component of astigmatism J45 for the vertical meridian.

本论文讨论了眼睛模型的两个版本。第一个版本显示了平均球体M，它可以引起相当大的变化（图11）。第二个版本有一个倾斜的晶状体和离心视网膜，它在预测周边屈光度变化方面取得了有限的成功（图12）。但是，这个模型有一些缺点。例如，它过分夸大了平均球体M的不对称性，尽管它可以合理地预测倾斜的散光J45在垂直子午线上的组成部分。

One challenge in designing model eyes is showing variation without losing generality. To improve this, future modelling should use a toroidal cornea. The position of the line of sight is not constant relative to other parameters. Though the position relative to the cornea keratometric axis has been identified, the pupil centre is not fixed and is more temporal as pupil size increases. The location of the cornea reference point could be better identified as the "apex," the flattening cornea's steepest part. Identifying the apex requires eccentric fixation relative to the fixation target of corneal topographers. Decentration and tilt of the cornea were not included in the model.

设计模型眼睛的一个挑战是在保持一般性的同时展现变化。为了改进这一点，未来的建模应该使用一个环形角膜。注视线的位置相对于其他参数不是恒定的。尽管相对于角膜角轴的位置已经确定，瞳孔中心并不固定，而且随着瞳孔大小的增加更趋向于颞侧。角膜参考点的位置可以更好地确定为“顶点”，即倒扁角膜最陡峭的部分。确定顶点需要相对于角膜地形图的凝视目标偏心凝视。偏心和倾斜的角膜未包括在这个模型中。

The models described in this paper have a constant posterior corneal radius of curvature of 6.4mm in section 2.3.2.1. Future optical models of myopia should include a change in posterior surface radius of curvature found in a recent study using Scheimpflug photography. The change does have small effects on dependent model parameters and optical performance.

本文中描述的模型在2.3.2.1节中具有恒定的6.4mm后角膜曲率半径。未来的近视光学模型应该包括最近使用Scheimpflug摄影技术发现的后表面曲率半径的变化。该变化对依赖模型参数和光学性能有小的影响。None

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