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Optical models for human myopic eyes

David A. Atchison *

School of Optometry, Queensland University of Technology, Victoria Park Road, Kelvin Grove, Qld 4059, Australia

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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

* Fax: +61 7 3864 5665.
E-mail address: d.atchison@qut.edu.au.

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

人类近视眼的光学模型

大卫·阿奇森

昆士兰科技大学视光学院, 澳大利亚昆士兰省开尔文·格罗夫维多利亚公园路4059号

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摘要

本文采用作者调查和其他研究的数据构建折射依赖模型。这些模型包括梯度折射率透镜以及非球面角膜、透镜和视网膜表面。随着折射率变化的元素包括前房角膜半径、玻璃体长度和视网膜形状（顶点曲率半径和非球形度）以及偏心。模型的两个版本是中心对称的光学元件和透镜和视网膜的倾斜及偏心。中心模型预测近视球形像差的增加。它预测了近期实验研究中观察到的水平和垂直子午线周边平均球的相对变化。它高估了大约50%的周边散光。偏心版本在预测平均眼周边屈光度变化方面具有有限的成功。

关键词：像差；散光；近视；眼的光学；周边屈光度；屈光错误；示意眼

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; Pomera- ntzeff, Rankratov, Wang, & Dufault, 1984). With the advent of more knowledge about the gradient index struc- ture and advances in the ability to trace through gradient index media, a shell structure can be replaced by two sur- faces and a gradient index media as has been done in recent models (Blaker, 1991; Liou & Brennan, 1997; Smith, Pier- scionek, & Atchison, 1991).

2. 简介 过去150年中，出现了一些人眼的光学模型，通常被称为示意眼。它们的复杂程度不同，从简化眼（一个折射表面），到三个折射表面（单面角膜和两面镜片），四个折射表面（两个角膜表面和两个镜片表面），以及允许晶状体屈光性变化的模型。最后一种类型中的第一种是Gullstrand No.1（精确）眼（Gullstrand，1909），其中通过在两个壳层镜片中建模来描述梯度屈光性，内壳层（核心）的折射率比外壳层（皮质）更高，并且拥有更加弯曲的表面。其他人使用了更复杂的壳层结构（Atchison& Smith，1995; Mutti，Zadnik& Adams，1995; Pomera- ntzeff，Rankratov，Wang& Dufault，1984）。随着对梯度屈光性结构的更多了解和追踪梯度屈光媒介的能力的提高，可以用两个表面和梯度屈光媒介来替代壳层结构，正如最近的模型所做的那样（Blaker，1991; Liou& Brennan，1997; Smith，Pier- scionek，& 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), Kooij- man (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 Atchi- son and Smith (2000). Some models allow predictions of chromatic aberrations by including media exhibiting chro- matic 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.

大多数早期眼睛模型，如Emsley的简化眼睛、Gullstrand-Emsley简化眼睛、Le Grand精确的眼睛和Gullstrand的第一眼睛，可以描述为副轴模型。这意味着它们仅对小孔径尺寸和小视场角有用，但在预测轴向像差（特别是球形像差）和偏轴像差方面仍有所欠缺（Atchison& Smith，2000）。自20世纪70年代以来，出现了"有限"眼模型，试图至少给出眼睛的某些像差的合理估计。Lotmar（1971年）、Drasdo和Fowler（1974年）、Kooij-man（1983年）、Navarro、Santamarı´a和Besco´s（1985年）和Liou和Brennan（1997年）的有限模型眼睛的预测轴向和偏轴像差的能力已经由Atchi-2020年）。一些模型允许通过包括展示色散的介质来预测色差如Le Grand的精确眼睛、Navarro的有限眼睛、Thibos等人的"印第安纳"眼睛（Thibos，Ye，Zhang和Bradley，1992）和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 www.elsevier.com/locate/visres
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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

$$R_{C1}\ (\mathrm{mm}) = 7.77 + 0.022SR \tag{1}$$

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

眼睛的示意图

Component	Symbol	Description
Cornea	()	Bends light, protects the eye
Pupil	()	Regulates the amount of light entering the eye
Iris	()	Controls the size of the pupil, gives the eye its color
Lens	()	Focuses light onto the retina
Retina	()	Contains photoreceptor cells that convert light into electrical signals
Optic Nerve	()	Transmits signals from the retina to the brain
Vitreous Humor	()	Clear gel that fills the posterior chamber of the eye
Aqueous Humor	()	Clear fluid that fills the anterior chamber of the eye

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.

具有完全适应形式的原理眼模型存在，Navarro模型眼为“自适应”，其镜头参数以及前房和玻璃体深度会随着眼睛的调节而连续变化。随着年龄的增长，晶状体变得更加厚，处于未调节状态下更加弯曲，其折射率分布也发生了变化，这已被考虑在成人眼模型的最新模型中(Atchison& Smith，2000；Blaker，1991；Norrby，2005；Rabbetts，1998；Smith，Atchison和Pierscionek，1992)。Zadnik等人(2003)最近描述了屈光正常的儿童的年龄相关变化，但这还没有被纳入正式的眼模型中。

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.

尚未在成人眼中进行折射状态的眼睛建模。最近我与同事合作，对年轻成人近视眼进行了许多解剖学和光学性能测量。在本文中，我将这些数据整合到依赖于屈光度的眼睛模型中。需要注意的是，人与人之间存在相当大的变异性，通常即使参数的变异与屈光度有显著关联，其参数与屈光度的相关性也很低。这些模型可以通过额外的知识来修改以考虑这种变异性。在开发出这些模型后，我将它们的轴向和离轴像差预测与实验结果进行了比较。

Methods

方法

Subjects and measurements

受试者和测量

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.

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本研究遵循赫尔辛基宣言的原则，经过昆士兰科技大学人类研究伦理委员会和查尔斯王子医院人类研究伦理委员会批准，并取得了所有参与者的知情同意。研究人群包括121名年龄为25±5岁（年龄范围18-36岁）的远视和近视参与者。使用Jackson交叉柱在phoroptor上对双眼进行非环扩散单目球柱镜主观屈光度检查。最大加和双眼平衡到±0.25 D。眼镜平均球镜度数（SR）的范围为+0.75 D至-12.38 D，假定为12毫米视轴距离。筛选标准为：通过主观验光检查测得的散光度数大于0.50 D或测试眼的矫正视力达不到6/6；任一眼有任何眼部疾病、以往眼部手术、眼压高于21毫米汞柱。94%的情况下测量右眼，当右眼屈光度超出球形或散光限制时，采用符合纳入标准的左眼检查，并在必要时将左眼的符号改为与右眼相匹配。

使用Medmont E300仪器对所有121名参与者的前角膜进行视角膜地形图图像采集。这产生了各种数据文件。数据相对于角膜曲率轴居中，该轴通过于角膜法线定位点。仪器生成的其中一个数据文件指示入射瞳孔中心相对于角膜曲率轴的位置，并与高度数据进行最小二乘拟合程序以确定适用于6毫米直径角膜的最佳配合顶点半径（R）和角膜齿形后翘（Q）使用公式：

```
(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.

其中Z轴通过视线。使用未扩张的瞳孔进行测量。平均瞳孔直径为4.4 ± 0.8毫米，范围为2.7-6.0毫米。当瞳孔被Placido圆盘环的反射或一些黑色虹膜主题覆盖时，瞳孔外形（因此中心）的近似不好。在这些情况下，需要手动估计瞳孔中心和大小。

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.

在一个眼睛上进行了119名参与者的A扫超声生物测量，而对侧眼睛则固定在距离（6米）的目标上。在超声测量前约1分钟，在测试眼中滴入一滴0.4%苄哌齐啶盐酸盐（Minims，Chauvin Pharmaceuticals Ltd）的局部麻醉剂。在保持穿透光学轴和施加最小角膜压力的同时，特别注意调整超声探头束探头的对准线。统计10个变异度小于0.08毫米的数据。

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

MRI测量对87名参与者进行（Atchison等，2004年）。

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.

| 人群中女性比例偏高，MRI参与者中女性比例达到60%，总人群中女性比例达到63%。男性和女性的平均屈光度分别为-2.2 ± 2.6和-2.8 ± 2.9 D。需要注意男女之间的差异。| |

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.

所有测量均未使用调节麻醉药。虽然意图使测量和建模适用于未调节状态，但某些被试可能存在某种程度的调节。这会导致前房深度减少，晶状体厚度略微增加的效果。

Statistical analysis

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

使用平均球面屈光度（SR）作为自变量进行不同参数的线性回归。如果未发现显著相关性，则使用单样本t检验将均值与零进行比较。男性和女性使用独立样本t检验进行比较，假定方差相等。所有测试使用的显著性水平为5%。统计软件包SPSS用于分

析。

Modelling

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. The selected values are compared with other literature values. Table 1 has the model parameters.

建模基于未经调节的视力正常的眼睛的先前模型（Liou& Brennan，1997年; Navarro等，1985年），使用Scheimpflug照相报告的角膜和晶状体形状的Dubbelman和同事（Dubbelman& Van der Heijde，2001年; Dubbelman， Van der Heijde和Weeber，2001年; Dubbelman，Weeber，van der Heijde和Volker-Dieben，2002年）以及体外晶体折射率测量（Jones，Atchison，Meder和Pope，2005年）、先前报告的MRI测量（Atchison等人，2004年; Atchison等人，2005年）、色散建模（Atchison和Smith，2005年）和以前未报道的前部角膜地形图和超声眼内距离测量。在使用年龄相关数据时，我使用了我的团体平均年龄25岁。所选值与其他文献值进行比较。表1显示了模型参数。

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.

除了考虑由折射引起的参数变化外，使用两个模型。集中的模型1的表面是同轴的，但是模型2的表面包含镜片和视网膜的倾斜和偏心。认为这些模型是右眼。

Anterior cornea (C1)

前表皮层（C1）

Vertex radius of curvature

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

角膜前表面的顶点曲率半径与屈光度有显著相关性（图1）。对于模型，角膜前表面的回归方程舍入为 。

```
RC1 (mm) = 7.77 + 0.022SR (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.

具有最大误差小于0.003。略高于Navarro模型眼（7.72毫米）。其他几项研究报告了在近视增加时前表面曲率半径显著降低，或者在正视和近视组之间存在显著差异。

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							3.15
		11.48	−5		[b]	[b]		
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} $-12.91 - 0.094SR$ R_{Ry} $-12.72 + 0.004SR$	Q_{Rx} $0.27 + 0.026SR$ Q_{Ry} $0.25 + 0.017SR$	−3.6	−11.5	$-2.52 + 0.032SR$	$0.44 - 0.010SR$	
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.

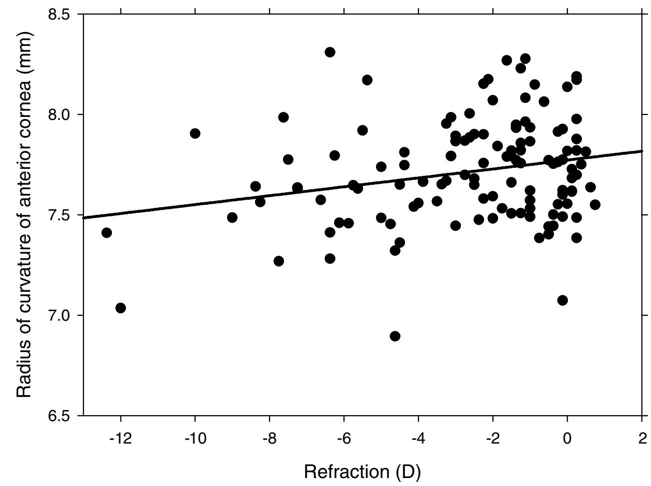

Fig. 1. Effect of refractive correction on anterior corneal radius of curvature, using the line of sight as the reference axis. The regression fit is $R_{C1} = 7.773 + 0.0221SR$, $n = 121$, adj. $R^2 = 0.048$, $p < 0.001$.

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

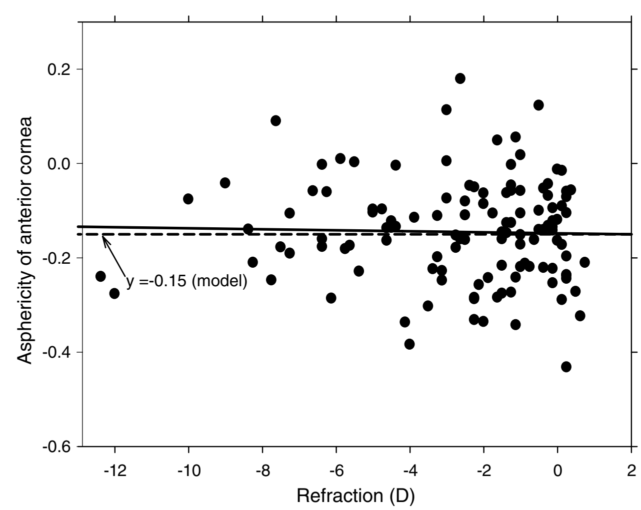

Fig. 2. Effect of refractive correction on anterior corneal asphericity. The regression fit is $Q_{C1} = -0.136 - 0.0002SR$, $n = 121$, adj. $R^2 = -0.008$, $p = 0.962$. The fit for the model of $Q = -0.15$ is also shown.

References

- 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)

参考文献

- 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

RC1 ðmmÞ = 7.762 + 0.036SR

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(n = 105, R2 = 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

按性别分析

The regression fits: - males RC1 = 7.84 + 0.021SR - females RC1 = 7.73 + 0.020SR

- 男性回归拟合：RC1 = 7.84 + 0.021SR
- 女性回归拟合：RC1 = 7.73 + 0.020SR

Males had 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).

男性的角膜前半径比相同屈光度的女性平均降低了0.12毫米，这是显著的 (t = □2.43, df = 119, p = 0.017)。以前对这种性别差异的估计范围从0.09到0.19毫米(Alsbirk, 1977; Dunne, Royston, & Barnes, 1992; Koretz, Kaufman, Neider, & Goeckner, 1989; Lam 等人,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, so

非球度

图2显示参考视线时，非球度随着屈光度的变化。屈光度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 (□) | 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 | 3.15 | 11.48 | □5 | | Anterior lensa | 1.371 + 0.0652778Z □ 0.0226659Z^2 □ 0.0020399(X^2 + Y^2)| 1.44 | Infinity | --- | --- | | Posterior lens | 1.418 □ 0.0100737Z^2 □ 0.0020399(X^2 + Y^2) | 2.16 | □5.9 | □2 | --- | --- | | Vitreousc | 1.336 | 16.28 □ 0.299SR | RRx □12.91 □ 0.094SR | QRx 0.27 + 0.026SR | Parameter | Value | | Retina | RRy □12.72 + 0.004SR | QRy 0.25 + 0.017SR | --- | --- | 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.

表格1

| 视觉模型参数与眼镜折射度（SR）的函数之间的关系 | | --- | | 介质 | 折射率 555 nm | 曲率半径（mm） | 偏心率 | 绕x轴倾斜（°） | 绕y轴倾斜（°） | 偏心距x（mm） | 偏心距y（mm） | 到下一个表面的距离（mm） | | 空气 | 1.0 | 7.77 + 0.022SR | -0.15 | --- | --- | --- | --- | --- | | 角膜 | 1.376 | 0.55 | 6.4 | -0.275 | --- | --- | --- | --- | | 玻璃体前 | 1.3374 | 3.15 | 11.48 | -5 | --- | --- | --- | --- | | 眼晶体前方a | 1.371 + 0.0652778Z □ 0.0226659Z^2 □ 0.0020399(X^2 + Y^2)| 1.44 | 无穷远 | --- | --- | --- | --- | | 眼晶体后方 | 1.418 □ 0.0100737Z^2 □ 0.0020399(X^2 + Y^2) | 2.16 | -5.9 | -2 | --- | --- | --- | --- | | 玻璃体c | 1.336 | 16.28 □ 0.299SR | RRx □12.91 □ 0.094SR | QRx 0.27 + 0.026SR | 参数 | 值 | | 视网膜 | RRy □12.72 + 0.004SR | QRy 0.25 + 0.017SR | --- | --- | a 在表面顶点平面上的限制. b 在二号模型中，晶状体绕其中心垂直轴倾斜 ±4°. c 在二号模型中，需要长度校正在 -0.26 到 -0.29 之间。

Refraction (D)	**Radius of curvature of anterior cornea (mm)**
-12	6.5
-10	7.0
-8	7.5
-6	8.0
-4	8.5

折射（D）	**前角膜曲率半径（毫米）**
-12	6.5
-10	7.0
-8	7.5
-6	8.0
-4	8.5

Refraction (D)	**Asphericity of anterior cornea**
-12	-0.6
-10	-0.4
-8	-0.2
-6	0.0
-4	0.2

y =-0.15 (model)

折射（D）	**角膜前面的非球形度**
-12	-0.6
-10	-0.4
-8	-0.2
-6	0.0
-4	0.2

y =-0.15（模型）

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.

回归拟合为 QC1 = -0.136 - 0.0002SR，n=121，adj. R2 = -0.008，p = 0.962。Q = -0.15模型的拟合结果也显示在下表中。

(D.A. Atchison, 2006)

()

$$Q_{C1} = -0.15 \tag{2}$$

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:

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

$$n_{C1} = 1.376. \tag{4}$$

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

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

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

$$Q_{C2} = -0.275. \tag{6}$$

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

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

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

$$n_{AC} = 1.3374. \tag{8}$$

2.3.4. Stop

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

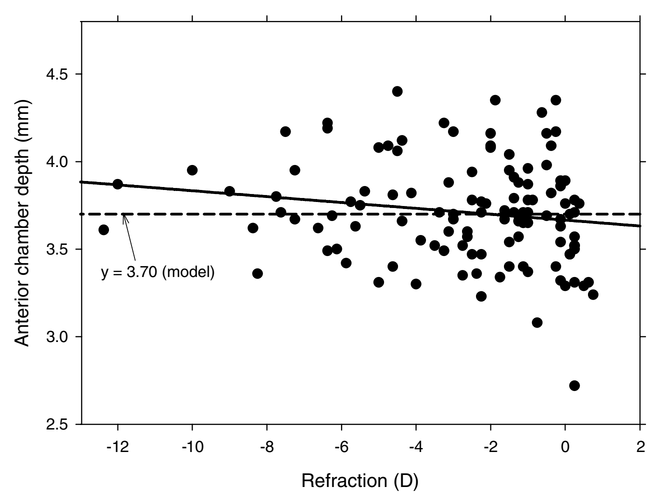

Fig. 3. Effect of refractive correction on anterior chamber depth (includes corneal thickness). The regression fit is $d_C + d_{AC} = 3.666 - 0.0168SR$, $n = 119$, adj. $R^2 = 0.017$, $p = 0.082$. The fit for the model of $d_C + d_{AC} = 3.70$ mm is also shown.

QC1 ¼ □0:15

ð2Þ

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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).

用于该模型的地形曲率值少于Navarro模型眼值的0.26，但与多项采用Placido环角膜地形图的研究的非加权平均非球面度相似，如Kiely、Smith和Carney(1982)的0.26±0.18(受试者人数(n)=88)、Edmund和Sjøntoft(1985)的0.28±0.13(n=40)、Guillon、Lydon和Wilson(1986)的0.18±0.15(n=110)、Sheridan和Douthwaite(1989)的0.11(n=56)、Lam和Loran(1991)的0.16(n=65)(中国人)和0.19(n=63)(英国人)、Patel、Marshall和Fitzke(1993)的0.01±0.25(n=20)、Eghbali、Yeung和Maloney(1995)的0.18±0.21(n=41)、Lam和Douthwaite(1996)的0.15(n=24)、Lam和Douthwaite(1997)的0.30±0.13(n=60)、Carney等人(1997)的0.33±0.23(n=105)、Budak等人(1999)的0.04±0.23(n=150)、Guirao、Redondo和Artal(2000)的0.10±0.06(n=27，他们的年轻群组)。

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 Car- ney et al. (1997) obtained a significant correlation of

0.14 (p<0.01) between higher-order corneal aberrations and refractive error.

均值性别差异为0.002，在我的研究中不显著（t=0.111，df=119，p=0.91）。Budak等人（1999）未能发现角膜前凸性与屈光度存在显著依赖性，但Carney等人（1997）在高级别角膜像差和屈光度之间获得了显著相关性为0.14（p <0.01）。

QC1 ¼ □0:402 □ 0:032SR ðn ¼ 105; R2 ¼ 0:076; p ¼ 0:005Þ;

with decreasing prolateness as myopia increased.

随着近视度数的增加，体形不对称度逐渐降低。

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: dC1 ðmmÞ ¼ 0:55; nC1 ¼ 1:376. 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.

2.3.1.3. 折射率和厚度。

我采用 Navarro 模型眼睛的中央角膜厚度和折射率是0.55mm和1.376，即：dC1（mm）=0.55；nC1=1.376。厚度大约比文献中的估计平均值高0.05毫米：Martola和Baum（1968）0.52±0.04毫米；Lowe（1969）0.52±0.03；Leighton和Tomlinson（1972）0.56毫米；Alsbirk（1977）0.52±0.03；Soni和Borish（1979）0.49±0.04；Koretz等（1989）0.47±0.04. Alsbirk 发现女性的角膜厚度比男性高0.01毫米，但 Martola 和 Baum 没有发现角膜厚度与性别或屈光度有相关性。

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 RC2 ðmmÞ ¼ 6:4. 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 RC2 ¼ 0:409 þ 0:791RC1 and Dunne et al. (1992) found this relationship to be RC2 ¼ 0:823RC1. This can be expected to have a partially counteracting influence on the increase of anterior corneal power as myopia increases.

2.3.2. 后角膜 (C2)

2.3.2.1. 曲率半径。

后角膜没有进行测量。Dubbelman等人（2002）发现平均值为6.40 ±0.28毫米，因此我使用了以下公式： RC2 ðmmÞ ¼ 6:4. 这与Navarro眼的6.5毫米值相似，也与文献中的其他估计值相似，例如Lowe和Clark（1973）6.46 ±0.26毫米，Dunne等人（1992）6.6 ±0.2毫米和Patel等人（1993）5.81 ±0.41毫米。Dunne等人（1992）发现，男性的角膜比女性更平坦，平均值为0.12毫米。我不知道有关后角膜参数与屈光度的研究，但Lowe和Clark（1973）发现前后角膜曲率半径之间的关系为 RC2 ¼ 0:409 þ 0:791RC1 而Dunne等人（1992）发现此关系为 RC2 ¼ 0:823RC1. 这可以预期在近视增加时部分对抗前角膜力增加的影响。

2.3.2.2. Asphericity.

Dubbelman et al. (2002) found that posterior corneal surface asphericity is dependent upon age according to the equation k ¼ QC2 þ 1 ¼ 0:9 □ 0:007 □ age. At 25 years QC2 ¼ □0:275. Previous estimates are those of Lam and Douthwaite (1997) of □0.66 ± 0.38 and of Patel et al. (1993) of □0.42.

2.3.2.2. 不规则度。

Dubbelman等人（2002）发现，后角膜表面的不规则度取决于年龄，其方程为 k ¼ QC2 þ 1 ¼ 0:9 □ 0:007 □ 年龄。 在25岁时 QC2 ¼ □0:275。 先前的估计值是Lam和Douthwaite（1997）的-0.66±0.38和Patel等人（1993）的-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 dAC ðmmÞ ¼ 3:15. 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 (Alsb- irk, 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 * 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.

2.3.3. 前房（AC）

2.3.3.1. 厚度。

眼球的屈光度对前房深度没有明显的影响（图3）。平均深度为3.71 ± 0.29毫米。将其四舍五入为3.7毫米，从眼部测量数据中减去0.55毫米的角膜厚度，我使用3.15毫米作为模型中的前房深度，因此 dAC ðmmÞ ¼ 3:15。 这比Navarro眼值的3.05毫米大0.10毫米。前房和晶状体厚度都高度依赖于年龄（Alsb- irk，1977；Brown，1973；Cook，Koretz，Pfahnl，Hyun和Kaufman，1994；Dubbelman等人，2001；Koretz，Cook和Kaufman，1993；Niesel，1982）和调节（Dubbelman等人，2001；Koretz等人，1993），因此，为了进行比较，我考虑与我使用的相似年龄组以及非调节情况。以角膜厚度为参考的先前研究结果包括Jansson（1963）20-29岁组的3.8毫米，Koretz等人（1989）25岁4.12 * 0.011 *年龄= 3.85毫米，Leighton和Tomlinson（1972）19-51岁组的3.6毫米，Carney等人（1997）的等距小组3.60 ± 0.37毫米15-52岁，以及Goss等人（1997）21-44岁的3.8毫米。这些的无加权平均值为3.73毫米，与我的平均值3.71毫米非常接近。

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 significant- ly 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).

男性的前房深度比女性更深，但平均差异为0.11mm，未能显著 (t = □1.94, df = 117, p = 0.056)。其他研究发现，男性的前房深度显著大于女性，20-29岁年龄组差异0.13mm (Jansson, 1963)， 0.18mm (Alsbirk, 1977)，和 0.13mm (Goss等，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.

我的能力无法发现折射对前房深度的显着影响，支持 Jan韦松（1963）和 Goss 等人 (1997) 的观点，但 Stenstrom(1948c) 和 Carney 等人 (1997) 发现近视度数增加前房深度也随之增加。

2.3.3.2. Refractive index.

I used the Navarro et al. model eye value, so ``` nAC ¼ 1

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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).

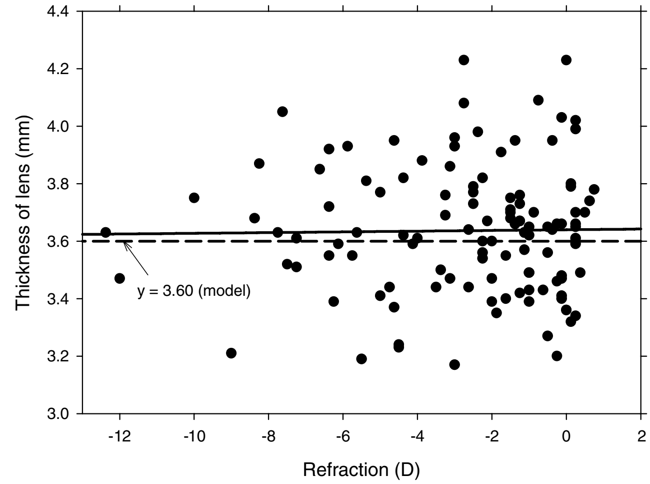

Fig. 4. Effect of refractive correction on lens thickness. The regression fit is $d_L = 3.640 + 0.0123SR$, $n = 119$, adj. $R^2 = -0.008$, $p = 0.867$. The fit for the model of $d_L = 3.60$ mm is also shown.

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 sub-thicknesses 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,

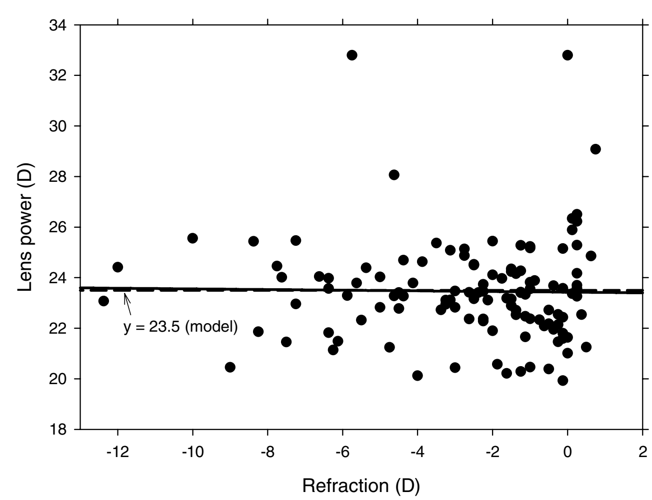

Fig. 5. Effect of refractive correction on lens equivalent power. The regression fit is $F_L = 23.43 - 0.0.0130SR$, $n = 119$, adj. $R^2 = -0.008$, $p = 0.848$.

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±0.009age (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. 透镜（L）

2.3.5.1. 前表面半径

透镜的力量似乎不会随着屈光度的变化而改变（见下文），因此我假设透镜表面曲率半径和非球面性质不受屈光度的影响。Dubbelman和Van der Heijde于2001年基于3毫米区域进行的前表面半径拟合，结果为rL1 = 12.9±0.4 – 0.057±0.009age（n = 102; R2 = 0.29; p < 0.0001）。在25岁时，这个值是11.47525毫米，四舍五入后可得到rL1（mm）= 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±0.04age (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）基于5毫米区域的非球形度的拟合公式为Q = -6.4±1.6 + 0.03±0.04age（n = 90; R2 = 0.006; p = 0.44）。这并不具有统计学显著性。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±0.006age (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

我改变 Dubbelman 和 Van der Heijde (2001) 的拟合符号，以便后面的镜片具有负曲率半径。他们基于 3 毫米区域的拟合结果为 rL1 = -6.2±0.02 + 0.012±0.006age (n = 65; R2 = 0.06; p = 0.053)。我使用了 25 岁的值，因此 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±0.06age (n = 41; R2 = 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 QL2 = -2. (12)

2.3.5.4. 后表面非球面度

Dubbelman和Van der Heijde（2001）基于4mm区域的拟合，其非球面度的公式为QL2=-6±2+0.07±0.06age（n=41；R2=0.04；p=0.21），平均值为-4±5。由于在他们的Scheimpflug技术中，反向光线追踪时累积了误差，因此这种非球面度最有可能是不准确的。使用这个值将导致球差水平较低。为了确保模型具有与文献一致的Zernike球差，即对于6毫米进入瞳孔（Thibos，Bradley和Hong，2002；Wang& Koch，2003；Wang，Zhao，Jin，Niu和Zuo，2003），至少对于等视眼，我使用了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)

2.3.5.5. 镜片厚度

折射对镜片厚度没有显著影响（图4）。平均厚度为3.64±0.22毫米，对于我使用的模型，dL(mm) = 3.6。（13）

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).

2.3.5.6. 功率

Bennett（1988）开发了一种在没有晶体测量的情况下估算等效透镜力的方法。该程序基于三个屈光面的Gullstrand-Emsley眼模型，假设透镜保留与模型中相同的前后表面半径比。透镜根据屈光度、前表面角膜半径测量和眼内距离测量进行修改。图5显示了眼的等效透镜功率随屈光度变化的情况。平均值为23.5±2.0 D。以前的透镜功率估计较低，分别为17.4±1.5D（Stenstrom，1948a）和21D（Goss等，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 ($t = 3.59$, $df = 116$, $p < 0.001$).

在本研究中，晶状体度数并没有受到屈光度的显著影响，正如Stenstrom (1948c)和Goss等人(1997)所发现的那样。 然而，女性的晶状体度数比男性显著高1.3D($t = 3.59$, $df = 116$, $p <0.001$)。

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)

我将晶状体分为前部和后部，其中前部占厚度的40%，与Liou& Brennan（1997）所用的相同。分厚度如下: dL1(mm) = 1.44。（14） dL2(mm) = 2.16。 （15）

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.

这些用超声测量的数据与MRI测量进行比较是很有趣的。后者尽管分辨率低，但不受眼媒体内的假设速度的影响。MRI给出了一个相似的平均估算值为3.63±0.25mm。

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–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.

以下数值要远小于 Navarro 模型值 4.0 毫米，但是与先前的测量值相似：Jansson（1963）20-29 岁组 3.6 毫米；Leighton 和 Tomlinson（1972）19 岁组 3.6 毫米；Koretz 等人（1989）校正超声测量值 3.46 + 0.013 * 年龄 = 3.79 毫米；Carney 等人（1997）15-52 岁组 3.51±0.26 毫米，平均年龄 27 岁；Goss 等人（1997）3.7 毫米；Dubbelman 和 Van der Heijde（2001）25 岁组 2.93 + 0.024 * 年龄 = 3.53 毫米。

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).

统计指标	数值
平均厚度差	0.06 mm（女性较大）
t值	1.49
自由度df	117
p值	0.139

Alsbirk（1977）、Carney等人（1997）、Goss等人（1997）和Jansson（1963）也未发现厚度受性别或屈光度的显著影响（Goss等人，1997；Jansson，1963）。

$p < 0.001$). 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):

$$N_{0,0} = c_0 + c_1,$$
$$N_{0,1} = -2c_1/d_{L1},$$
$$N_{0,2} = c_1/d_{L1}^2,$$
$$N_{1,0} = c_1/b^2,$$

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

$$N_{0,0} = c_0,$$
$$N_{0,2} = c_1/d_{L2}^2,$$
$$N_{1,0} = c_1/b^2,$$

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:

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

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

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

$$\theta_{yL}\ (°) = -4. \quad (18)$$

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

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

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 ($t = -1.902$, df = 82, $p = 0.061$). Although not used in my raytracing, a useful diameter to use for modelling the unaccommodated lens is

$$D_L\ (\text{mm}) = 9.1.$$

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

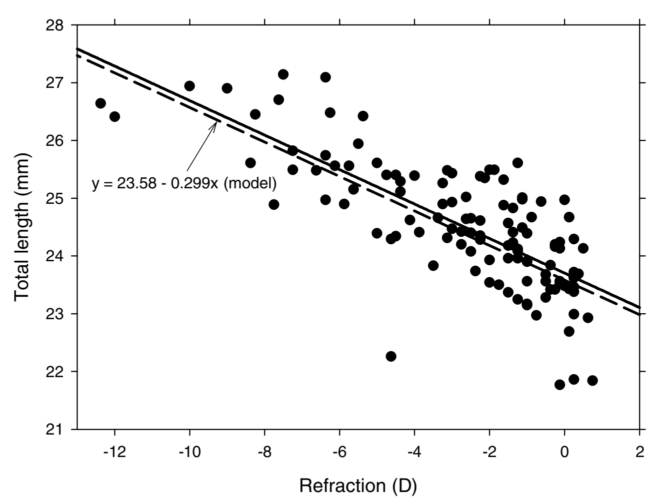

Fig. 6. Effect of refractive correction on ocular length. The regression fit is $d_{total} = 23.70 - 0.298SR$, $n = 119$, adj. $R^2 = 0.570$, $p < 0.001$. The fit for the model of $d = 23.58 - 0.299SR$ is also shown.

Ocular Anatomy and Refraction

眼部解剖和屈光学

Refraction Results

折射结果

- 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.
- 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.

- 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 contributes 63% of the lens power.

- Goss等人（1997）没有发现显著的性别差异，尽管他们确实发现女性的后角膜比男性陡峭得多。

- Jones等人（2005）发现，晶状体的折射率从边缘的1.371变化到中心的1.418，在不同年龄段变化不大。
- 等效透镜功率是表面贡献和梯度折射率贡献的组合。前面和后面的表面力分别为2.93和5.69 D。梯度折射率贡献了透镜功率的63%。

Ocular Anatomy

眼部解剖学

Gradient index and components of lens power

渐变指数和透镜功率组成部分

- The refractive index is described by a parabolic equation of the form: $n(q) = c0 + c1q^2$ where q is the relative distance from the center of the lens to the edge and c0 and c1 are coefficients.
- For raytracing purposes, this equation can be converted into N(X, Y, Z) coefficients.
- The corresponding Ni,j coefficients for the front and back half of the lens are given.

描述	翻译
折射率由抛物线方程描述，形式为：$n(q) = c0 + c1q^2$，其中q是镜片中心到边缘的相对距离，c0和c1是系数。	
为了进行光线跟踪，可以将该方程转换为N(X, Y, Z)系数。	
给出了前半部分和后半部分的Ni,j系数。	

Tilt

倾斜

- Lenses of eyes are considerably tilted about the vertical axis.

- Tilt was not significantly affected by refraction, and the horizontal component of the mean tilt was significantly different from zero at 4.0 ± 2.4°.

- 眼睛的晶状体相对于垂直轴倾斜较大。

- 倾斜并未受到折射的显著影响，平均倾斜的水平分量在4.0 ± 2.4度处显著不同于零。

Decentration

分心

- Having no information about this, it is assumed that the lens center coincides with the line of sight.

- This requires horizontal decentration of the anterior and posterior surfaces of equal amounts but in opposite directions.

- 没有关于此的信息，假设镜片中心与视线重合。

- 这需要前表面和后表面水平偏心相等但方向相反。

Diameter

直径

- 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 mean diameter for all subjects being 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.

	Mean diameter (mm)	Standard deviation (mm)
All subjects	9.08	0.41
Males	9.18	0.42
Females	9.01	0.38

在MRI图像中，通过轴向横截面测量了84个被试的晶状体直径。所有被试的平均直径为9.08±0.41mm，范围为7.8-9.9mm，没有明显趋势。男性的晶状体直径(9.18±0.42mm)大于女性(9.01±0.38mm)，但差异不显著。