We measured optical and biometric parameters of emmetropic eyes as a function of age. There were approximately 20 subjects each in age groups 18–29, 30–39, 40–49, 50–59, and 60–69 years with similar male and female numbers. One eye was tested for each subject, having spherical equivalent in the range $-0.88 \text{ D} \leq \text{SE} \leq +0.75 \text{ D}$ and $\leq 0.50 \text{ D}$ astigmatism.

Despite considerable data scatter, we found significant age changes: anterior chamber depth decreased 0.011 mm/year, lens central thickness increased 0.024 mm/year, anterior segment depth increased 0.013 mm/year, eye length increased 0.011 mm/year, anterior lens radius of curvature decreased 0.044 mm/year, and lens equivalent refractive index decreased 0.0003/year. Males had higher anterior corneal radii of curvature (0.16 mm), lower lens equivalent refractive index (0.006), longer vitreous lengths (0.51 mm), and longer axial lengths (0.62 mm) than females. Superficially, the results suggest that eyes get bigger as they age. However, results can be related to refraction patterns in which refraction is stable in 20s to 40s and then moves in the hypermetropic direction. It is likely that several young subjects will become hypermetropic as they age, and it is possible that some of the older subjects were myopic when younger.

Keywords: ageing, anterior chamber depth, anterior segment length, asphericity, axial length, cornea, emmetropia, lens, lens thickness, ocular parameters, radius of curvature, refractive index, vitreous chamber depth

Considerable changes take place in size, shape, and mass of the lens as age increases. A related phenomenon is the eye losing its ability to accommodate until the mid-50s by which it is completely lost (Hamasaki, Ong, & Marg, 1956; Sun et al., 1988). This is understood to be due mainly to declines in elasticity of the lens and its capsule (Fisher, 1969, 1971, 1973; Glasser & Campbell, 1999).

The central thickness of the unaccommodated lens increases because of increases in cortical thickness, while at the same time there are decreases in anterior chamber depth (Brown, 1973; Dubbelman, van der Heijde, & Weeber, 2001; Koretz, Kaufman, Neider, & Goeckner, 1989a; Niesel, 1982). However, there is no change in equatorial diameter (Jones, Atchison, & Pope, 2007; Strenk et al., 1999). The radius of curvature of the surfaces of the unaccommodated lens decrease, particularly for the anterior surface (Brown, 1974; Dubbelman & van der Heijde, 2001). Some estimates of lens asphericity have been made (Brown, 1973, 1974; Dubbelman & van der Heijde, 2001), with Dubbelman and van der Heijde (2001) finding average anterior and posterior surface asphericities based on measurements restricted to the “optically active” zone being highly negative at −5 and −4, with no significant changes with age.

Lens refractive index decreases away from its center. This gradient index provides a considerable component of the lens power, which can only be modeled in homogeneous lenses by using a refractive index higher than the refractive index in the lens center. Most of our understanding of this is based on in vitro studies (Pierscionek, 1994; Pierscionek, Chan, Ennis, Smith, & Augusteyn, 1988). Results from an MRI technique suggested a decrease in refractive index of the nucleus with increase in age (Moffat, Atchison, & Pope, 2002a, 2002b), but the changes were found not to be statistically significant in a subsequent more detailed study (Jones, Atchison, Meder, & Pope, 2005), which confirmed proposed changes in shape of the refractive index profile with age (see below). A recent study by our group was able for the first time to make in vivo estimates of lenticular refractive index, but because of data noise, analysis was restricted to estimates of the central index. Within experimental error, this was unaffected by ageing or accommodation (Jones et al., 2007).

As mentioned above, the lens becomes more curved with increase in age. This suggests that eyes should become more myopic with increase in age, but the trend is the opposite direction during the forties to sixties (Attebo, Ivers, & Mitchell, 1999; Katz et al., 1996; Saunders, 1981, 1986; Shufelt, Fraser-Bell, Ying-Lai, Torres, & Varma, 2005; Slataper, 1950; Wang, Klein, Klein, & Moss, 1994; Wensor, McCarty, & Taylor, 1999; Wickremasinghe et al., 2004; Wong et al., 2001; Wu, Nemesure, & Leske, 1999). This failure of change in refraction to match changes in lens shape is referred to as the “lens paradox.” It can be explained by reductions in the gradient index power in which the central plateau of high refractive index becomes wider and then the refractive index changes more steeply toward the edge (Smith, Atchison, & Pierscionek, 1992). In models with homogeneous lenses, this can be mimicked by the refractive index reducing with age (Atchison & Smith, 2000; Dubbelman & van der Heijde, 2001). Several of the studies of age-related refraction, but not all (Attebo et al., 1999; Wang et al., 1994), have found a myopic shift in refraction in the seventies or eighties.

The eye transmission decreases with increase in age, mostly attributable to increases in absorption and in backward scatter in the lens. Light loss is more marked for short as compared with longer wavelengths. Work over the last 50 years has been modeled by van de Kraats and van Norren (2007). Light scatter of the lens, both forward and backward, also increases throughout life (Bettelheim & Ali, 1985; Donnelly, Pesudovs, Marsack, Sarver, & Applegate, 2004).

Total higher-order aberrations increase with age throughout adulthood for fixed pupil sizes (Artal, Berrio, Guirao, & Piers, 2002; Calver, Cox, & Elliott, 1999; Fujikado et al., 2004; Kuroda et al., 2002; McLellan, Marcos, & Burns, 2001), although Brunette, Bueno, Parent, Hamam, and Simonet (2003) found that the total higher-order aberrations actually declined until the thirties after which they increased. There have been reports of certain aberrations increasing in absolute magnitude and in particular of spherical aberration increasing toward more positive values (Amano et al., 2004; Artal et al., 2002; Calver et al., 1999; McLellan et al., 2001; Smith, Cox, Calver, & Garner, 2001). Changes in both anterior corneal (Amano et al., 2004; Guirao et al., 2000; Oshika, Klyce, Applegate, & Howland, 1999; Wang, Dai, Koch, & Nathoo, 2003) and internal aberrations (Artal et al., 2002; Marcos, Barbero, McLellan, & Burns, 2004; Smith et al., 2001) have been noted with age, with the internal aberrations calculated from the difference between total and corneal aberrations. Artal et al. (2002) and Artal, Benito, and Tabernero (2006) have suggested that there is a degree of balance between corneal and internal aberrations for young eyes, with the corneal aberrations being higher than the total aberrations, but that this is lost with increasing age. Some compensation is provided for aberrations, as well as small refractive errors and loss of accommodation, by the decrease in pupil size with age (Applegate, Donnelly, Marsack, Koening, & Pesudovs, 2007; Winn, Whitaker, Elliott, & Phillips, 1994).

The above gives a brief overview of important changes in the optics of human eyes with age. However, these have been based on cross-sectional studies rather than longitudinal studies, and results may be compounded by changing refractive error patterns with age and subject populations. Koretz et al. (1989a) counteracted the latter by conducting a study on a nearly emmetropic group, although by including spherical equivalent up to ±2 D there may have been unreported drifts in refraction with age. We have updated this study by investigating an emmetropic group with tighter refraction limits and
additional optical parameters. The most striking findings were that the older groups had longer anterior segments and axial lengths than those of the younger groups.

Methods

The research followed the tenets of the Declaration of Helsinki and was 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.

Participants

The study cohort consisted of 106 emmetropes, with approximately 20 subjects in each of age groups 18–29, 30–39, 40–49, 50–59, and 60–69 years, and with similar numbers of males and females in each age group (Table 1). All but four participants in the 18- to 29-year group were of Caucasian origin. Corrected visual acuities, measured using a Bailey–Lovie chart, were 6/6 or better. Pelli-Robson contrast sensitivities were ≥1.65 for subjects aged 18–39 years and ≥1.50 for older subjects. All participants passed a Humphrey FDT C-20-1 visual field screening test. A desaturated D15 test was used to exclude any subjects with an acquired blue–yellow color defect, often a sign of ocular disease. Based on lens and fundus photography and grading using AREDs scales (AREDS, 2001a,b), lenses were Grade 1 or better for nuclear, cortical, and posterior subcapsular cataract, and fundi were Grade 2 or better for age-related maculopathy. Accommodative amplitudes were measured with a Badal Optometer to check that these were within the normal range for age. Exclusion criteria included ocular disease in either eye, previous ocular surgery, intraocular pressure >21 mm Hg, and blood pressure >140/90.

Non-cycloplegic monocular sphero-cylinder subjective refraction was performed on both eyes using a Jackson crossed cylinder in a phoroptor. Maximum plus and minus spherical and cylindrical components of refraction were recorded. The second visit was required for Oculus Pentacam and Purkinje imaging tests, and a third visit was required for a subset of subjects for MRI measurements. Not all tests were able to be conducted on all participants. Reasons included discomfort with the contact technique of ultrasound, unable to be dilated with phenylephrine due to conflicting medications (relevant for Pentacam and Purkinje imaging), left eyes could not be measured with the Purkinje imaging device, not all subjects returned for Pentacam and Purkinje techniques, and only a subset of the youngest and oldest age groups had magnetic resonance imaging (MRI).

There may have been some degree of accommodation for some younger subjects. This would have the effect of decreasing anterior chamber and increasing lenticular thickness slightly. As part of our work, measurements were made for different accommodation stimuli for Pentacam, Purkinje, and MRI techniques in the youngest age group. This study considers only the unaccommodated case: results for accommodated states will be reported later.

Techniques

Refraction

As appropriate, refractions were converted from conventional sphero-cylinder notation \( S/C \times \theta \) to spherical equivalent \( M \), 90°–180° astigmatism component \( J_{180} \), and 45°–135° astigmatism component \( J_{45} \), where

\[
M = S + C/2, \quad J_{180} = -C \cos 2\theta/2, \quad J_{45} = -C \sin 2\theta/2. \tag{1}
\]

Corneal topography

Videokeratographic placido disk images with undilated pupils were taken of anterior corneas of 101 participants with the Medmont E300 instrument. This instrument was validated by Tang, Collins, Carney, and Davis (2000). The instrument had an “accuracy index,” and we used an image for each subject for which the index was above

<table>
<thead>
<tr>
<th>Age group</th>
<th>Number</th>
<th>R/L eyes</th>
<th>Males/females</th>
<th>Age, mean ±SD (years)</th>
<th>Refraction, mean ±SD (D)</th>
</tr>
</thead>
<tbody>
<tr>
<td>18–29</td>
<td>23</td>
<td>19/4</td>
<td>11/12</td>
<td>22.7 ± 3.6</td>
<td>+0.03 ± 0.33</td>
</tr>
<tr>
<td>30–39</td>
<td>20</td>
<td>17/3</td>
<td>10/10</td>
<td>36.5 ± 3.1</td>
<td>-0.12 ± 0.33</td>
</tr>
<tr>
<td>40–49</td>
<td>22</td>
<td>16/6</td>
<td>11/11</td>
<td>44.6 ± 2.2</td>
<td>-0.06 ± 0.35</td>
</tr>
<tr>
<td>50–59</td>
<td>21</td>
<td>14/7</td>
<td>10/11</td>
<td>54.9 ± 2.7</td>
<td>+0.14 ± 0.41</td>
</tr>
<tr>
<td>60–69</td>
<td>20</td>
<td>11/9</td>
<td>10/10</td>
<td>64.1 ± 3.0</td>
<td>+0.13 ± 0.33</td>
</tr>
</tbody>
</table>

Table 1. Characteristics of age groups.
95%. The instrument produced several data files. The height data were referenced to the keratometric axis, which passed to the fixation point normal to the cornea. We developed software to find the position of the corneal apex relative to the geometric center of the corneal limbus and eventually to find the position of the corneal apex relative to the pupil center determined with a Wavefront Sciences COAS aberrometer (paper in preparation). Pupil diameters with the aberrometer were at least 5 mm. The shift from corneal apex to aberrometer pupil center was used with the height data 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

$$X^2 + Y^2 + (1 + Q)Z^2 - 2ZR = 0,$$  \hspace{1cm} (2)

where the Z-axis passes through the line of sight. The change in reference position made non-significant changes to the mean radius of curvature and mean asphericity of $-0.004 \pm 0.021$ mm and $-0.014 \pm 0.09$, respectively.

Images with dilated pupils were taken for 97 participants with an Oculus Pentacam, a Scheimpflug system that gave both anterior and posterior corneal topography as well as corneal thickness and anterior chamber depth. The instrument provided a “Quality value” and flagged images that did not seem to be good. In such cases, we took additional images as necessary. Although the instrument indicated the position of pupil center with respect to corneal apex, there was insufficient information to determine the geometric center of the cornea limbus, and so we were unable to reference the corneal data to the aberrometer pupil center as we did for the Medmont E300 instrument. We determined the best fitting R and Q to the anterior corneal apex for both the anterior and posterior surfaces.

The Pentacam instrument provided the principal radii of curvature and their meridians for both corneal surfaces, and this information was used to analyse surface toricity.

**Distances**

Distances were measured using the Oculus Pentacam (corneal central thickness, anterior chamber depth, lens central thickness), ultrasonography (corneal central thickness, anterior chamber depth including corneal central thickness, lens central thickness, vitreous chamber depth), and magnetic resonance imaging (anterior chamber depth including corneal thickness, lens central thickness, anterior segment length, vitreous chamber depth, internal axial length, lens diameter, and maximum internal horizontal and vertical dimensions). Derived quantities for the Pentacam were anterior segment length (sum of corneal thickness, anterior chamber depth, and lens central thickness), and derived quantities for ultrasonography were anterior segment length and internal axial length.

A-scan ultrasonographic measurements for corneal central thickness using a Cilco Sonometrics Villaseñor Ultrasonic Pachymeter were taken on the tested eye for 104 participants while the contralateral eye fixated a distance target. Other ultrasonographic measurements using Quantel Medical A-scan model AXIS-II were similarly taken for 102 participants. One drop of anesthetic oxybuprocaine hydrochloride 0.4% (Minims, Chauvin Pharmaceuticals) was instilled in the test eye 1 min before measurement. Care was taken to align the transducer beam probe along the visual axis and to exert minimal pressure. Ten measures were taken. Usually standard deviations were <0.08 mm.

Magnetic resonance imaging (MRI) was performed with a 1.5-T General Electric “Twin Speed” clinical MR scanner for 30 participants, 7 males and 8 females each in the youngest and oldest age groups, using procedures similar to those reported previously (Atchison et al., 2004, 2005). A customized 3.5-cm receive-only surface coil (Nova Medical) together with a Fast Spin Echo sequence (FSE) was used to obtain images with 40-mm field of view and 3-mm slice thickness (effective echo time TE = 19 ms, echo train length of 4, a 320 × 320 matrix size interpolated to 512 × 512 pixel images, recycle time TR = 400 ms, total image acquisition time of 131 s). Resolution was 0.125 mm. Participants lay supine on a table with the head stabilized with foam pads. The surface coil, with a viewing hole in the middle, was clamped in place as close as possible over the tested eye. A front silvered mirror tilted by 45° was placed 10 cm above the eye. The subject looked at the center of the reflected image of a wheel-like target fixed on a wall 6.1 m away. A set of scout images was taken to ensure that the eye looked straight upward and the crystalline lens did not appear to be tilted, followed by an FSE image in the sagittal plane of the eye and an FSE image in the transverse axial plane. If the crystalline lens appeared tilted vertically in the scout image, the mirror was adjusted appropriately and another set of scout images was obtained. The axial scout image was used to set up the plane of measurement for the first sagittal FSE image. The sagittal FSE image was used to set up the plane of measurement for the transverse axial FSE image.

Apart from lens diameter, dimensions reported here with MRI were made from axial and sagittal images at 50× magnification on a computer monitor. The DICOM image was displayed, and contrast adjusted until edges of interest were best defined. Distances were measured using a line caliper and converted from pixels to millimeters. Eye width was measured retina to retina across the transverse axial image at the widest point. Eye height (retina to retina) was measured similarly from the image through the sagittal eye section. Measurements were made to two decimal places, and averages were taken of three measures. Lens diameter with MRI was determined with a Matlab algorithm identifying extreme X, Y coordinates of the lens (Kashtuwirangan, Markwell, Atchison, Pope, & Smith, 2007).
Apart from the lens diameter and internal eye dimensions, MRI results are reported for the axial images, which tended to be better defined than the sagittal images.

**Lens radii of curvature and equivalent refractive index**

The experimental technique was based upon that of Rosales and Marcos (2006). LED sources (890 nm) separated vertically by 18 mm were placed to the temporal side of the right eye at 20° angle and 75 mm distance and photographed through a telecentric lens by a CCD camera. Using a telecentric lens meant that camera re-focusing was not required for each Purkinje image. Image analysis software was written to determine the vertical separation of paired Purkinje images I (anterior cornea), III (anterior lens), and IV (posterior lens). Lens radii of curvature and equivalent refractive index were estimated by varying them to minimize a merit function based on previous work (Garner, Owens, Yap, Frith, & Kinnear, 1997; Smith & Garner, 1996). A raytrace into the eye to the retina gave a depth provided by ultrasonography was used. 1.336 for both cornea and aqueous, and the anterior chamber back surface was ignored by using a refractive index of model in which corneal thickness was set to zero, corneal aqueous/vitreous of 1.336) and one using a three surface eye model (using the corneal radii of curvature, corneal thickness (ultrasonography), and refraction along the vertical meridians. Two other raytraces into and then out of the eye after using independent sample t tests with equal variances assumed. Different measures of the same parameter were compared with paired t tests. Univariate analyses of variance were used for a comparison of MRI results across gender and two age groups. The level of significance used for all tests was 5%. The programs SPSS (SPSS, Inc.) and Sigmaplot (Systat Software, Inc.) were used for analyses.

**Results**

**Refraction**

There was no significant influence of age for mean sphere or for astigmatic components $J_{180}$ and $J_{45}$, although there was a trend toward a positive shift of mean sphere with increase in age (0.0044 D/year, $p = 0.07$).

**Anterior corneal radii of curvature**

Figure 1 shows results with the Medmont E300 and Oculus Pentacam instruments. There was no significant trend with age. The Medmont E300 gave significantly smaller radius of curvature (mean 7.75 ± 0.24 mm) than did the Pentacam (mean 7.79 ± 0.24 mm). Males had larger radii of curvature than females by a mean 0.17 mm (Table 2).

**Anterior corneal asphericity**

Figure 2 shows results with Medmont E300 and Oculus Pentacam instruments. There was no significant trend with age for the Medmont E300 with a mean of $-0.13 \pm -0.14$. However, the Pentacam showed a significant trend with age of $-0.0036 + 0.0038 \text{ age}$ and had more positive
results than the Medmont E300 for all but 16 of 92 subjects. Males and females had similar asphericities (Table 2).

**Corneal central thickness**

Figure 3 shows results with ultrasonography and the Oculus Pentacam. Ultrasonography results show a significant age trend of 0.567 \( \pm \) 0.00077 \( \text{age} \) with a mean of 0.533 \( \pm \) 0.047 mm. For Pentacam results referenced to the corneal apex, there was no significant age trend with a mean of 0.540 \( \pm \) 0.035 mm. Results referenced to pupil center under the illumination conditions were significantly smaller by 0.0014 \( \pm \) 0.0014 mm (\( t = 9.76, df = 9, p < 0.001 \)). Males had slightly thicker corneas than females by means of 0.011 and 0.005 mm by the two techniques, but differences were not statistically significant (Table 2).

**Posterior corneal radius of curvature**

Figure 4 shows results with the Oculus Pentacam instrument. There was no significant trend with age with a mean of 6.50 \( \pm \) 0.25 mm. Male radii of curvature were a mean 0.06 mm flatter than those of females, but this difference was not statistically significant (Table 2).

**Posterior corneal asphericity**

These are not shown because of poor confidence in the anterior corneal asphericities with the Oculus Pentacam. For completeness, the regression fit was 1.06 \( \pm \) 0.016 \( \text{age} \) (adjusted \( R^2 = 0.022, t = -5.55, n = 104, p < 0.001 \)), with most asphericities positive, but becoming negative with increase in age.

**Corneal toricity and astigmatism**

Both anterior and posterior corneal surfaces are toric. The mean radii of curvature of the more horizontal and more vertical principal meridians for the front surface were 7.81 and 7.70 mm, respectively, while the corresponding values for the posterior surface were 6.58 and 6.24 mm. Thus, the toricity on the back surface is about 3 times that of the front (0.11 mm versus 0.34 mm). The mean anterior and posterior radii of curvature of 7.76 and 6.41 mm given by the instrument were slightly smaller than those determined from our best fitting procedure (7.79 and 6.50 mm, respectively).

The mean astigmatisms of the front and back surfaces, using a corneal refractive index of 1.376 and an aqueous index of 1.336, were +0.80 \( \pm \) 0.41 D \( C_{180} \) and -0.33 \( \pm \) 0.12 \( D \times 8.8^\circ \). In a more sophisticated analysis, we determined the \( J_{180} \) and \( J_{45} \) astigmatic components for each subject’s corneal surfaces. The two \( J_{180} \)s were added, the two \( J_{45} \)s were added, and the two sums were combined to give the total corneal astigmatism. The mean of the total astigmatism across subjects was compared with the mean of the anterior astigmatism across the subjects. The back surface compensated for 53%, 23%, and 22% of the anterior surface’s \( J_{180} \), \( J_{45} \), and astigmatism, respectively.

**Anterior chamber depth**

Figure 5 shows results with ultrasonography, the Oculus Pentacam and MRI. To make the results comparable, the corneal thickness was included in the measurements. The depth decreased significantly with age at a rate of 0.011 mm/year. The Pentacam gave significantly higher values than did ultrasonography, with a mean difference of 0.05 \( \pm \) 0.11 mm. Males had slightly deeper depths than females, but the 0.06-mm mean difference was not significant (Table 2). Trends with MRI matched ultrasonography and the Pentacam.

**Lens radii of curvature**

Figure 6 shows results obtained with Purkinje imagery (4-surface model) and MRI. These was a significant decrease for the anterior radius of curvature of 0.0438
mm/year with Purkinje imagery, but no significant age change for the posterior radius of curvature, which had a mean of $-6.86 \pm 0.85$ mm. The differences between males and females were not significant (Table 2).

The 3-surface model gave similar results as did the 4-surface model, but the anterior radius of curvature estimate was slightly smaller by $0.05 \pm 0.010$ mm ($t = 4.36, n = 66, p < 0.001$) while the posterior radius of curvature was similar at $-6.85 \pm 0.86$ mm. Trends with MRI matched ultrasonography and the Pentacam, but the posterior estimates were smaller (mean $-5.9 \pm 0.09$ mm).

### Lens central thickness

Figure 7 shows results obtained with ultrasonography and MRI. There was a significant increase of $0.0235 \pm 0.0075$ mm/year with ultrasonography. Males had slightly greater thicknesses than females but the $0.06$-mm mean difference was not significant (Table 2). Trends with MRI matched ultrasonography and the Pentacam.

### Lens equivalent refractive index

Figure 8 shows results obtained with Purkinje imagery for the 4-surface eye model. There was a significant decrease of $0.00035$/year. A similar rate of change occurred for the 3-surface model, but the mean estimate was significantly smaller by $0.0048 \pm 0.0047$ ($t = 8.30, df = 65, p < 0.001$). Males had lower refractive indices than females by a mean of $0.007$ (Table 2).

### Lens diameter

For the horizontal (transverse axial) section, the young group (19–28 years) and the older group (61–69 years) had means of $9.03 \pm 0.34$ and $9.31 \pm 0.29$ mm. For the vertical (sagittal) section, the corresponding means were $9.19 \pm 0.34$ and $9.51 \pm 0.26$ mm. Using a 2-way univariate analysis of variance, lens diameter was significantly dependent on age ($p < 0.02$), but not on gender, for either section.

### Lens equivalent power

Figure 9 shows lens equivalent power for the 4-surface eye model. There was a significant decrease of $0.033$ D/year. A slightly higher rate of $0.038$ D/year occurred for the 3-surface model. The 4-surface model had a significantly higher mean of $23.9 \pm 2.3$ D than that of the 3-surface model.
Figure 2. Anterior corneal asphericity as a function of age with Medmont E-300 and Pentacam instruments. The regression fit for the Medmont E300 has a non-significant slope; the mean (shown in figure) is $-0.132 \pm 0.137$ ($n = 101$). There is a significant age trend for the Pentacam instrument: $-0.0036 + 0.0038 \text{ age}$ (adjusted $R^2 = 0.030$, $t = 2.03$, $n = 97$, $p = 0.045$).

Figure 3. Corneal central thickness as a function of age with ultrasonography and the Pentacam instrument. There is a significant age trend for ultrasonography: $0.5667 - 0.00077 \text{ age}$ (adjusted $R^2 = 0.051$, $t = -2.58$, $n = 104$, $p = 0.011$). The regression fit with the Pentacam has a non-significant slope; the mean (shown in figure) is $0.540 \pm 0.035 \text{ mm}$ ($n = 97$).

Figure 4. Posterior corneal radius of curvature as a function of age with the Pentacam instrument. The regression fit has a non-significant slope: $6.609 - 0.00247 \text{ age}$ (adjusted $R^2 = 0.02$, $t = -1.43$, $p = 0.16$). The mean (shown in figure) is $6.50 \pm 0.25 \text{ mm}$ ($n = 97$).

Figure 5. Combined corneal and anterior chamber depths with ultrasonography, the Pentacam instrument, and MRI. There are significant age trends with ultrasonography and the Pentacam instrument: ultrasonography $3.857 - 0.0106 \text{ age}$ (adjusted $R^2 = 0.196$, $t = -4.91$, $n = 102$, $p < 0.001$); Pentacam $3.909 - 0.0105 \text{ age}$ (adjusted $R^2 = 0.219$, $t = -5.433$, $n = 97$, $p < 0.001$). The mean difference between ultrasonography and the Pentacam instrument is significant: $-0.05 \pm 0.11 \text{ mm}$ ($t = -4.67$, $df = 94$, $p < 0.001$).
Anterior segment length

Figure 8 shows the anterior segment length for ultrasonography and MRI. There was a significant increase of 0.0132 mm/year with ultrasonography. Males had longer lengths than females, but the mean difference of 0.12 was not statistically significant (Table 2). Trends with MRI matched ultrasonography.

model at 22.9 ± 2.4 D ($t = 10.03$, $df = 65$, $p < 0.001$). Males had significantly lower powers than females by a mean of 1.1 D.
Vitreous length

Figure 11 shows vitreous length for ultrasonography and MRI. There was no significant trend with age for either, with a mean 15.92 ± 0.70 mm for ultrasonography, but males had longer chambers than females by 0.51 mm (Table 2).

Axial eye length

Figure 12 shows axial length for ultrasonography and MRI. There was a significant increase of 0.0113 mm/year with ultrasonography. Males had greater lengths than females by a mean of 0.62 mm (Table 2). The MRI results did not show the age-related trend.

Internal horizontal and vertical eye dimensions

For the horizontal (transverse axial) section, the young and the older groups had means of 23.07 ± 1.15 and 23.01 ± 0.78 mm with MRI. For the vertical (sagittal) section, the corresponding means were 23.15 ± 0.87 and 22.70 ± 0.65 mm. Using 2-way univariate analyses of variance, eye dimension was not significantly dependent on age nor gender for either horizontal or vertical sections.

Discussion

Summary

In the midst of considerable scatter in the data, the following age-related changes were found in emmetropic eyes: anterior chamber depth decreased 0.011 mm/year, lens central thickness increased 0.024 mm/year, anterior segment length increased 0.013 mm/year, eye length increased 0.011 mm/year, anterior lens radius of curvature
decreased 0.044 mm/year, lens equivalent power decreased 0.033 D/year, and equivalent lens refractive index decreased 0.0003/year. Age-related changes were mainly related to the crystalline lens, with age-related changes in anterior chamber depth, anterior segment length, lens anterior radius of curvature, lens thickness, and equivalent refractive index being more clearly evident (as indicated by the R-squared values) than changes in axial length and lens equivalent power. This suggests that age-related changes in the former mentioned aspects are over and above any refractive error associated confounds and would have been obvious in a longitudinal study as well as a cross-sectional study as conducted here.

Figure 13 shows parameters of average 20- and 70-year-old eyes based on the non-gender relationships we have obtained.

Gender differences were found, with males having significantly flatter anterior corneal radii of curvature, lower equivalent refractive indices, lower lens powers, and longer vitreous chambers and axial lengths than those of females. There were tendencies for other gender differences such as increased corneal thickness, deeper anterior chambers, and thicker lenses in males that were not significantly different but were of the order of significant differences found in larger scale studies (see later).

An interesting finding was that older emmetropic eyes were longer than young emmetropic eyes. There was no significant change in the vitreous depth with age, and the axial length increase was due to increase in the lens central thickness so that the lens posterior surface moved away from the cornea with increase in age at about the same rate that the lens anterior surface moved toward the cornea. Some caution must be applied to the axial length results. While the age trend was significant for the whole group, the correlation was low (adjusted $R^2 = 0.04$) and the trend was not significant for either males or females alone.

Our results are at variance with another study of emmetropic eyes by Koretz et al. (1989a), which did not find age-dependent changes in anterior segment length. We believe that this is due to that group’s use of an age-dependent ultrasonography velocity in the lens. Our comparison of lens thicknesses determined by ultrasonography and magnetic resonance imaging showed that this correction is not needed. Without the correction, the two studies agree well (see later).

The simplistic explanation for our finding of increased length of emmetropic eyes with increase in age are that eyes continue to grow throughout life, both in their external dimensions as well as that of the lens. However, it is more likely that the results reflect the refraction pattern throughout life. Refraction tends to be stable in the 20s to 40s and thereafter moves in the hypermetropic direction by about 1.5 D over the next 20 years, to be followed by a myopic shift in the 70s (Saunders, 1981, 1986; Slataper, 1950). It is likely that many of the younger subjects will become hypermetropic as they become older, and it is possible that some of the older subjects were myopic when younger. Also, cycloplegic refraction was not done to unearth latent hypermetropia, and it is possible that some of the older subjects were myopic when younger. Also, cycloplegic refraction was not done to unearth latent hypermetropia, and it is possible that some of the younger subjects were in this category. Consequently, it is likely that the older subjects had bigger eyes when young than do our young subjects now. The major cause of difference in eye length is the vitreous. The longer vitreous in the older subjects as young people would be replaced by a relatively smaller vitreous as they age, thus giving the apparent result in this cross-sectional study that the vitreous is constant, to be replaced by a larger anterior segment.

**Anterior corneal radius of curvature**

We obtained estimates of mean radius of curvature of 7.75 ± 0.24 and 7.79 ± 0.24 mm with the Medmont E-300 and Scheimpflug Pentacam instruments, respectively (Figure 1). The values agree well with Atchison’s estimate (Atchison, 2006) of 7.77 mm for emmetropes (using the Medmont E-300) but are slightly higher than Koretz et al.’s (1989a) estimate with an emmetropic group of 7.70 mm (this group gave corneal powers that we converted to radii of curvature using the 1.3375 equivalent refractive index used by Bausch and Lomb keratometers).

Similarly to Koretz et al. (1989a), in emmetropes, and Douthwaite et al. (Douthwaite, Hough, Edwards, & Notay, 1999), we did not find age-related changes in anterior radius of curvature of emmetropes. Most previous studies not restricted to emmetropes have found the anterior corneal radius of curvature decreases with age with either similar decreases of horizontal and vertical meridians (Dunne et al., 1992), more decrease in the...
horizontal meridian than in the vertical meridian (Hayashi et al., 1995; Kiely et al., 1984; Topuz, Ozdemir, Cinal, & Gumusalan, 2004), or decrease in the horizontal meridian only (Goto et al., 2001; Lam, Chan, Lee, & Wong, 1999; Lam & Douthwaite, 2000). Goto et al. (2001) found a gender difference in which the vertical meridian flattened in males but steepened in females. As astigmatism tends to change from “with-the-rule” (correction with negative cylinder × 180) to “against-the-rule” with increase in age (Goss, 1998), and our study was restricted to emmetropes with ≤0.5 D astigmatism, there is little point in making a detailed comparison of the changing relationship between meridians with age for our results.

Males had flatter corneas than females. The mean gender-related differences we found of 0.17 and of 0.15 mm for the Medmont E-300 and Pentacam Scheimpflug instruments, respectively, were slightly toward the upper end of the 0.09- to 0.19-mm range reported previously (Alsbirk, 1977; Atchison, 2006; Cheung, Cho, & Douthwaite, 2000; Cho & Lam, 1999; Douthwaite et al., 1999; Dunne et al., 1992; Eysteinsson et al., 2002; Kiely et al., 1984; Koretz et al., 1989a; Lam et al., 1994; Shufelt et al., 2005; Suzuki, Suzuki, Iwase, & Araie, 2005; Wickremasinghe et al., 2004; Wong et al., 2001).

**Anterior corneal surface asphericity**

The mean asphericity with the Medmont E-300 instrument of −0.13 ± 0.14 (Figure 2) was near the middle of the −0.30 to −0.01 range of previous estimates (Atchison, 2006; Cheung et al., 2000; Douthwaite et al., 1999; Dubbelman et al., 2006; Edmund & Sjottoft, 1985; Guillon et al., 1986; Kiely et al., 1982; Lam & Douthwaite, 1997; Pardhan & Beesley, 1999; Patel, Marshall, & Fitzke, 1993; Smith et al., 2001). We did not find a gender difference with this instrument, consistent with previous studies (Douthwaite et al., 1999; Dubbelman et al., 2006; Kiely et al., 1984). Like us, Kiely et al. (1984) found no age trend, but others have reported decrease in negative asphericity (Dubbelman et al., 2006; Guirao et al., 2000; Pardhan & Beesley, 1999) with Dubbelman et al. (2006) and Pardhan and Beesley (1999) reporting changes of +0.002 and +0.003/year, respectively.

The mean asphericity with the Pentacam instrument of +0.18 ± 0.28 was so far away from the Medmont E-300 estimate and those of previous studies as to indicate that this instrument is not reliable for determining corneal surface shape.

**Posterior corneal radius of curvature**

We obtained an estimate of mean radius of curvature of 6.50 ± 0.24 mm with the Scheimpflug Pentacam instrument (Figure 3). The estimate is similar to mean values of 6.5–6.6 mm obtained in previous studies (Dubbelman et al., 2006; Dunne et al., 1992; Lam & Douthwaite, 2000). We found no change with age, which was also found by Lam and Douthwaite (2000). Dunne et al. (1992) obtained 0.20-mm smaller radii of curvature for their older as compared with their young group. Our results showed a non-significant trend with gender (males flatter than females by 0.07 mm), as did those of Dunne et al. (1992) (0.12 mm). However, Dubbelman et al.’s (2006) gender-related difference of 0.14 mm was significant.

**Posterior corneal surface asphericity**

As the anterior corneal asphericities for the Pentacam instrument were at variance with results with the Medmont E-300 and all previous studies, we do not have confidence in the posterior corneal asphericities obtained with the Pentacam (Figure 2). Previous estimates of posterior asphericities include −0.66 ± 0.38 (Lam & Douthwaite, 1997) and 0.0 ± 0.006 age (Dubbelman et al., 2006). Lam and Douthwaite (1997), but not Dubbelman et al. (2006), found a significant relationship between anterior and posterior surface asphericities. Dubbelman et al. (2006) found no difference with gender.

**Ratio of anterior and posterior radii of curvature and equivalent refractive index of the cornea**

The mean ratio of the posterior and anterior radii of curvature in our study was 0.834, which is in the range of 0.83 to 0.85 reported by others (Dubbelman et al., 2006; Edmund, 1994; Garner et al., 1997; Lam & Douthwaite, 2000). From their mean radii of 7.79 and 6.53 mm, Dubbelman et al. (2006) concluded that the equivalent refractive index of the cornea based on a single surface model eye would be better given as 1.329 rather than in the range 1.3315 to 1.3375 used by keratometers. Using our mean radii of curvature, central thickness, refractive indices of 1.376 and 1.336 for the cornea and aqueous, and taking account of the posterior principal plane of the cornea being about 0.06 mm in front of the anterior surface, we obtained a similar estimate to Dubbelman et al. of 1.330.

**Corneal toricity and astigmatism**

We found the toricity on the back surface to be about 3 times that of the front. This was generally similar to that found in previous studies (Dubbelman et al., 2006; Dunne et al., 1992; Lam & Douthwaite, 2000) except that the anterior toricity (mean 0.11 mm) was smaller than reported in these studies. We found that the posterior surface compensated for 22% of the front surface’s...
astigmatism, which was less than the 31% found by Dubbelman et al. (2006).

Central corneal thickness

There are several ways to determine corneal thickness, including optical pachymetry, ultrasonography, Scheimpflug photography, specular microscopy, slitlamp photography, and partial coherence interferometry. The majority of studies over the last 10 years have used ultrasonography. This study adds to the few studies using Scheimpflug photography for corneal thickness (Barkana et al., 2005; Buehl, Stojanac, Sacu, Drexler, & Findl, 2006; Dubbelman et al., 2006; Fujioka et al., 2007; Lackner, Schmidinger, Pieh, Funovics, & Skorpik, 2005; Lam & Chen, 2007; O'Donnell & Maldonado-Codina, 2005).

Doughty and Zammas (2000) surveyed the considerable literature on corneal thickness up to the year 2000. They reported a mean central thickness of 0.536 ± 0.031 mm across studies that reported group variation. They found that age did not appear to influence central thickness across the studies of Caucasian groups, but that age-related decreases were reported in non-Caucasian groups. Our results in a mainly Caucasian group were similar to Doughty and Zammas’ mean, with 0.540 ± 0.035 mm for the Pentacam Scheimpflug instrument and 53.4 ± 0.047 mm for ultrasonography (Figure 4). However, the latter set had a significant age-related change of −0.0008 mm/year. Some recent studies have reported age effects (Cosar & Sener, 2003; Landers, Billing, Mills, Henderson, & Craig, 2007; Lekskul et al., 2005; Nomura, Ando, Niino, Shimokata, & Miyake, 2002; Rüfer, Schroder, Bader, & Erb, 2007; Shimmyo, Ross, Moy, & Mostafavi, 2003; Suzuki et al., 2005), while other recent studies have not found them (Altinok et al., 2007; Eysteinsson et al., 2002; Khoramnia, Rabsilber, & Auffarth, 2007; Sanchis-Gimeno, Lleo-Perez, Alonso, & Rahhal, 2004). Doughty and Zammas (2000) found no apparent gender influence across Caucasian groups. Some recent studies with more than 500 subjects have reported males having thicker corneas than females, generally about 0.006–0.007 mm (Li, Hu, Xu, Zhang, & Mai, 2006; Nomura et al., 2002; Shimmyo et al., 2003; Suzuki et al., 2005), but others have not found gender-related differences (Altinok et al., 2007; Cosar & Sener, 2003; Eysteinsson et al., 2002; Lekskul et al., 2005; Rüfer, Schroder, Arvani, & Erb, 2005; Rüfer et al., 2007). Our non-significant gender differences were 0.005 and 0.011 mm for Scheimpflug and ultrasonography techniques, respectively.

Anterior chamber depth, lens central thickness, and anterior segment length

Like many previous studies, we have found the anterior chamber depth decreasing with age and the lens central thickness increasing with age (Figures 5 and 7). We have found that the decrease in anterior chamber depth with age was only half the increase in lens thickness with age i.e the anterior segment length increases at the same rate as the anterior chamber depth decreases. Our results were similar to the Scheimpflug study of Dubbelmann et al. (2001), where the rates of change for the anterior chamber depth, lens central thickness, and anterior segment length were −0.010 mm/year, +0.024 mm/year, and +0.015 mm/year, respectively. Our results were also similar to those of Koretz et al.’s (1989a) with emmetropes using uncorrected lens results, where the rates of change for the anterior chamber depth, lens central thickness, and anterior segment length were −0.011 mm/year, +0.021 mm/year, and +0.010 mm/year, respectively.

However, our results were very different from those of Koretz et al.’s (1989a) “corrected” results for which they used a lens velocity of 1733 – 2.830 age m/s rather than 1641 m/s. This increased and reduced the estimate of lens thickness for subjects below 32.5 years and above 32.5 years, respectively. This correction brought their ultrasonographic estimates into line with their estimates using Scheimpflug photography (Koretz, Kaufman, Neider, & Goeckner, 1989b), which can be criticized for not taking into account the image distortions produced by imaging the lens anterior and posterior surfaces by the more anterior optics (Dubbelman et al., 2001).

We compared our ultrasonographic lens results with those obtained with magnetic resonance imaging (MRI) for 15 young (19–28 years) and 15 older subjects (61–69 years). While MRI cannot offer the precision obtained by ultrasonography, it is not affected by optical distortions nor by estimates of velocity in media. Figure 14 shows
differences between lens thicknesses obtained using ultrasonography and MRI. Ultrasonography results were shown with the uncorrected lens measurements and with Koretz et al.’s (1989a) velocity correction for age. MRI results were for both transverse axial and for sagittal images. The ideal result is that the difference between ultrasonography and MRI techniques is the same for the young and the older groups. This was much better satisfied by uncorrected ultrasonography, for which the mean difference between techniques of 0.04 mm was not significant different from zero (95% confidence range of ±0.15) as compared with corrected ultrasonography where the mean difference of 0.28 was highly significant (95% confidence range of ±0.15). The comparison between ultrasonography and MRI indicates that no age-related correction is required for lens ultrasonography velocity.

We found a significant difference between ultrasonography and Pentacam anterior chamber measurements of 0.05 ± 0.11 mm that was not age dependent (Figure 5). By comparison, Németh, Vajas, Kolozsvári, Berta, and Modis (2006) obtained a non-significant mean difference of 0.02 mm.

Recent results for age-related changes in non-refraction specific groups for anterior chamber depth and lens thickness are quite varied, including −0.010 and +0.024 mm/year (Dubbelman et al., 2001), −0.016 and +0.021 mm/year (Allouch, Touzeau, Kopito, Borderie, & Laroche, 2005), −0.021 and +0.019 mm/year (Wojciechowski, Congdon, Anninger, & Teo Broman, 2003), and −0.011/ year and +0.010 mm/year (Shufelt et al., 2005) (the latter two suggesting a decrease in anterior segment length with age). Koretz, Strenk, Strenk, and Semmlow (2004) also compared Scheimpflug results with MRI results, although on two different subject groups, with similar results for both techniques of −0.022 and +0.019 mm/year for anterior chamber and lens thickness changes, respectively.

While we did not find a significant effect of gender on anterior chamber depth or lens thickness, other studies have found significantly deeper anterior chamber depths for males of up to 0.18 mm (Cosar & Sener, 2003; Eyesteinsson, Jonasson, Arnarsson, Sasaki, & Sasaki, 2005; Foster et al., 1997; Klein, Klein, & Moss, 1998; Shufelt et al., 2005; Wickremasinghe et al., 2004; Wong et al., 2001) and significantly greater lens thicknesses for males of up to 0.06 mm (Klein et al., 1998; Shufelt et al., 2005; Wickremasinghe et al., 2004), although Wong et al. (2001) found females to have the greater lens thicknesses by a mean 0.05 mm.

Lens radii of curvature

As for other studies (Brown, 1974; Dubbelman & van der Heijde, 2001; Koretz et al., 2004; Lowe & Clark, 1973), we found significant age-related reduction in the anterior surface radii of curvature (−0.044 mm/year), but we did not find significant changes in the posterior radii of curvature (mean −6.9 mm, Figure 6). Using Scheimpflug photography, Dubbelmann and van der Heijde (2001) obtained significant age-related effects of 12.9 − 0.057 age and −6.2 + 0.012 age for the surfaces, although the significance of the regression for the posterior surface was marginal (p = 0.053). Koretz et al. (2004) obtained results of 13.4 − 0.08 age and −5.6 mm using MRI and of 13.7 − 0.08 age and −6.1 mm using Scheimpflug photography. Thus, our estimate of the rate of change of front surface radius of curvature with age was less than the other two studies, and our estimate of the back surface radius of curvature was greater than obtained in the other studies.

Lens equivalent refractive index

Our estimate of equivalent refractive index was 1.451 − 0.00035 age for the 4-surface model, which had a similar rate of change but higher constant than Dubbelman and van der Heijde’s (2001) 1.441 − 0.00038 age. Mean refractive index was 1.437. This was considerably higher than the 1.406–1.42 found in the common paraxial schematic eyes (Atchison & Smith, 2000). As recent in vitro and in vivo determinations of refractive index indicate that the central refractive index itself is about 1.42 (Jones et al., 2005, 2007), this suggests that the lens refractive indices of the schematic eyes are too low.

Various models have been proposed for the refractive index distribution, with recent work on in vitro eyes (Jones et al., 2005) supporting the model of Smith et al. (1992) in which the pattern of refractive index distribution from the center to the edge of the lens changes rather than a change in either edge or central refractive index. In this model, the central refractive index plateau increases in size with age, followed by a more rapid change toward the edge of the lens than occurs for young lenses. Our finding of a reduction in equivalent refractive index with age is supportive of this model.

Lens diameter

We found a mean increase in lens diameter of 0.3 ± 0.6 mm from the youngest to the oldest group for both horizontal and vertical sections. Previous studies have not found any age dependence. Our mean result of 9.26 ± 0.34 mm, across both sections, is similar to these studies: 9.18 ± 0.30 mm (Strenk et al., 1999), 9.43 ± 0.36 mm (Fea et al., 2005), and 9.33 ± 0.33 mm (Jones et al., 2007).

Lens power

We found a slight decrease in lens equivalent power with age of 0.033/year (Figure 9). The mean powers of
23.9 D (4-surface model) and 22.9 D (3-surface model) were higher than the 19.1 to 22.1 D powers of the Gullstrand No. 1, Bennett-Rabbetts, Gullstrand-Emsley, Le Grand full theoretical, and Liou-Brennan schematic eyes (Atchison & Smith, 2000).

Vitreous length

Like Koretz et al. (1989a), we did not find the vitreous length to change with age (Figure 11). We found males had bigger vitreous chamber depths than females by 0.50 mm. Some previous estimates were from 0.31 to 0.53 mm (Koretz et al., 1989a; Shufelt et al., 2005; Wong et al., 2001).

Axial length

The increase in axial length with age of emmetropic eyes has already been discussed in the Summary section. Like other studies, this study has found that males have longer axial lengths than females amounting here to 0.62 mm. Some previous estimates range between 0.47 and 0.65 mm (Koretz et al., 1989a; Shufelt et al., 2005; Wickremasinghe et al., 2004; Wong et al., 2001).

Modelling

Some of the findings, most notably the lens equivalent refractive index, lens power, and axial length, indicate that the common schematic eyes are in need of revision. This will be addressed in a later paper.

New instrumentation

Two recent instruments that were not used in this study are the IOLMaster (Zeiss), which uses partial coherence interferometry to measure axial length, and the Visante (Zeiss), which uses optical coherence tomography to measure corneal and anterior chamber thickness. Undoubtedly, both of these instruments have higher resonance than ultrasound and magnetic resonance. The IOLMaster uses a single assumed refractive index for the whole eye, and its measurements could be influenced by age-related changes in the optics of the crystalline lens (higher index lens taking up more of the eye and its refractive index distribution changing). The Visante is likely to be of considerable value in anterior eye diagnosis, and with development may become at least as versatile as the Pentacam Scheimpflug instrument, but for the present there is doubt about the adequacies of its algorithms for determining distance and curvature parameters (Dunne, Davies, & Wolffsohn, 2007).

Conclusions

We have conducted a study of optical parameters of emmetropic eyes. We found that the anterior chamber depth, anterior lens surface radius of curvature, equivalent lens refractive index, and lens equivalent power reduce with age, while lens central thickness, anterior segment length, and axial length increase with age. The latter changes at about 0.01 mm/year and most likely reflects the refractive correction pattern with change in age rather than ongoing growth of the eye itself.

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