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Total ocular, anterior corneal and lenticular higher order aberrations in hyperopic, myopic and emmetropic eyes

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ABSTRACT

Total ocular higher order aberrations and corneal topography of myopic, emmetropic and hyperopic eyes of 675 adolescents (16.9 ± 0.7 years) were measured after cycloplegia using COAS aberrometer and Medmont videokeratoscope. Corneal higher order aberrations were computed from the corneal topography maps and lenticular (internal) higher order aberrations derived by subtraction of corneal aberrations from total ocular aberrations. Aberrations were measured for a pupil diameter of 5 mm. Multivariate analysis of variance followed by multiple regression analysis found significant difference in the fourth order aberrations (SA RMS, primary spherical aberration coefficient) between the refractive error groups. Hyperopic eyes (+0.083 ± 0.05 μm) had more positive total ocular primary spherical aberration compared to emmetropic (+0.036 ± 0.04 μm) and myopic eyes (low myopia = +0.038 ± 0.05 μm, moderate myopia = +0.026 ± 0.06 μm) ($p < 0.05$). No difference was observed for the anterior corneal spherical aberration. Significantly less negative lenticular spherical aberration was observed for the hyperopic eyes (−0.038 ± 0.05 μm) than myopic (low myopia = −0.088 ± 0.04 μm, moderate myopia = −0.095 ± 0.05 μm) and emmetropic eyes (−0.081 ± 0.04 μm) ($p < 0.05$). These findings suggest the existence of differences in the characteristics of the crystalline lens (asphericity, curvature and gradient refractive index) of hyperopic eyes versus other eyes.

1. Introduction

It has been suggested that higher order aberrations (HOA) may play a role in the development of refractive errors by reducing retinal image quality (Charman, 2005). Studies have attempted to determine whether higher order aberrations (HOA) are a causal factor in the development and/or progression of refractive errors by investigating the mean levels of aberrations in different refractive error groups in both children (Carkeet et al., 2002; He et al., 2002; Kirwan, O'Keefe, & Soeldner, 2006; Martinez et al., 2009) and adults (Atchison, Schmid, & Pritchard, 2006; Buehren, Collins, & Carney, 2005; Cheng et al., 2003; Collins, Wildsoet, & Atchison, 1995; He et al., 2002; Jinhua Bao et al., 2009; Kwan, Yip, & Yap, 2009; Llorente et al., 2004; Paquin, Hamam, & Simonet, 2002; Radhakrishnan et al., 2004). Findings to date, however, have been equivocal with some studies reporting either relatively higher levels of HOA, coma or spherical aberration in myopic eyes compared to emmetropic or hyperopic eyes (Buehren, Collins, & Carney, 2005; He et al., 2002; Kirwan et al., 2006), or finding no differences between groups (Atchison et al., 2006; Carkeet et al., 2002; Cheng et al., 2003; Jinhua Bao et al., 2009).

An understanding of the contribution of various ocular refractive elements i.e. the anterior and posterior corneal surfaces and the crystalline lens to ocular aberrations will improve our knowledge of the development and/or progression of refractive errors. Aberrations from the posterior cornea contribute only a modest proportion of aberrations due to the negligible difference in refractive index between the cornea and the aqueous humor (Artal et al., 2002). Thus, internal aberrations mainly arise from the crystalline lens i.e. front and rear surfaces and the gradient index (Smith et al., 2001).

Only a few studies have reported on corneal and internal aberrations in various refractive error groups. Marcos (2002) observed that in young adults, an increase in myopia was associated with a significant increase in the corneal spherical aberration in the

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positive direction but the internal spherical aberration became more negative. Llorente et al. (2004) found that total ocular aberrations (root mean square (RMS) of third order (trefoil and coma) and spherical aberration) and corneal spherical aberration were significantly greater in young hyperopic eyes than in young myopic eyes whereas internal spherical aberration did not differ significantly between the two groups.

In young eyes, corneal aberrations are compensated by internal aberrations (Artal, Benito, & Tabernero, 2006; Artal & Guirao, 1998; Artal et al., 2001; Kelly, Mihashi, & Howland, 2004; Lu et al., 2008; Tabernero et al., 2007) resulting in an eye with little total aberrations. However, with an increase in age, total aberrations also increase due to loss of compensation of aberrations due to age related changes in both the anterior cornea and the crystalline lens (Atchison et al., 2008; Dubbelman & Van der Heijde, 2001; Smith et al., 2001). The pronounced age related variations occur to coma and spherical aberrations with increase in coma aberrations generated by anterior cornea (Amano et al., 2004; Berrio, Tabernero, & Artal, in press; Fujikado et al., 2004; Oshika et al., 1999) and change in negative to positive value for spherical aberration generated by crystalline lens (Berrio, Tabernero, & Artal, in press).

We aimed to determine the distribution of total ocular, anterior corneal and internal aberrations in a large group of adolescents with myopia, hyperopia and emmetropia and to determine differences if any, between the groups. We employed a procedure to correct the misalignment of the reference axes of the aberrometer and videokeratoscope and measured the total ocular aberrations and corneal topography of emmetropic, hyperopic and myopic eyes of adolescents enrolled in the Sydney Adolescent Vascular and Eye Study (SAVES). Anterior corneal aberrations were derived from corneal topography maps obtained from videokeratoscope and the internal aberrations determined by subtracting corneal aberrations from total aberrations. The results are presented.

2. Methods

As part of the SAVES study, higher order aberration profiles (3rd to 6th order) and corneal topography were measured in a sample of 755 adolescents aged 16–19 years (examined from June 2009 to August 2010). This sample included 458 participants who were previously examined in the Sydney Myopia Study (SMS, 2004–2005) (Ojaimi et al., 2005) and a further 297 new participants. SAVES followed the tenets of the Declaration of Helsinki and was approved by the Human Research Ethics Committee, University of Sydney and the New South Wales State Department of Education and Training, Australia. Written informed consent was obtained from at least one parent of each participant <18 years and directly from the participants aged 18 years or above.

All eyes were cyclopleged prior to measurements as per the protocol. First, a drop of topical anesthetic (1% amethocaine hydrochloride, MINIMS, Chauvin Pharmaceuticals Ltd., London, England) was instilled in both eyes to enhance absorption of the cycloplegic drops (Mordi, Lyle, & Mousa, 1986). Cycloplegia and mydriasis of both eyes were obtained by instilling one drop cyclopentolate 1% and one drop tropicamide 1% (MINIMS, Chauvin Pharmaceuticals Ltd., London, England). Drugs were instilled in two cycles, with an interval of 5 min between the two cycles. An additional two drops of phenylephrine 2.5% were administered in participants who had dark irides. Aberrometry and corneal topography measurement were performed 25–30 min after the instillation of the last drop ensuring no residual accommodation was present.

2.1. Instruments and procedure

Refractive error and total ocular aberration data were obtained using a COAS aberrometer (Wavefront Sciences, Inc., Albuquerque, NM, USA, version 1.41.05). The method used by the COAS to compute aberrations has been described elsewhere (Salmon & van de Pol, 2005; Thibos, 2000). The aberrations were calculated at a reference wavelength of 550 nm. The COAS aberrometer uses the line of sight as the reference axis and the pupil diameter was set at 5 mm for analysis. The results reported are based on a single aberration map per subject which was deemed sufficient to measure aberrations and refractive error (Martinez et al., 2006). Zernike coefficients were fitted up to 6th order using the standards recommended by the Optical Society of America (OSA) (Thibos et al., 2000).

Refractive errors were calculated using power vectors (M, J_0 and J_{45}) from second and fourth order Zernike coefficients (Atchison, 2005). The root mean square (RMS) of third order, fourth order, HOA (third to sixth order), spherical aberration $\left(\begin{smallmatrix}0\\C\\4\end{smallmatrix}\right.$ and $\left.\begin{smallmatrix}0\\C\\6\end{smallmatrix}\right)$ and coma $\left(\begin{smallmatrix}-1\\C\\3\end{smallmatrix}, \begin{smallmatrix}-1\\C\\5\end{smallmatrix}, \text{and } \begin{smallmatrix}1\\C\\5\end{smallmatrix}\right)$ was also calculated.

Corneal topography maps were obtained using a commercially available videokeratoscope Medmont E300 (Medmont Pty Ltd., Melbourne, Australia) that operates using the Placido disk principle. This instrument was shown to be repeatable in *in vivo* studies (Cho et al., 2002). The Medmont E300 automatically captures corneal topographic images once good focus and alignment of the eye is attained (Read et al., 2006). Each measurement gives a set of four images. Each image was given a score that ranges from 0 to 100 (called as the accuracy index) that was dependant on the focusing, alignment and completeness of the ring pattern. All the four images had an accuracy index of >80. From these, the image with the highest accuracy index was used for analysis.

Anterior corneal aberrations up to 6th order were computed from axial curvature data derived from the corneal topography map using commercially available software, VOL CT 7.3 (Sarver and Associates, Inc., Carbondale, IL). This software follows the ANSI Z80.28 standards in computing aberrations (as reported in the reference manual for VOL-CT). Using standard guidelines (Applegate et al., 2000; Thibos et al., 2002), the line of sight was applied as the reference axis for measurement and calculation of ocular aberrations and therefore the pupil center served as the origin of the Cartesian reference frame (Thibos et al., 2002). Hence, the corneal topographic map obtained from the Medmont E300 was centered to the entrance pupil center in order to correct for any misalignment of the reference axes. VOL-CT uses 1.3375 as the refractive index for the calculations.

Internal aberrations were computed by direct subtraction of corneal aberrations from the total ocular aberrations. During this process, the corneal topography map was referenced to the entrance pupil center using the VOL-CT software to correct for any misalignment error of the instrument reference axes. Since the pupils were cyclopleged, pupil center was constant during the collection of ocular aberrations and corneal topography measurements.

In addition, anterior corneal shape factors were calculated using VOL-CT software for 5 mm pupil diameter. VOL-CT describes the corneal shape by the equation for the rotationally symmetric conic surface

$$x^2 + y^2 + pz^2 - 2rz = 0$$

where z is the axis of revolution of conicoid or the axis of the videokeratoscope. The line of sight was considered the z axis. r the apical radius of curvature and p, the conic parameter equal to

$$p = 1 + Q$$

where Q is an asphericity parameter used to describe the type of conicoid.

The compensation of corneal aberrations with internal aberrations was determined by calculating the compensation factor

(CF) (Artal, Benito, & Tabernero, 2006). CF of coma RMS, SA RMS and HOA RMS for the various refractive error groups were calculated using the equation.

$$\mathrm{CF} = (\text{RMS of cornea} - \text{RMS of eye})/\text{RMS of cornea}$$

Positive values for compensation factor denote compensation of anterior corneal aberrations with internal aberrations and values that are small and close to zero indicate lack of compensation. Negative values indicate addition of aberrations by crystalline lens.

3. Data analysis

Participants wearing contact lenses, with astigmatism $\geqslant$1.00D and those with ocular pathology were excluded from the analysis. Classification of cases into refractive error groups was based on spherical equivalent (M); emmetropia (M −0.50D to +0.50D), low myopia (M −0.51D to −3.00D), moderate myopia (M −3.01D to −6.00D), high myopia (M more than −6.00D), low hyperopia (M +0.51D to +3.00D), moderate hyperopia (M +3.01D to +6.00D) and high hyperopia ($M > +6.00$D).

Of the 755 participants, 71 participants were excluded due to astigmatism $\geqslant$1.00D and a further 9 participants (4 with moderate hyperopia, 4 with high myopia and 1 with high hyperopia) were excluded as the sample size for each of these categories was small for comparisons. Data for the remaining 675 participants was included in the analysis.

Whilst measurements were obtained from both eyes of each participant, only data from right eyes were considered for statistical analysis as a strong correlation was found between both eyes of each participant ($r = 0.80$, C_4^0 coefficient of the right and left eyes) for HOA. Multivariate-adjusted analysis of variance (MANOVA) with Bonferroni correction, was performed to determine differences in the mean levels of HOA coefficients and RMS of third order, fourth order, HOA (third to sixth order), spherical aberration (SA) (C_4^0 and C_6^0), coma $\left(C_3^{-1}, C_3^1, C_5^{-1} \text{ and } C_5^1\right)$, anterior corneal shape factors and compensation factor between refractive error groups, using SPSS 17 (SPSS, Inc., Chicago, IL, USA) statistical software. After performing MANOVA, a multiple linear regression was done to determine the association of the significant coefficients with the refractive error. Statistical significance was set as $p < 0.05$. Age and gender were entered as fixed factors when doing the analysis.

4. Results

4.1. Biometric data

The mean age of the participants was 16.9 ± 0.7 years (range 16.0–19.0 years) and there were 339 females and 336 males. Details of M, J_0 and J_{45} (mean, range) are given in Table 1.

4.2. Total ocular aberrations

The coefficients and RMS of total ocular aberrations for various refractive error groups are presented in Table 2. Significant differences were found between the refractive error groups for C_4^0, C_4^2 and C_6^0 coefficients. C_4^0 was significantly less positive for low myopic, moderate myopic and emmetropic eyes compared to low hyperopic eyes. C_4^2 was significantly more positive for emmetropic eyes compared to low hyperopic eyes. Multiple regression analysis of the significant coefficients compared to the spherical equivalent showed that total C_4^0 was significantly associated with the refractive error ($R^2 = 0.13$, $p < 0.05$). Correlation of total C_4^0 with the spherical equivalent is depicted as a scatter plot in Fig. 1.

Compared to low hyperopic eyes, low myopic and emmetropic eyes had significantly less HOA, fourth order and SA RMS and moderately myopic eyes had less fourth order and SA RMS. The difference observed for C_6^0 was considered negligible.

4.3. Anterior corneal aberrations

Table 3 details the coefficients and RMS of corneal HOA for each refractive error group. Significant differences were found only for C_4^2 and C_6^{-4} coefficients between the various refractive error groups. C_4^2 was significantly less negative for emmetropia compared to low hyperopia. Multiple regression analysis of the significant coefficients compared to the spherical equivalent refractive error showed no association of these coefficients with the refractive error. The difference observed for C_6^{-4} was considered negligible.

4.4. Anterior corneal shape factors

The anterior corneal shape factors (apical radius of curvature (r) and asphericity (Q)) of eyes from various refractive error groups did not significantly differ from each other. The mean values of r and Q of anterior cornea are presented in Table 4.

4.5. Internal aberrations

The coefficients and RMS of internal HOA coefficients for the different refractive error groups are presented in Table 5.

Table 1
Power vectors M, J_0 and J_{45} for various refractive error groups.

Refractive error group	Sample size, n	M		J_0		J_{45}	
		Mean ± SD (D)	Range (D)	Mean ± SD (D)	Range (D)	Mean ± SD (D)	Range (D)
Emmetropia	197	+0.13 ± 0.26	+0.49 to −0.47	+0.03 ± 0.21	+0.47 to −0.46	−0.05 ± 0.11	0.25 to −0.40
Low myopia	100	−1.34 ± 0.62	−0.51 to −2.95	+0.04 ± 0.22	+0.45 to −0.47	−0.03 ± 0.12	+0.36 to −0.46
Moderate myopia	25	−4.02 ± 0.60	−3.01 to −5.64	+0.11 ± 0.20	+0.47 to −0.22	−0.01 ± 0.13	+0.25 to −0.40
Low hyperopia	353	+1.03 ± 0.42	+0.50 to +2.94	+0.04 ± 0.18	+0.48 to −0.45	−0.04 ± 0.10	+0.39 to −0.48
Total	675	+0.23 ± 1.24	+2.94 to −5.64	+0.04 ± 0.20	+0.48 to −0.47	−0.04 ± 0.11	+0.39 to −0.48

Table 2
Total aberration coefficients and RMS for refractive error groups. $p < 0.05$, MANOVA is shown by italicized and bold letters. *, ** and *** Depict group significantly different from other.

	Zernike coefficients	Low hyperopia ($n = 353$) Mean ± SD (μm)	Emmetropia ($n = 197$) Mean ± SD (μm)	Low myopia ($n = 100$) Mean ± SD (μm)	Moderate myopia ($n = 25$) Mean ± SD (μm)
Third order	C(3,−3)	−0.027 ± 0.07	−0.028 ± 0.07	−0.025 ± 0.06	−0.031 ± 0.07
	C(3,−1)	−0.038 ± 0.10	−0.015 ± 0.10	−0.016 ± 0.09	0.003 ± 0.09
	C(3,1)	−0.011 ± 0.06	0.001 ± 0.06	−0.001 ± 0.06	−0.007 ± 0.04
	C(3,3)	0.003 ± 0.06	0.003 ± 0.05	0.011 ± 0.05	0.033 ± 0.06
Fourth order	C(4,−4)	0.011 ± 0.02	0.007 ± 0.02	0.012 ± 0.02	0.007 ± 0.02
	C(4,−2)	−0.008 ± 0.02	−0.007 ± 0.02	−0.004 ± 0.02	−0.005 ± 0.02
	C(4,0)	***0.083 ± 0.05****,**,***	***0.036 ± 0.04****	***0.038 ± 0.05*****	***0.026 ± 0.06******
	C(4,2)	***−0.002 ± 0.03****	***0.007 ± 0.03****	0.000 ± 0.03	0.000 ± 0.04
	C(4,4)	0.013 ± 0.02	0.007 ± 0.02	0.012 ± 0.02	0.013 ± 0.03
Fifth order	C(5,−5)	−0.001 ± 0.01	−0.001 ± 0.01	0.000 ± 0.01	0.000 ± 0.01
	C(5,−3)	0.000 ± 0.01	0.000 ± 0.01	−0.003 ± 0.01	0.000 ± 0.01
	C(5,−1)	0.014 ± 0.01	0.012 ± 0.01	0.010 ± 0.01	0.008 ± 0.02
	C(5,1)	0.003 ± 0.01	0.001 ± 0.01	0.000 ± 0.01	0.000 ± 0.01
	C(5,3)	0.001 ± 0.01	0.002 ± 0.009	0.000 ± 0.01	0.000 ± 0.01
	C(5,5)	−0.001 ± 0.01	0.000 ± 0.01	0.001 ± 0.01	0.005 ± 0.01
Sixth order	C(6,−6)	0.001 ± 0.01	0.000 ± 0.01	0.001 ± 0.00	0.001 ± 0.01
	C(6,−4)	0.000 ± 0.00	0.001 ± 0.00	0.000 ± 0.007	0.000 ± 0.00
	C(6,−2)	0.000 ± 0.00	0.000 ± 0.007	−0.001 ± 0.007	−0.001 ± 0.00
	C(6,0)	***−0.002 ± 0.01****,**,***	***0.000 ± 0.01****	***0.001 ± 0.01*****	***0.003 ± 0.00******
	C(6,2)	0.000 ± 0.00	0.000 ± 0.00	0.002 ± 0.01	0.000 ± 0.00
	C(6,4)	0.000 ± 0.00	0.000 ± 0.00	0.000 ± 0.01	0.000 ± 0.00
	C(6,6)	0.000 ± 0.01	−0.002 ± 0.00	0.000 ± 0.01	0.000 ± 0.00
RMS	Third order	0.147 ± 0.06	0.143 ± 0.06	0.134 ± 0.05	0.138 ± 0.05
	Fourth order	***0.105 ± 0.04****,**,***	***0.076 ± 0.03****	***0.080 ± 0.03*****	***0.077 ± 0.05******
	HOA	***0.192 ± 0.06****,**	***0.171 ± 0.05****	***0.168 ± 0.05*****	0.168 ± 0.06
	SA	***0.087 ± 0.04****,**,***	***0.050 ± 0.03****	***0.054 ± 0.04*****	***0.046 ± 0.04******
	Coma	0.111 ± 0.06	0.107 ± 0.06	0.103 ± 0.05	0.093 ± 0.05

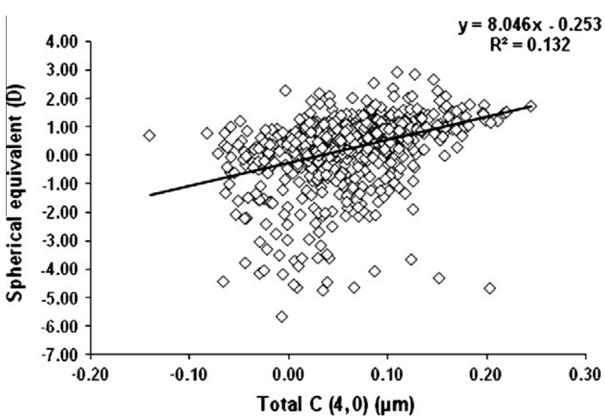

Fig. 1. Correlation between total C_4^0 and spherical equivalent (M) for 675 eyes.

Significant differences were found for C_3^{-1}, C_3^1, C_3^3, C_4^{-2}, C_4^0, C_5^{-1} and C_6^{-4} between the various refractive error groups. Emmetropia had significantly more positive C_3^1 than low hyperopia. C_3^{-1} coefficient was more negative in low hyperopic eyes compared to emmetropic and low myopic eyes. C_3^3 was significantly less positive for emmetropia compared to low myopia. C_4^0 was more negative for moderate and low myopia and emmetropia compared to low hyperopia. A multiple regression analysis of the significant coefficients compared to the spherical equivalent refractive error showed that internal C_4^0 was the only coefficient that was significantly associated with the refractive error ($R^2 = 0.14$, $p < 0.05$). Correlation of internal C_4^0 with the spherical equivalent is depicted as a scatter plot in Fig. 2. Fourth order and SA RMS was higher for low myopia, moderate myopia and emmetropia compared to low hyperopia ($p < 0.05$). The differences observed for C_5^{-1} and C_6^{-4} were considered negligible.

Compensation factors for coma RMS, SA RMS and HOA RMS for the various refractive error groups are presented in Fig. 3. Irrespective of the refractive error group, there was greater compensation for SA RMS compared to coma RMS and HOA RMS. There were differences between the groups for SA and HOA compensation factor with eyes of low hyperopes showing less compensation compared to emmetropes and low myopes ($p < 0.05$).

5. Discussion

5.1. Differences in mean levels of aberrations between refractive error groups

Our study using a large sample of adolescents, found differences in the aberrations between the refractive error groups with low myopic and emmetropic eyes showing significantly less total ocular HOA RMS fourth order aberrations (fourth order RMS, SA RMS and less positive primary spherical aberration $\left(C_4^0\right)$) than hyperopic eyes. The fifth and sixth order aberrations were generally small in magnitude with negligible differences between the groups. Whilst some of the previously published studies reported results similar to ours (Carkeet et al., 2002; Kwan, Yip, & Yap, 2009; Llorente et al., 2004; Martinez et al., 2009), others have observed that myopic eyes exhibit higher aberrations than non-myopic eyes (Buehren, Collins, & Carney, 2005; He et al., 2002). The reasons for

Table 3
Corneal aberration coefficients and RMS for refractive error groups. $p < 0.05$, MANOVA is shown by italicized and bold letters. * Depicts group significantly different from other.

	Zernike coefficients	Low hyperopia ($n = 353$) Mean ± SD (μm)	Emmetropia ($n = 197$) Mean ± SD (μm)	Low myopia ($n = 100$) Mean ± SD (μm)	Moderate myopia ($n = 25$) Mean ± SD (μm)
Third order	C(3, −3)	−0.042 ± 0.06	−0.034 ± 0.06	−0.036 ± 0.06	−0.063 ± 0.07
	C(3, −1)	0.013 ± 0.10	−0.004 ± 0.10	−0.014 ± 0.10	0.015 ± 0.11
	C(3, 1)	−0.087 ± 0.07	−0.096 ± 0.06	−0.094 ± 0.06	−0.072 ± 0.06
	C(3, 3)	−0.036 ± 0.05	−0.033 ± 0.05	−0.038 ± 0.05	−0.009 ± 0.05
Fourth order	C(4, −4)	0.007 ± 0.02	0.007 ± 0.01	0.010 ± 0.02	0.000 ± 0.01
	C(4, −2)	−0.002 ± 0.01	−0.002 ± 0.01	−0.005 ± 0.01	−0.004 ± 0.01
	C(4, 0)	0.122 ± 0.04	0.119 ± 0.03	0.126 ± 0.04	0.121 ± 0.05
	C(4, 2)	***−0.017 ± 0.02****	***−0.008 ± 0.02****	−0.015 ± 0.02	−0.018 ± 0.04
	C(4, 4)	−0.004 ± 0.02	−0.008 ± 0.02	−0.002 ± 0.02	0.000 ± 0.03
Fifth order	C(5, −5)	0.002 ± 0.01	0.002 ± 0.01	0.001 ± 0.01	0.003 ± 0.01
	C(5, −3)	−0.001 ± 0.01	−0.002 ± 0.01	−0.002 ± 0.01	−0.007 ± 0.02
	C(5, −1)	0.002 ± 0.02	0.001 ± 0.01	0.001 ± 0.01	0.012 ± 0.02
	C(5, 1)	−0.003 ± 0.01	−0.003 ± 0.01	−0.002 ± 0.01	−0.001 ± 0.00
	C(5, 3)	0.010 ± 0.01	0.010 ± 0.01	0.099 ± 0.01	0.007 ± 0.01
	C(5, 5)	−0.004 ± 0.01	−0.005 ± 0.01	−0.004 ± 0.01	0.000 ± 0.01
Sixth order	C(6, −6)	0.001 ± 0.00	0.000 ± 0.01	0.000 ± 0.00	0.000 ± 0.00
	C(6, −4)	***0.000 ± 0.01****	0.000 ± 0.00	0.001 ± 0.01	***0.005 ± 0.00****
	C(6, −2)	0.000 ± 0.00	−0.001 ± 0.00	−0.001 ± 0.00	0.000 ± 0.00
	C(6, 0)	0.000 ± 0.01	0.002 ± 0.01	0.000 ± 0.01	0.000 ± 0.01
	C(6, 2)	−0.001 ± 0.01	−0.001 ± 0.01	0.001 ± 0.01	0.000 ± 0.01
	C(6, 4)	0.001 ± 0.01	0.003 ± 0.01	0.001 ± 0.01	0.000 ± 0.01
	C(6, 6)	−0.003 ± 0.01	−0.003 ± 0.01	0.000 ± 0.01	−0.003 ± 0.01
RMS	Third order	0.175 ± 0.06	0.176 ± 0.06	0.176 ± 0.06	0.170 ± 0.07
	Fourth order	0.134 ± 0.04	0.127 ± 0.03	0.137 ± 0.04	0.137 ± 0.06
	HOA	0.231 ± 0.06	0.227 ± 0.06	0.235 ± 0.05	0.229 ± 0.08
	SA	0.126 ± 0.04	0.119 ± 0.03	0.127 ± 0.04	0.122 ± 0.05
	Coma	0.142 ± 0.07	0.147 ± 0.06	0.144 ± 0.07	0.136 ± 0.06

Table 4
Anterior corneal radius of curvature (r) and asphericity (Q) for different refractive error groups.

Refractive error groups	Apical radius of curvature (r) (mm)	Asphericity (Q)
Emmetropic eyes	7.78 ± 0.26	−0.15 ± 0.10
Low myopic eyes	7.73 ± 0.25	−0.13 ± 0.14
Moderate myopic eyes	7.73 ± 0.31	−0.20 ± 0.22
Low hyperopic eyes	7.77 ± 0.27	−0.13 ± 0.14

these differences are not entirely clear, however there are methodological differences between the studies that make direct comparison difficult. For example, Buehren, Collins, and Carney (2005) used spectacle/trial lenses during measurements and in addition, the eyes were not cyclopleged. He et al. (2002) employed a slow subjective method of recording aberrations in non-cyclopleged eyes. However, RMS of total, corneal and internal HOA for the subjects in our study is similar to that reported in literature for similar age groups (Atchison & Markwell, 2008; Berrio, Tabernero, & Artal, in press).

In accordance with reported data for young adults (Artal, Benito, & Tabernero, 2006; Artal et al., 2002; Berrio, Tabernero, & Artal, in press Llorente et al., 2004; Tabernero et al., 2007; Wei Wang, Wang, & Zou, 2006), corneal primary spherical aberration was positive for all eyes with no differences between the various refractive error groups. Also as reported previously (Mainstone et al., 1998; Sheridan & Douthwaite, 1989), the anterior apical radius of curvature (r) and asphericity (Q) values were not different between the refractive error groups and explains for the similarity in corneal primary spherical aberration values between the groups.

As there were no differences in the corneal aberrations between the various refractive error groups, aberrations from the crystalline lens need to be considered as the possible source of the origin of the differences in total aberrations (Carkeet et al., 2002; Martinez et al., 2009). Carkeet et al. (2002) observed no difference in anterior corneal aberrations and hence speculated aberrations from crystalline lens responsible for the difference in total aberrations between refractive error groups. Martinez et al. (2009) hypothesized that difference in aberrations from the crystalline lens was the most likely cause for the difference in total aberrations in their study. However, Llorente et al. (2004) had observed significant difference for corneal aberrations but not for internal aberrations. The reasons for the difference in results are not clear but methodological differences exist with respect to the instruments used and age range and refractive range of participants.

In considering lenticular (internal) aberrations, myopic and emmetropic eyes exhibited higher negative spherical aberration than hyperopic eyes. Using a schematic eye which generated spherical aberration close to the population mean, Liou and Brennan (1997), suggested that the negative lenticular primary spherical aberration could be a result of either aspheric surfaces of the crystalline lens or the gradient refractive index of the lens or a combination of both (Smith, 2003). It is possible that variations in these factors between the refractive error groups may be contributing for the observed differences in spherical aberration.

A higher negative lenticular spherical aberration may also occur as a result of increase in the radii of curvature of the anterior and posterior surface of the crystalline lens during the equatorial and axial growth of myopic eyes (Atchison et al., 2004; Cheng et al., 1992; Mutti et al., 1998). It may be thus hypothesized that compared to emmetropic or low myopic eyes, the hyperopic eyes fail to grow or expand axially and equatorially resulting in smaller radii of curvature of the anterior and posterior surfaces of the crystalline lens. This would account for the lower negative lenticular spherical aberration in hyperopic eyes.

In addition to the fourth order coefficients, a significant difference was also observed for the third order coefficients (comatic terms) of internal aberrations between the refractive error groups. Hyperopic eyes had less positive horizontal coma $\begin{pmatrix}1\\C\\3\end{pmatrix}$ and a higher negative vertical coma $\begin{pmatrix}-1\\C\\3\end{pmatrix}$ compared to emmetropic eyes.

Table 5
Internal aberration coefficients and RMS for refractive error groups. $p < 0.05$, MANOVA is shown by italicized and bold letters. *, ** and *** depict group significantly different from other.

	Zernike coefficients	Low hyperopia ($n = 353$) Mean ± SD (μm)	Emmetropia ($n = 197$) Mean ± SD (μm)	Low myopia ($n = 100$) Mean ± SD (μm)	Moderate myopia ($n = 25$) Mean ± SD (μm)
Third order	C(3,−3)	0.013 ± 0.05	0.006 ± 0.04	0.011 ± 0.04	0.031 ± 0.05
	C(3,−1)	***−0.050 ± 0.09****,**	***−0.008 ± 0.08****	***−0.001 ± 0.08*****	−0.011 ± 0.09
	C(3,1)	***0.076 ± 0.07****	***0.097 ± 0.059****	0.093 ± 0.06	0.064 ± 0.05
	C(3,3)	0.039 ± 0.04	***0.036 ± 0.03****	***0.050 ± 0.04****	0.043 ± 0.04
Fourth order	C(4,−4)	0.004 ± 0.02	0.000 ± 0.02	0.001 ± 0.02	0.006 ± 0.02
	C(4,−2)	−0.005 ± 0.02*	−0.005 ± 0.02*	0.000 ± 0.02*,**	0.000 ± 0.02
	C(4,0)	***−0.038 ± 0.05****,**,***	***−0.081 ± 0.04****	***−0.088 ± 0.04*****	***−0.095 ± 0.05******
	C(4,2)	0.014 ± 0.03	0.015 ± 0.03	0.014 ± 0.03	0.019 ± 0.04
	C(4,4)	0.018 ± 0.02	0.015 ± 0.02	0.015 ± 0.02	0.014 ± 0.03
Fifth order	C(5,−5)	−0.004 ± 0.01	−0.003 ± 0.01	−0.001 ± 0.02	−0.003 ± 0.01
	C(5,−3)	0.001 ± 0.01	0.003 ± 0.01	0.000 ± 0.01	0.008 ± 0.01
	C(5,−1)	***0.010 ± 0.02****,**	0.009 ± 0.01	***0.011 ± 0.02****	***−0.003 ± 0.02*****
	C(5,1)	0.007 ± 0.01	0.005 ± 0.01	0.003 ± 0.01	0.002 ± 0.01
	C(5,3)	−0.008 ± 0.01	−0.007 ± 0.01	−0.009 ± 0.01	−0.007 ± 0.01
	C(5,5)	0.003 ± 0.01	0.004 ± 0.01	0.006 ± 0.01	0.006 ± 0.01
Sixth order	C(6,−6)	0.000 ± 0.01	0.000 ± 0.01	0.000 ± 0.01	0.002 ± 0.01
	C(6,−4)	***0.001 ± 0.01****	0.001 ± 0.01	0.000 ± 0.01	***−0.006 ± 0.00****
	C(6,−2)	0.000 ± 0.00	0.000 ± 0.00	0.000 ± 0.00	−0.001 ± 0.00
	C(6,0)	0.003 ± 0.01	−0.001 ± 0.01	0.001 ± 0.01	0.003 ± 0.01
	C(6,2)	0.001 ± 0.01	0.000 ± 0.01	0.000 ± 0.01	0.000 ± 0.01
	C(6,4)	−0.001 ± 0.01	−0.002 ± 0.01	0.000 ± 0.01	−0.001 ± 0.01
	C(6,6)	0.002 ± 0.01	0.001 ± 0.01	0.000 ± 0.01	0.004 ± 0.01
RMS	Third order	0.156 ± 0.06	0.146 ± 0.06	0.152 ± 0.05	0.136 ± 0.07
	Fourth order	***0.079 ± 0.04****,**,***	***0.102 ± 0.03****	***0.107 ± 0.04*****	***0.120 ± 0.04******
	HOA	0.190 ± 0.07	0.191 ± 0.06	0.201 ± 0.05	0.195 ± 0.07
	SA	***0.056 ± 0.04****,**,***	***0.084 ± 0.04****	***0.091 ± 0.04*****	***0.096 ± 0.05******
	Coma	0.138 ± 0.07	0.128 ± 0.06	0.133 ± 0.05	0.112 ± 0.06

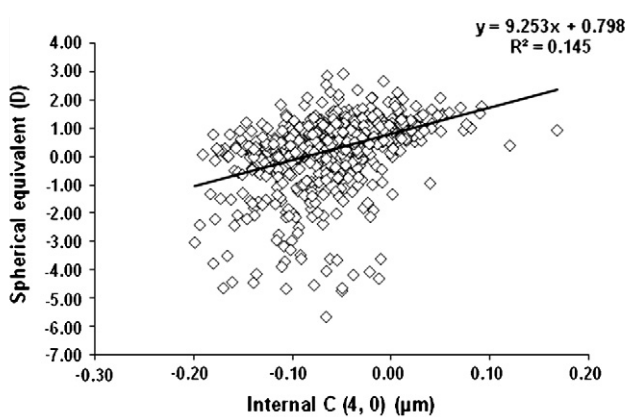

Fig. 2. Correlation between internal C_4^0 and spherical equivalent (M) for 675 eyes.

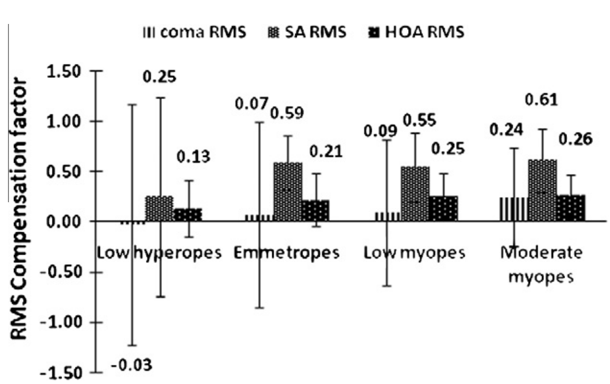

Fig. 3. Compensation factors for RMS of coma, SA and HOA for various refractive error groups. Error bars indicate standard deviation.

Intrinsic factors such as the shape of the surfaces (Skjaerlund, 1988) or an angular origin related to the alignment of the optical components (Artal, Benito, & Tabernero, 2006) have been considered responsible for comatic aberration. It is therefore possible that the crystalline lens in the hyperopic eye may have a more positive shape factor (the coma becomes negative when lens shape becomes positive (Skjaerlund, 1988)). The internal C_3^3 coefficient or horizontal trefoil was also significantly different between the groups. However, the difference in internal third order aberration coefficients $\left(C_3^{-1}, C_3^1 \text{ and } C_3^3\right)$ did not lead to a significant difference in the total ocular third order coefficients between the refractive error groups.

Interestingly, whilst some studies (Artal, Benito, & Tabernero, 2006; Kelly, Mihashi, & Howland, 2004) reported a difference in corneal horizontal coma coefficient between the various refractive error groups, we found no such differences. The possible reason for this may be that in this study, to correct for the misalignment of the reference axes of the instruments, corneal aberrations were calculated by centering the corneal topography map to the entrance pupil center resulting in minimal angle lambda (λ) for all eyes.

5.2. Compensation of aberrations

We observed that the interaction between corneal and internal aberrations helped reduce the total SA RMS as evidenced by the high compensation factor. The lower SA RMS compensation for low hyperopes results in increase in magnitude of total spherical aberration $\left(C_4^0\right)$ compared to other refractive error groups. Previous studies reported that hyperopic eyes had greater compensation for horizontal coma (Artal, Benito, & Tabernero, 2006) however, our data found no difference. This could possibly be due to the negligible difference for angle lambda (λ) from our study.

Whilst previous studies have discussed passive and active adaptive mechanisms (Artal, Benito, & Tabernero, 2006; Kelly, Mihashi, & Howland, 2004) that contribute to compensation of aberrations, we do not have sufficient information to comment on the mechanism.

6. Conclusions

In summary, we found that the hyperopic eyes differed from myopic and emmetropic eyes especially for fourth order aberrations and our data suggests that the refractive components of the crystalline lens (e.g. curvature, asphericity or gradient refractive index) may have contributed to these differences.

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