Chapter 6

OPTICAL ABERRATIONS IN MYOPIC AND HYPEROPIC EYES.

This chapter is based on the article by Llorente, L. et al., "Myopic versus hyperopic eyes: axial length, corneal shape and optical aberrations", Journal of Vision, 4(4):5, 288-298 (2004), http://journalofvision.org/4/4/5/. The coauthors of the study are: Barbero, S., Cano, D., Dorronsoro, C., & Marcos, S.

The contribution of the author of this thesis to the study includes the experimental measurements, data processing and analysis, and statistical analysis (the statistician Laura Barrios performed the ANOVAs).

6.1.- ABSTRACT

PURPOSE: To investigate differences in geometrical properties and optical aberrations between hyperopic and myopic eyes.

METHODS: Measurements were performed in a group of myopic and a group of hyperopic eyes (age-matched 30.3±5.2 and 30.5±3.8 years old, respectively, and with similar absolute refractive error 3.0±2.0 and –3.3±2.0, respectively). Axial length (AL) was measured by means of optical biometry, and corneal apical radius of curvature (CR) and asphericity (Q) were measured by fitting corneal topography data to biconic surfaces. Corneal aberrations were estimated from corneal topography by means of virtual ray tracing, and ocular (total) aberrations were measured using Laser Ray Tracing (LRT). Internal aberrations were estimated by subtracting corneal from ocular aberrations.

RESULTS: AL was significantly higher in myopes than in hyperopes and AL/CR was highly correlated with refractive error spherical equivalent (SE). Hyperopic eyes tended to have higher (less negative) Q and higher ocular and corneal spherical aberration (SA) than myopic eyes. RMS for third-order aberrations was also significantly higher for the hyperopic eyes. Internal aberrations were not significantly different between the myopic and hyperopic groups, although internal SA showed a significant age-related shift towards less negative values in the hyperopic group.

CONCLUSIONS: For these age and refraction ranges, our cross-sectional results do not support evidence of cause-effect relationship between ocular aberrations and ametropia onset (regarded as a fail in the emmetropisation process). Our results may be indicative of presbyopic changes occurring earlier in hyperopes than in myopes.

6.2.- INTRODUCTION

There is a clear motivation for studying myopia due to its high prevalence in developed countries and the public health issue it represents because of its associated ocular pathologies. Research on myopia is mainly aimed at finding optimal alternatives for optical correction of this condition, as well as understanding the mechanisms of emmetropisation and the factors leading the eye to become myopic in order to prevent it. Hyperopia, however, has been less studied due to its lower prevalence in developed countries, relative stability over time, and difficulties in measuring its magnitude accurately in young subjects (Strang et al., 1998).

Most of the existing studies on ametropia have used a biometric approach. However their results are contradictory, probably due to different age groups, refractive error ranges, populations and ethnicities, differences in the statistical power of the studies, and differences across methods of measurement of the different parameters (Gilmartin, 2004). Ametropia can be considered a lack of coordination between the AL and the refractive power of the eye, so that the focused image yielded by the optical system of the eye does not lie on the retina. Therefore, studies on geometrical properties of the eye have mainly focused on AL and corneal parameters.

Myopic eyes are larger than hyperopic eyes, not only in the anteroposterior axis (Strang et al., 1998, Carney et al., 1997, Mainstone et al., 1998, Grosvenor and Scott, 1994), but in all three dimensions (i.e., equatorial, anteroposterior, and vertical axes) (Cheng et al., 1992), with a prolate shape (Atchison et al., 2004). In terms of CR and Q, myopic eyes have steeper corneas (Grosvenor and Goss., 1998, Carney et al., 1997) than hyperopic eyes (Sheridan and Douthwaite, 1989).

Whereas some studies have reported significant differences between refractive groups (Sheridan and Douthwaite, 1989), or significant correlation between CR and refractive error in myopes (Carney et al., 1997) and hyperopes (Strang et al., 1998), other authors did not find significant correlation (Mainstone et al., 1998, Grosvenor and Goss, 1999). The axial length/corneal radius of curvature ratio (AL/CR) seems to be negatively correlated with refractive error more strongly than CR itself in both refractive groups (Strang et al., 1998, Grosvenor and Scott, 1994). Regarding Q, cross-sectional (Carney et al., 1997) and longitudinal (Horner et al., 2000) studies report higher Q (less negative or even positive) with increasing myopia, although this tendency is reduced when only low and moderate myopes are considered (Marcos et al., 2002a). For hyperopes, no correlation has been found between Q and refractive error (Mainstone et al., 1998, Sheridan and Douthwaite, 1989, Budak et al., 1999, Carkeet et al., 2002), although Budak et al. (1999) reported more positive Q values for their moderately myopic eyes than for their hyperopic eyes and for the high myopic eyes included in their study.

In terms of ocular (total) aberrations, whereas some authors did not find a correlation between aberrations and refractive error (Porter et al., 2001, Cheng et al., 2003) or differences in the amount of aberrations across refractive groups (Cheng et al., 2003), other authors reported higher amounts of aberrations in myopes when compared to emmetropes (Collins et al., 1995, He et al., 2002, Paquin et al., 2002, Marcos et al., 2002). For SA specifically, some authors found significant correlation between SA and myopia (Collins et al., 1995), consistent with higher corneal Q with increasing myopia. Some authors found significant differences in SA across high myopes with respect to low myopes, emetropes, or hyperopes (Carkeet et al., 2002), whereas others did not find a significant correlation between SA and a wide range of myopia (Marcos et al., 2002). Ocular aberrations have been reported to increase with age (Mclellan et al., 2001, Artal et al., 2002, Smith and al, 2001, Calver et al., 1999), probably due to a disruption (Artal et al., 2002) of the balance between corneal and internal optics found in young eyes (Artal and Guirao, 1998). In particular, the increase of SA with age has been attributed to a shift of the SA of the crystalline lens towards more positive values (Glasser and Campbell, 1998). Although age-related effects would not be expected within the small range of ages of our subjects (≤40 years) (Mclellan et al., 2001, Artal et al., 2002, Smith et al., 2001, Calver et al., 1999), some studies found differences related to presbyopia (reading glasses demand, reduced amplitude of accommodation) between hyperopes and myopes within our ages range (Spierer and Shalev, 2003, Abraham, 2005).

In this study, a comparison of geometrical properties (AL, CR, and corneal Q) and optical aberrations (ocular, corneal, and internal) between two age- and absolute refraction-matched groups of myopic and hyperopic eyes is presented. The aim of this work is to understand the optical and geometrical properties of the ocular components associated with myopia and hyperopia, and to find out whether differences in these properties between myopic and hyperopic eyes may cause differences in the aberration pattern. Furthermore, this comparison will shed some light on the hypothetical cause-effect relation between myopia and aberrations: retinal image degradation has been reported to induce excessive eye elongation (Schaeffel and Diether, 1999, Rasooly and BenEzra, 1988, Gee and Tabbara, 1988), and since aberrations degrade retinal image, an increased amount of aberrations might be involved with myopia development. Finally, potential differences in the corneal/internal compensation of the SA between myopes and hyperopes were studied, and particularly whether age-related differences exist in the degree of compensation between both groups. Studies of these effects in different refractive groups, particularly if the time scale of those changes is different between these groups, may provide insights to the understanding of the mechanisms of presbyopia.

6.3.- METHODS

6.3.1.- SUBJECTS

Twenty-four myopic and 22 hyperopic eyes with SE ranging from –0.8 to –7.6 D (-3.3 ± 2.0 D) and from +0.5 to +7.4 D (3.0 ± 2.0D), respectively, were measured. Both groups were age-matched: mean ± std was 30.5 ± 3.8 years (range, 26-39 years) for the myopic and 30.3 ±5.2 years (range, 23-40 years) for the hyperopic group.

6.3.2.- *AXIAL LENGTH AND CORNEAL SHAPE*

Axial length was obtained using an optical biometer based on optical coherence interferometry (IOL Master; Carl Zeiss, Germany). Each measurement consisted on the average of 3-5 scans.

Corneal shape (CR and Q) were obtained by fitting the anterior cornea height data from the placido disk videokeratographer (Atlas Mastervue; Humphrey Instruments-Zeiss, San Leandro, CA) to a biconic surface (Schwiegerling and Snyder, 2000) using custom software written in Matlab (Matlab; Mathworks, Natik, MA)(Marcos et al., 2003). The average corneal apical radius of curvature and asphericities are reported for a 6.5-mm diameter.

6.3.3.- *OCULAR ABERRATIONS*

Two different devices were used for the measurement of ocular aberrations in this study: 11 hyperopes and 12 myopes were measured using LRT1, and 11 hyperopes and 12 myopes were measured with LRT2. Both instruments were calibrated before this study and provided similar Zernike coefficients (within 6 mm diameter) on an artificial eye with a phase plate with known aberrations and two real eyes (see Chapter 2, section 2.3.8.1). In addition, the influence of the LRT device in the results was discarded (section 6.4.2.-).

6.3.4.- *CORNEAL TOPOGRAPHY: ESTIMATION OF CORNEAL AND INTERNAL ABERRATIONS.*

The procedure used to estimate the optical aberrations produced by the anterior surface of the cornea has been described in depth by Barbero et al. (2002b, 2002a, 2004): height data of the anterior surface of the cornea obtained from a placido disk videokeratographer (Atlas Mastervue; Humphrey Instruments-Zeiss, San Leandro, CA) were processed using custom routines in Matlab (Matlab; Mathworks, Natik, MA) and exported to an optical design software (Zemax V.9; Focus software, Tucson, AZ), which computes the optical aberrations of the anterior surface of the cornea by virtual ray tracing. Corneal wave aberration was described in the same terms as ocular wavefront aberration (by a 7th Zernike polynomial expansion, using the same pupil diameter). The refractive indices used for the computations were those of the air and aqueous humour (1.3391) corresponding to the same wavelength used to measure ocular aberrations (785 nm). Custom routines in Matlab were used to change the reference of the corneal aberrations from the corneal reflex (keratometric axis) to the pupil centre (line of sight) to ensure alignment of ocular and corneal wave aberration patterns (Barbero et al., 2001, Marcos et al., 2001). For simplicity, the term "corneal aberrations" will be used reference to the aberrations of the anterior surface of the cornea.

Internal aberrations were computed by subtracting, term by term, corneal aberrations from ocular aberrations (after realignment), both expressed in terms of Zernike polynomials. Internal aberrations included, apart from crystalline lens aberrations, the aberrations corresponding to the posterior corneal surface. However, due to the small difference between refractive indices of the aqueous humour and the cornea, these aberrations are negligible in normal eyes (Barbero et al., 2002a).

A compensation factor was defined to quantify the compensation between corneal and internal SA. This factor was 1 when there was compensation and 0 when there was not compensation. The compensation was considered to occur when the sign of the corresponding internal and corneal SA was different and their ratio (internal/corneal) was equal to or greater than 0.5 (compensation of at least 50%).

6.3.5.- REFRACTION

Refraction measurements with the Autorefractometer HARK-597 (Carl Zeiss) were performed in 40 of the 46 subjects included in this study.

In the hyperopic eyes, measurements were performed both prior and after instillation of the tropicamide.

Defocus and astigmatism were also estimated from the corresponding Zernike terms (Z_2^0, Z_2^{-2} and Z_2^2) of the ocular aberration measurement, expressed in dioptres (D). Because the aberration values were estimated from IR measurements, the defocus difference (-0.78 D) between visible (543 nm) and infrared light (786 nm) was added. This value was obtained experimentally (see Chapter 4) and is close to the reported value of longitudinal chromatic aberration between these wavelengths (-0.82 D) (Thibos et al., 1992). When correction for spherical error was necessary during the measurement, the corresponding values in dioptres of the focusing block and trial lenses were considered in the estimation of the final defocus.

The SE obtained from the autorefractor measurements was compared to that estimated from the aberrometry in the 40 eyes. A good agreement between both types of measurements (coefficient of linear correlation r=0.97, and a slope of 0.9997) was found. Autorefraction was shifted by -0.28 D on average with respect to the aberrometry refraction corrected for visible (see Chapter 4). This offset could be due to the refractometer not being perfectly calibrated or a deeper penetration in the retina of the longer wavelengths used in the autorefractometer.

6.3.6.- STATISTICAL ANALYSIS

Student's t-test was used to verify the significability of the differences between groups, and Pearson's correlation test was used to analyse the correlations between two variables. A two-way ANOVA was applied to analyse , using the age as the dependent variable and the refractive group (myope or hyperope) and compensation factor as fixed factors. A three-way ANOVA of the internal SA with the age as the covariate (in order to control its influence), and compensation factor, refractive group and the LRT device used to measure ocular aberrations as fixed factors was performed.

6.4.- RESULTS

6.4.1.- AXIAL LENGTH AND CORNEAL SHAPE

The AL of the hyperopic eyes (22.62 ± 0.76 mm) was significantly lower ($p<0.001$) than the AL of the myopic eyes (25.16 ± 1.23 mm) (Figure 6.1 A). Myopic eyes showed a statistically significant linear correlation of AL with absolute SE ($p=0.001$, $r= 0.57$, slope =0.38 mm/D, intercept at 0 D=24.2 mm). Hyperopic eyes tended to be shorter as AL increased but the correlation was not statistically significant within the sampled SE ($p=0.25$, $r=-0.26$, slope=–0.10 mm/D, intercept at 0 D=22.9 mm).

The CR (Figure 6.1 B) was, on average, steeper in the myopic eyes (7.86 ± 0.37 mm) than in the hyperopic eyes (7.97 ± 0.30 mm). However, this difference was not statistically significant. AL/CR was significantly ($p<0.0001$) higher in the myopic group (3.2 ± 0.2) than in the hyperopic group (2.8 ± 0.1). The correlation between AL/CR and SE was also highly significant ($p<0.0001$, $r=-0.93$, slope=$-0.058D^{-1}$, intercept at 0 D=3.02) including both groups, as well as for myopes ($p<0.0001$, $r=0.87$, slope= $-0.07D^{-1}$) and hyperopes ($p<0.0001$, $r=0.72$, slope= $-0.04D^{-1}$) alone. Q (Figure 6.1 C) was less negative for the hyperopic (–0.10 ± 0.23) than for the myopic group (–0.20 ± 0.17), indicating a more spherical shape of the hyperopic corneas versus a more prolate shape of the myopic ones. This difference was marginally significant ($p=0.054$).

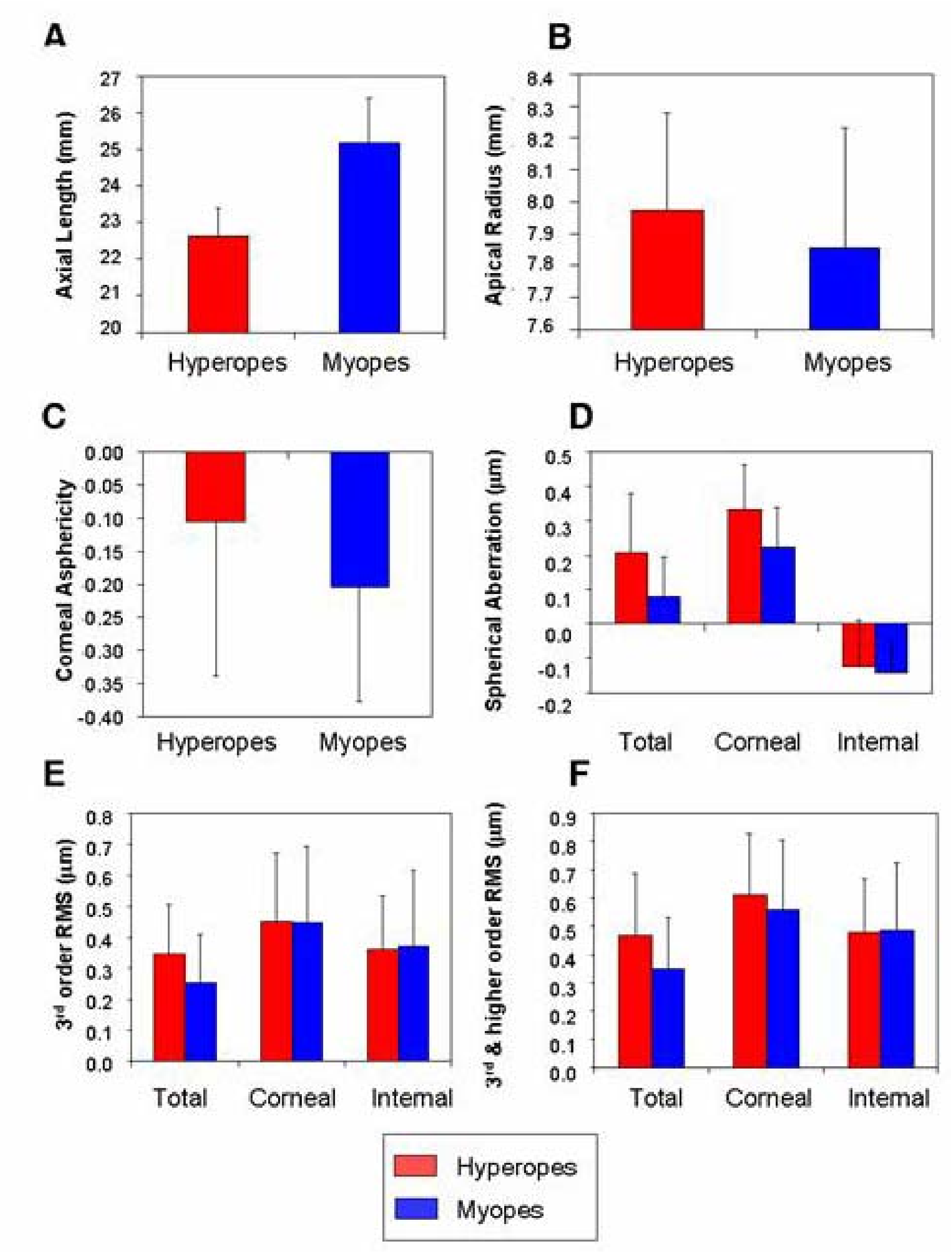

Figure 6.1. Axial length (A), corneal apical radius of curvature (B), corneal Q (C), total, corneal, and internal spherical aberration (D), third-order RMS (E), and third and higher order RMS (F), averaged across hyperopes (red) and myopes (blue). Error bars represent corresponding standard deviation.

6.4.2.- OPTICAL ABERRATIONS

Figure 6.2 shows ocular, corneal, and internal wave aberration maps for myopic (#M2, #M8, and #M6) and three of the hyperopic eyes (#H10, #H17, and #H16). Only HOA are represented (i.e., piston, tilts, defocus, and astigmatism are excluded). A common characteristic shown in six of the eyes is that the corneal map is dominated by the positive SA pattern. Myopic eyes #M4, #M7, and #M5 are representative of the general behaviour in the group of myopes. Internal SA is negative, and partly balances the positive SA, resulting in a less positive ocular SA. Occasionally it may happen that the internal SA overcompensates for the corneal SA, resulting in a slightly negative ocular SA (eye #M4). The examples for hyperopic eyes show the case (eye #H10) of an internal map dominated by negative SA that partly compensates for the positive SA of the cornea, and the case (eyes #H17 and #H11) where ocular and corneal maps are quite similar, indicating a small role of the ocular internal aberrations (i.e., ocular aberration pattern dominated by the positive corneal SA).

Figure 6.1 D shows the average ocular (0.22 ± 0.17 µm and 0.10 ± 0.13 µm), corneal (0.34 ± 0.13 µm and 0.24 ±0.13 µm), and internal (-0.12 ± 0.14 µm and -0.14 ± 0.09 µm) SA for the hyperopic and the myopic groups, respectively, included in this study. Ocular and corneal SAs were significantly higher in the hyperopic group than in the myopic one ($p=0.005$ and $p=0.004$, respectively). However, internal SA was not significantly different ($p=0.62$) between hyperopic and myopic eyes.

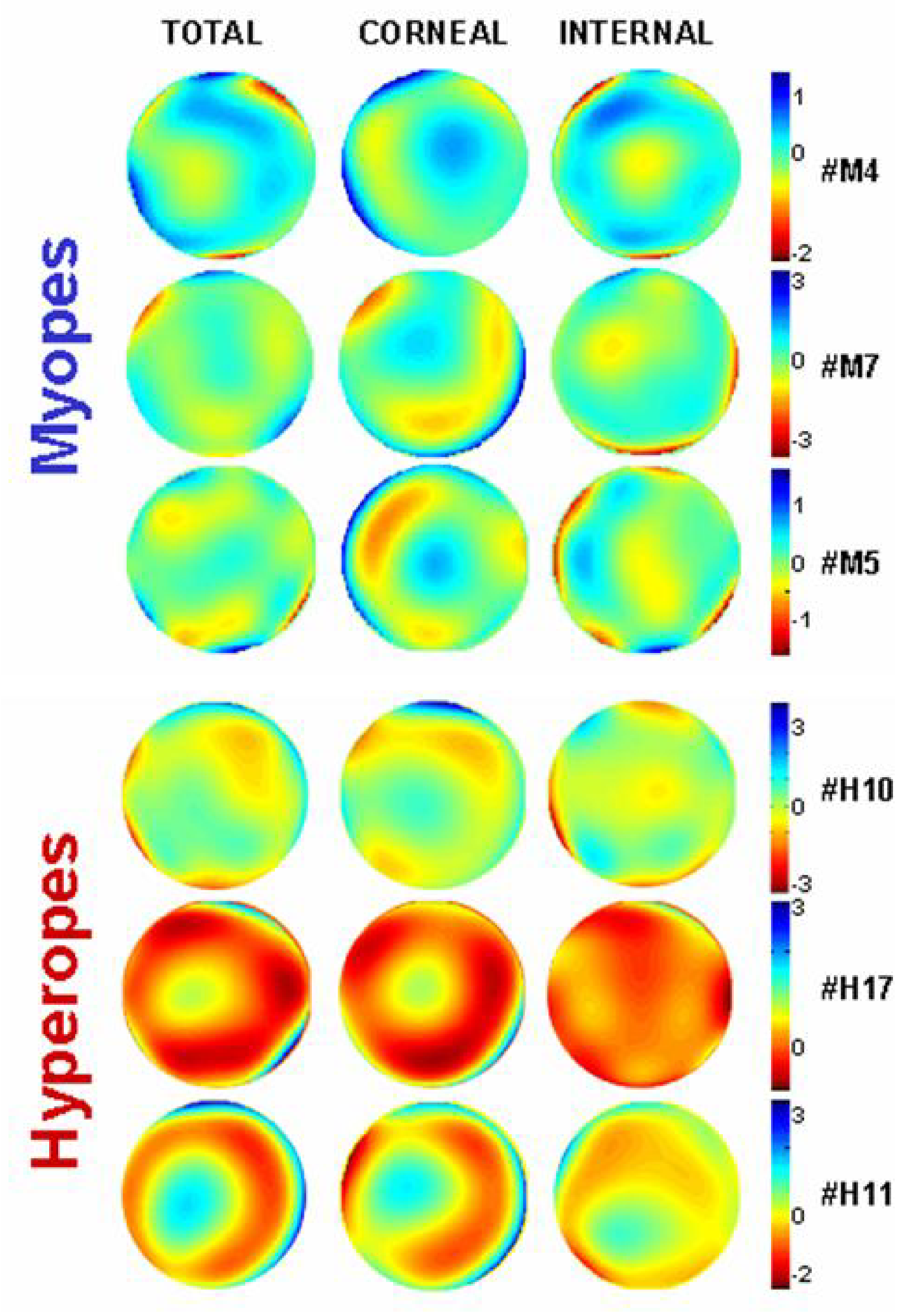

Figure 6.2 Total, corneal, and internal wave aberration maps for three of the hyperopic and three of the myopic eyes. Only HOA are represented. The pupil size was 6 mm.

Although only eyes ≤40 years were recruited for this study, and both groups were age-matched, age-related trends were found in the hyperopic group. Figure 6.3 shows the ocular (green), corneal (red), and internal (blue) SA for each eye sorted by age for the myopic (Figure 6.3 A) and the hyperopic (Figure 6.3 B) group. For the myopic group, there is no particular tendency with age: In most of the eyes, as previously shown, the internal SA is negative and compensates for the positive SA of the cornea. In the hyperopic group, however, this behaviour is followed only by younger eyes (<30 years, n=11), whereas the older eyes (≥30 years, n=11) showed an internal SA significantly (p=0.002) less negative than the internal SA in the younger eyes (–0.04 ± 0.07 µm versus –0.20 ± 0.14 µm). This results in a loss of compensation of corneal and internal aberration in older hyperopes. When the same comparison was carried out between young (<30 years, n=10) and old myopes (≥30, n=14), statistically significant differences were not found in the internal SA of these groups. When comparing similar age groups, significantly higher (more positive) internal (p=0.004) and ocular (p=0.002) SAs were found in the hyperopic than in the myopic older group. In the hyperopic young group, internal SA (-0.20±0.14 µm) tended to be more negative than in the myopic young group (-0.17±0.10 µm), although it did not reach significant levels (p=0.06).

The relationship between age and compensation was statistically significant (p<0.001) whereas the relationship between age and the combination of compensation and refractive group did not reach the limit of significance (p=0.08) (two-way ANOVA, see section 6.3.6.-). The mean age for the hyperopic group with compensation equal or greater than 0.5 was 26.00±1.41 years compared to 29.53±3.50 years for the myopic group. In the case of eyes with less compensation than 50%, the mean age for the hyperopes was 29.67±2.94years, compared to 32.00±3.56 years for the myopes. This confirmed that age had an influence on the compensation of SA, and that there seem to be a displacement in the age of disruption of the compensation of SA between our myopic and hyperopic eyes. The compensation was significantly related to internal SA ($p<0.0001$), as it was the combination of compensation and refractive group ($p<0.05$) (three-way ANOVA, see section 6.3.6.-). The three-way ANOVA also discarded any influence of the LRT device used on the internal SA (and therefore ocular SA) obtained.

Figure 6.1 E shows the average ocular (0.35±0.16 µm and 0.25±0.16 µm), corneal (0.45±0.22 µm and 0.45±0.25 µm), and internal (0.36±0.17 µm and 0.37±0.25 µm) third-order RMS for the hyperopic and the myopic groups, respectively. Ocular third-order RMS was slightly higher in hyperopes than in myopes ($p=0.02$), due to the contribution of the comatic terms. The RMS of horizontal and vertical coma was also significantly higher in hyperopes ($p=0.004$), although when analyzed independently Z_3^1 and Z_3^{-1}were not significantly different across both groups of eyes. Average third and higher order RMSs for our hyperopic and myopic groups are shown in Figure 6.1 F: ocular (0.47±0.22 µm and 0.35±0.18 µm), corneal (0.61±0.22 µm and 0.56±0.25 µm), and internal (0.48±0.19 µm and 0.48±0.24 µm), respectively. Ocular third and higher order RMS was significantly higher ($p=0.03$) for the hyperopic group. Fifth and higher order RMS was not significantly different between both groups.

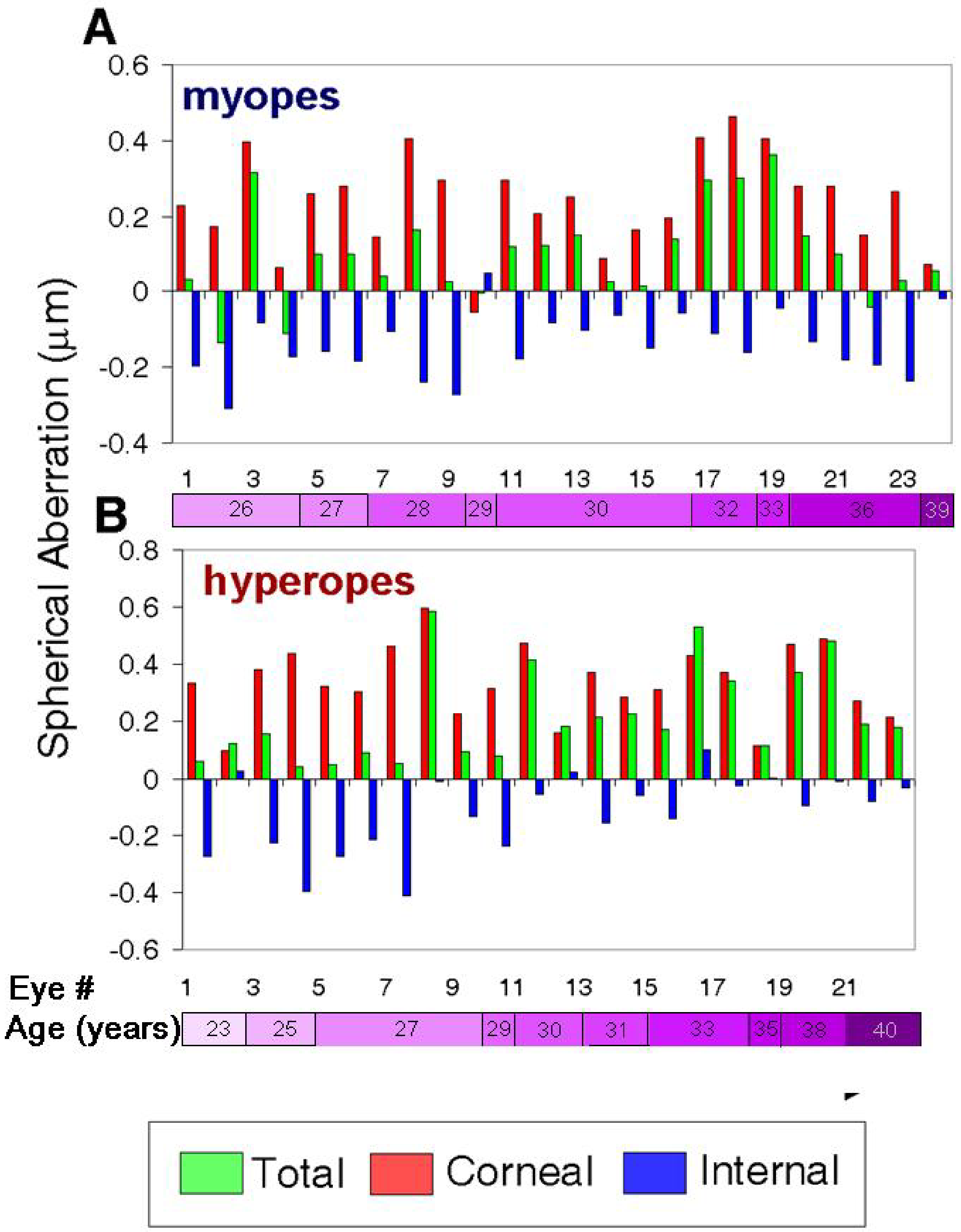

Figure 6.3. Corneal (red), total (green), and Internal (blue) spherical aberration for myopes (A) and hyperopes (B). Eyes are sorted by increasing age, ages ranging from 26 through 39 years in the myopic group and 23 through 40 years in the hyperopic group.

6.5.- DISCUSSION

In this study, geometrical parameters as well as optical aberrations of a group of myopic and hyperopic eyes were measured. Our study showed that differences were not limited to the well-known fact that hyperopic eyes are shorter than myopic eyes. The differences in corneal shape between groups, which are in agreement with some previous studies, resulted in differences in corneal and ocular SA. In addition, Age-related changes were found in the hyperopic internal aberrations, even in the studied small range of ages.

6.5.1.- CORNEAL SHAPE IN MYOPES AND HYPEROPES

As in previous studies (Strang et al., 1998, Carney et al., 1997, Sheridan and Douthwaite, 1989), the hyperopic eyes measured tended to be flatter than myopic eyes, although the variability was large in both groups and no a statistically significant differences were found. A trend towards increased Q in hyperopic eyes, compared with myopic eyes of similar absolute SE, is consistent with the increased corneal SA found in hyperopic eyes of this study. To our knowledge, only three studies (Mainstone et al., 1998, Sheridan and Douthwaite, 1989, Budak et al., 1999) have reported Q in hyperopic eyes, in comparison with myopic and emmetropic eyes. Sheridan and Douthwaite (Sheridan and Douthwaite, 1989) (12 hyperopes and 23 emmetropes) and Mainstone et al. (1998) (25 hyperopes and 10 emmetropes) did not find differences in Q across groups. Budak et al. (1999) did not find a correlation between Q and refractive error. In their group analysis, however, they found more positive Q-values in moderate myopia (-2 to –6 D) than in hyperopia, although this trend was not seen in high myopia or emmetropia. Previous studies (Horner et al., 2000, Carney et al., 1997), including ours (Marcos et al., 2002), found larger amounts of positive corneal SA and Q in high myopia. The present study shows larger amounts of SA in hyperopic than in moderately myopic eyes. The reasons for the corneal geometrical properties (CR and Q) leading to significant differences in SAs across groups may be associated to ocular growth (moderate hyperopic eyes being smaller (Cheng et al., 1992) and more spherical, whereas moderate myopic eyes may flatten more in the periphery than in the central cornea). As a result of increased corneal SA in hyperopic eyes, ocular SA is significantly higher in our group of hyperopes than in a group of myopes with similar absolute refractive error and age.

6.5.2.- AGE RELATED ABERRATION DIFFERENCES IN MYOPES AND HYPEROPES

As opposed to ocular and corneal SA, no significant differences in the internal (i.e., primarily the crystalline lens) SA were found between our groups of myopes and hyperopes. However, despite the fact that inclusion criteria was to be younger than 40 years, age-related differences were found in the hyperopic group, which are not present in the myopic group, as shown in Figure 4B. It seems fairly established that the positive SA of the cornea is balanced by the negative SA of the crystalline (Artal and Guirao, 1998). Artal et al. (2002) showed that this balance is disrupted with age. Several groups have reported changes of ocular SA as a function of age. Figure 6.4 represents data from different cross-sectional studies (Mclellan et al., 2001, Artal et al., 2002, Smith et al., 2001, Calver et al., 1999) showing the increase of SA with age resulting from a shift of the internal SA of the crystalline lens towards positive or less negative values. The myopic (blue) and hyperopic (red) eyes of our study have been superimposed. Ocular SA in myopic eyes does not correlate with age in the small range of ages of our study (p=0.49). However, there is a marginally significant dependence of ocular SA with age in the hyperopic group (p=0.06), with a slope higher than the average data from literature.

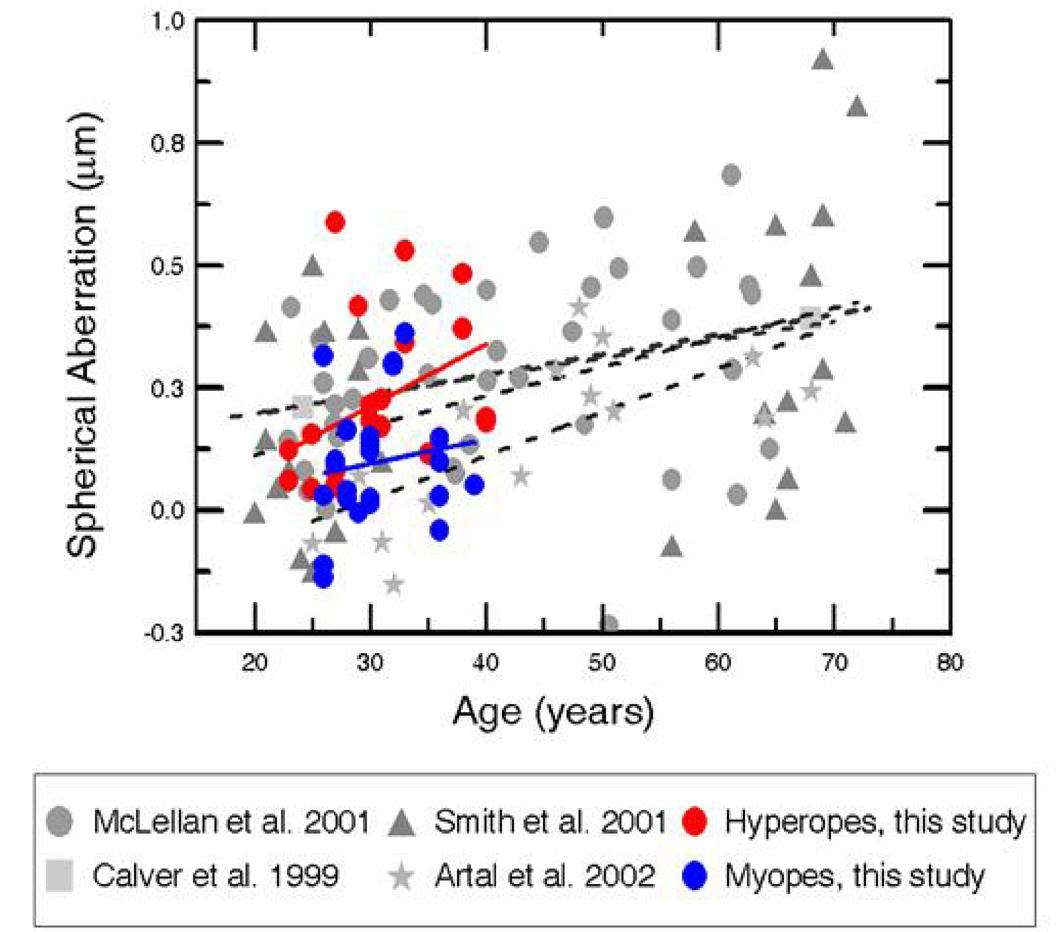

Figure 6.4. Spherical aberration of the hyperopic (red) and myopic (blue) eyes included in this study (6.5-mm pupil) as a function of age in comparison with spherical aberration of eyes from aging studies [circles are data from Mclellan et al. (2001) for 7.32 mm pupil; triangles are estimates from Smith et al. (2001) for a 7.32-mm pupil; squares are averages across two different age groups from Calver et al. (1999) for a 6-mm pupil; and stars are data from Artal et al. (2002), for a 5.9-mm pupil]. Solid lines are the corresponding linear regression to the data.

Our group of myopes shows in general a good compensation of corneal by internal SA. Marcos et al. (2002) showed that the SA balance was in fact well preserved in young myopes across a wide refractive error range. Both younger and older myopic groups show good average corneal by internal compensations (76% and 48%, respectively). The young hyperopes in our study also show a good balance of corneal and internal SA (56% on average), but the average compensation decreases to 14% in older hyperopes. In fact, because corneal SA is higher in hyperopes than in myopes, a more negative internal SA is required to achieve similar proportions of balance.

The negative SA of the crystalline lens is likely due to the aspheric shapes of the crystalline lens surface, with contributions of the radii of curvature and the refractive index distribution. Lack of knowledge of the crystalline lens geometrical and optical properties in hyperopes and myopes prevents assessment of the reasons for the differences in the SA of the crystalline lens in myopes and hyperopes. Reports of changes of SA with accommodation have shown a shift towards less positive (or even negative) ocular SA with increasing accommodative effort (He et al., 2000). Changes in crystalline lens properties that accompany accommodation (increased power, but more likely changes in Q, and perhaps the distribution of refractive index) result in negative SA of the crystalline lens. It is well known that achieving a totally unaccommodated state can be problematic in the hyperopic young eye that tends to accommodate continuously to self-correct for distance vision. Our measurements were performed under tropicamide instillation, which may not be fully paralyzing accommodation or paralyzes it in a resting state that differs between myopes and hyperopes. Our data showed that autorefraction measurements after tropicamide instillation were more positive (0.66 D on average for eight of our hyperopic eyes) than under normal viewing, indicating that tropicamide relaxed accommodation at least partially. It is interesting however that, regardless of whether or not the slight increased negative internal SA is a result of latent accommodation in young hyperopes, the balance is well preserved in both young hyperopes and myopes. A potentially interesting future study would be to investigate internal SA under natural viewing conditions. If the eye has a feedback system that enables balancing of the corneal and internal aberrations, then this balancing would perhaps be most prominent in the accommodative state that the eye is most often in.

Determining the reasons why the SA shifts significantly towards less negative values in hyperopes at an early age requires further investigation. It might indicate that some changes related to age just occur earlier in hyperopes (as shown in Figure 6.3). Most previous studies on the changes of aberrations with age do not report the refractive state of the subjects (to our knowledge only Smith et al. 2001 did explicitly, and only 6 of 27 eyes were hyperopes, all of them older than 58 years). Subjects in the McLellan et al. (2001) study were primarily myopes. Hyperopia has been identified to predispose to early development of presbyopia. Significantly lower amplitudes of accommodation have been found in hyperopes compared to emmetropes aged 20 years, the former requiring reading glasses at an earlier age (Spierer and Shalev, 2003). Hyperopes of an older group (35-39 years) were also found to have significant lower amplitude of accommodation when compared to myopes of the same age range (Abraham, 2005). A question remains whether the physical properties of the crystalline lens that lead to the development of presbyopia occur along with changes in the SA of the crystalline lens. In fact, the properties of the crystalline lens that produce the reported shift with age have never been fully explored. Several studies in vivo using Scheimpflug imaging (Koretz et al., 1997, Dubbelman and van der Heijde, 2001) showed that the posterior and anterior surface of the crystalline lens become steeper with age. Dubbelman and van der Heijde (2001) also reported changes of Q with age. Although those changes were not significant, computer simulations have shown that the combination of reported radii of curvature and asphericities predict the expected trend towards more positive SA with age, even without considering changes in the index of refraction (Marcos et al., 2004). Changes in the index of refraction are, however, expected to play a major role in the aging of the crystalline lens. They have been invoked to explain the so-called lens paradox (Koretz and Handelman, 1986): the apparent contradiction between age-related changes of the lens radii and the refractive error shift. It is likely that changes in the gradient index distribution with age contribute also to the reported changes in SA.

6.5.3.- ABERRATIONS AND DEVELOPMENT OF MYOPIA AND HYPEROPIA

The increased interest in measuring aberrations as a function of refractive error is in part motivated by the study of potential factors involved in the development of refractive errors. It seems fairly established, particularly from experimental myopia studies, that emmetropisation is visually guided (Rabin et al., 1981) and that an active growth mechanism uses feedback from the blur of retina image to adjust the focal length of the eye to the power of the ocular components. When the retinal image is degraded by diffusers, the eye becomes myopic (Bartmann and Schaeffel, 1994) and the induced refractive error correlates to the decrease in contrast and deprivation of spatial frequencies of the retinal image. Because aberrations cause a degradation of the retinal image, it has been argued that increased aberrations may play a role in the development of myopia. Higher amounts of aberrations in high myopes (Collins et al., 1995, Paquin et al., 2002) are consistent with that argument. However, the relationship between aberrations and refractive error may be just a result of the geometrical properties of the ocular components of the ametropic eye, somehow related to the axial elongation, rather than the cause of the ametropia. In this fashion, Garcia de la Cera et al. studied longitudinally the change in optical aberrations and refractive error in chicks subject to form deprivation (de la Cera et al., 2006), and concluded that their experiment supported the hypothesis that the aberrations were a consequence of the geometrical structure of the elongated myopic eye.

In this sense, it is interesting to study the ocular aberrations in both myopic and hyperopic eyes. The defects in an active growth feedback mechanism may be responsible for myopia, but this active growth mechanism does not adequately explain hyperopic error. If similar or larger amounts of aberrations are found in hyperopic than in myopic eyes, then the associations of retinal blur imposed by aberrations and myopia development are not evident. The present study shows that SA is higher in hyperopic eyes than in myopic eyes, and a previous study showed that ocular SA is close to zero even in high myopes (Marcos et al., 2002). Also, the present study shows that third-order aberrations are in fact slightly higher in hyperopes than in myopes of similar absolute refractive errors (up to 7.6 D). If increased HOA occur in myopic eyes, these seem to be more prominent in high myopia (Marcos et al., 2002). It is interesting that even if the emmetropisation mechanism is disrupted, the corneal and internal aberrations are well balanced in young myopes and hyperopes.

Our study is limited to young adults, and data are cross-sectional. Certainly, a possible involvement of the aberrations in the development of refractive errors cannot be fully ruled out unless longitudinal measurements are made at an earlier age. Longitudinal studies would also be useful to assess the reported rapid changes around 30 years of age observed in the cross-sectional data in hyperopic eyes.

6.5.4.- CONCLUSIONS

Some differences of structure and optical properties in hyperopic and myopic eyes have been shown. Myopic eyes, as previously reported, show a significantly higher AL than hyperopic eyes. The AL/CR ratio is also higher in myopic eyes, although no significant difference in CR has been found between both groups. Q tends to be less negative in hyperopic eyes (i.e., more spherical corneal shape), and as a consequence, the corneal SA is also higher in hyperopic than in myopic eyes. Ocular SA is also significantly higher in hyperopic eyes, although internal SA is not significantly different between both groups. HOA were also slightly higher for the hyperopic group, due to the contribution of the comatic terms. A tendency of ocular SA to increase with age at a faster rate in hyperopic than in myopic eyes was also found. Therefore, hyperopic eyes may show an earlier loss of the compensation of the corneal SA by the internal SA.