Myopic versus hyperopic eyes: axial length, corneal shape and optical aberrations

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This study investigated differences in geometrical properties and optical aberrations between a group of hyperopes and myopes (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 total aberrations were measured using a laser ray tracing technique. Internal aberrations were estimated by subtracting corneal from total aberrations. AL was significantly higher in myopes than in hyperopes and AL/CR was highly correlated with spherical equivalent. Hyperopic eyes tended to have higher (less negative) Q and higher total and corneal spherical aberration 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 spherical aberration showed a significant age-related shift toward less negative values in the hyperopic group. For these age and refraction ranges, our cross-sectional results do not support evidence of relationships between emmetropization and ocular aberrations. Our results may be indicative of presbyopic changes occurring earlier in hyperopes than in myopes.

Keywords: hyperopia, myopia, ocular aberrations, corneal aberrations, axial length, corneal shape, emmetropization, presbyopia

Introduction

Because of its high prevalence in the first world, myopia has been widely studied from different approaches. The motivation for these studies is the search for optimal alternatives to correct for the optical degradation induced by this condition and the understanding of the mechanisms of emmetropization and the factors that may lead the eye to become myopic. Hyperopia, however, has been less studied than myopia because of its lower prevalence in developed countries, relative stability, and difficulties in measuring its magnitude accurately in young subjects (Strang, Schmid, & Carney, 1998).

The main structural difference between hyperopic and myopic eyes is the axial length, which is higher for myopic eyes (Carney, Mainstone, & Henderson, 1997; Grosvenor & Scott, 1994; Mainstone et al., 1998; Strang et al., 1998). Cheng et al. (1992), using magnetic resonance for a small sample of eyes, showed that myopic eyes are larger in all three dimensions (i.e., equatorial, antero-posterior, and vertical axes).

There are discrepancies across studies with respect to the corneal shape (both corneal radius of curvature [CR] or asphericity [Q]) and optical aberrations in myopic and hyperopic eyes. Myopic eyes have been found to have steeper corneas (Carney et al., 1997; Grosvenor & Goss, 1998), as opposed to flatter corneas in hyperopic eyes (Sheridan & Douthwaite, 1989). Some studies found significant correlations between CR and myopic (Carney et al., 1997) or hyperopic (Strang et al., 1998) refractive error, or significant differences across refractive groups (Sheridan & Douthwaite, 1989). However, other authors (Grosvenor & Goss, 1999; Mainstone et al., 1998) did not find a significant correlation between CR and refractive error. The axial length/corneal radius of curvature ratio (AL/CR) seems to be negatively correlated with refractive error stronger than

CR itself in both hyperopes (Strang et al., 1998) and myopes (Grosvenor & Scott, 1994). Cross-sectional (Carney et al., 1997) and longitudinal (Horner, Soni, Vyas, & Himebaugh, 2000) studies show higher asphericity (less negative or even positive) with increasing myopia. However, this tendency, consistent with increased corneal spherical aberration in high myopes, is reduced when only low and moderate myopes are considered (Marcos, Barbero, & Llorente, 2002). For hyperopes, no correlation has been found between Q and refractive error (Budak, Khater, Friedman, Holladay, & Koch, 1999; Carkeet, Luo, Tong, Saw, & Tan, 2002; Mainstone et al., 1998; Sheridan & Douthwaite, 1989). However, Budak et al. (1999) reported more positive Q values for their moderately myopic eyes than those for their hyperopic eyes and those for their high myopic eyes.

There are not many studies comparing optical aberrations across refractive groups, and the results are somewhat controversial. Whereas some authors did not find a correlation between aberrations and refractive error (Porter, Guirao, Cox, & Williams, 2001; Cheng, Bradley, Hong, & Thibos, 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, Wildsoet, & Atchinson, 1995; He et al., 2002; Marcos et al., 2002; Paquin, Hamam, & Simonet, 2002). For the spherical aberrations specifically, some authors find significant correlation between spherical aberration and myopia (Collins et al., 1995) or significant differences across high myopes with respect to low myopes, emetropes, or hyperopes (Carkeet et al., 2002), whereas others did not find a significant correlation between spherical aberration and a wide range of myopia (Marcos et al., 2002).

The differences across studies may be due to several reasons: different age groups, refractive error ranges, and populations and ethnicities, differences in the statistical power of the studies, and differences across methods of measurement of CR, Q, and aberrations. Also, these studies correlate either geometrical properties or wave aberrations with refractive error, but to our knowledge, no attempt has been made to find relationships between geometrical features, wave aberrations (of the corneal and internal optics), and refractive error in myopic and hyperopic eyes. The mentioned differences across studies and the diversity of findings make it impossible to extract any conclusion on the relationships between geometrical and optical properties of ametropic eyes.

In this study, we present a comparison of geometrical properties (axial length, corneal apical radius of curvature, and corneal asphericity) and optical aberrations (total, corneal, and internal) between a group of myopic and hyperopic eyes, with age and absolute refraction matched between both groups. We aim to understand the optical and geometrical properties of the ocular components associated with myopia and hyperopia, and whether there are differences in the physical properties of the ocular components

of myopic and hyperopic eyes that may cause differences in the aberration pattern.

The role of the cornea can be directly assessed, whereas only speculations based on the indirect measurements of internal aberrations can be made on the role of the crystalline lens. On the other hand, aberrations have sometimes been invoked to play a role in emmetropization, based on evidence that a degraded retinal image (e.g., by diffusers in animal myopia models [Schaeffel & Diether, 1999] and corneal [Gee & Tabbara, 1998] and lens opacities [Rasooly & BenEzra, 1988] in infants) induce excessive eye elongation. Because aberrations degrade retinal image, one may speculate that increased aberrations may be involved in myopia development. A comparison of the aberrations in myopic and hyperopic eyes may shed light on this hypothesis.

Ocular aberrations have been reported to increase with age (Artal, Berrio, Guirao, & Piers, 2002; Calver, Cox, & Elliott, 1999; Mclellan, Marcos, & Burns, 2001; Smith, Cox, Calver, & Garner, 2001). Artal et al. (2002) showed that aging disrupts the balance between corneal and internal optics found in young eyes (Artal & Guirao, 1998). In particular, the increase of spherical aberration with age has been attributed to a shift of the spherical aberration of the crystalline lens toward positive (or less negative) values (Glasser & Campbell, 1998). According to previous literature (Artal et al., 2002; Calver et al., 1999; Mclellan et al., 2001; Smith et al., 2001), age-related effects would not be expected within the small range of ages of the subjects in our study (23-40 years). The few reports in the literature studying differences of the signs of presbyopia across refractive errors, which are limited to the amplitude of accommodation and need of reading glasses, are indicative that presbyopia may occur earlier in hyperopes (Spierer & Shalev, 2003). In this study, we also tested whether there are differences in the corneal/internal compensation of the spherical aberration between myopes and hyperopes, and in particular, whether there are age-related differences 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 in these groups, may provide insights to the understanding of the mechanisms of presbyopia.

Methods

Subjects

We measured 24 myopic and 22 hyperopic eyes. These eyes did not show any ocular disease or condition apart from the corresponding ametropia. Both groups were age-matched: mean $\pm$ 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. The spherical equivalent refractive error ranged from -0.8 to -7.6 D (-3.3 ± 2.0 D) for the myopic group and from $+0.5$ to $+7.4$ D (3.0 ± 2.0

D) for the hyperopic group. Astigmatism was less than 2.5 D for all of subjects.

This study followed the tenets of the Declaration of Helsinki. Subjects were properly informed and signed written consent forms before enrollment in the study. This consent form was approved by the institutional review board. All measurements were usually performed during the same session at Instituto de Óptica, Madrid, Spain.

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 was described by a biconic surface (Schwiegerling & Snyder, 2000) defined by the apical radii of curvature and asphericities along the steeper (at angle θ) and flatter meridians (at θ+π/2) . The procedure for estimating these parameters has been described in previous publications (Marcos, Cano, & Barbero, 2003). In brief, we used the anterior corneal surface height data obtained from a corneal topography system (Atlas Mastervue, Humphrey Instruments-Zeiss) and fit these data to a biconic surface using custom software written in Matlab. The average corneal apical radius of curvature and asphericities is reported for a 6.5-mm diameter.

Optical aberrations

Total aberrations

Total aberrations were measured using the laser ray tracing technique (LRT), which was developed at the Instituto de Óptica in Madrid, Spain. Its concept has been described in detail previously (Moreno-Barriuso, Marcos, Navarro, & Burns, 2001; Navarro & Losada, 1997). In this technique, collimated light rays are sequentially delivered through different positions of the pupil, and the light reflected off the retina is simultaneously captured by a cooled CCD camera. Ray aberrations are obtained by estimating the deviations of the centroids of the aerial images corresponding to each entry pupil location with respect to the reference (chief ray). These deviations are proportional to the local derivatives of the wave aberrations, which are fitted to a seventh-order Zernike polynomial expansion.

Two different devices were used for the measurement of total aberrations in this study: 11 hyperopes and 12 myopes were measured with a first generation of the instrument described previously (Moreno-Barriuso et al., 2001), and 11 hyperopes and 12 myopes were measured using a second generation of the instrument. Both instruments were calibrated before this study and provided similar Zernike coefficients (within 6.5 mm) with an artificial eye with a phase plate with known aberrations and a real eye. A schematic diagram of the system is shown in Figure 1.This new setup shows specific advantages for measurements on ametropic eyes, such as those of this particular
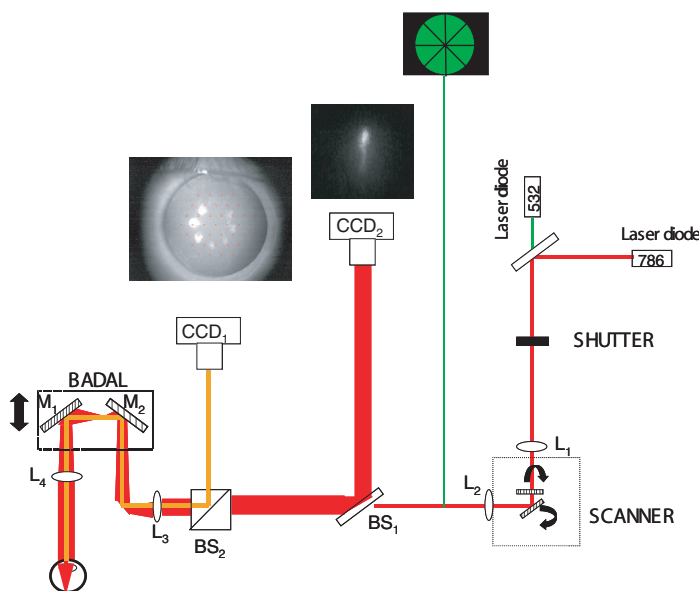

Figure 1. Schematic diagram of a second-generation laser ray tracing. The light source is either a green (532 nm) or infrared (786 nm) laser diode. The beam is focused and collimated by lenses L1 and L2. An x-y scanner system (at the focal point of L2) deflects the rays. A Badal system (formed by lenses L3, L4, and mirrors M1 and M2) corrects for the eye's spherical refractive error. The light reflected back from the retina passes through the Badal system again, and is captured by high-resolution camera CCD2 conjugate to the retina. Another camera (CCD1) conjugate to the pupil and coaxial with the system captures images of the pupil simultaneously with CCD2 and is used for continuous alignment. The fixation target is displayed on a CRT monitor and is viewed through the focusing block.

study: Defocus (between -5.50 D and +13 D) can be continuously corrected with a focusing block, consisting of two flat mirrors and a pair of Badal lenses; in addition, trial lenses can be placed on a plane conjugate to the pupil plane. This makes possible the measurement of eyes with a wide range of spherical error. Defocus is corrected in the illumination, imaging, and fixation channels as well as in the pupil-monitoring channel, without pupil magnification or changes in the sampling density. Best-focus was assessed by the subject while viewing a green target displayed on the fixation channel. A final adjustment was made by the operator while assessing in real time the aerial image for a centered ray. The instrument system presents some other advantages: It is more compact and light, and pupil images are continuously viewed during the measurement and recorded simultaneously with the corresponding aerial images. In addition, the new software and hardware have made it possible to increase the speed from about 4 s to less than 2 s for an entire typical run. Sampling density and pattern can be changed by software.

Each run consisted on 37 rays sampling a 6.5-mm effective pupil in 1-mm steps, arranged in a hexagonal pattern, and each measurement consisted of 5 runs. Movie 1 shows
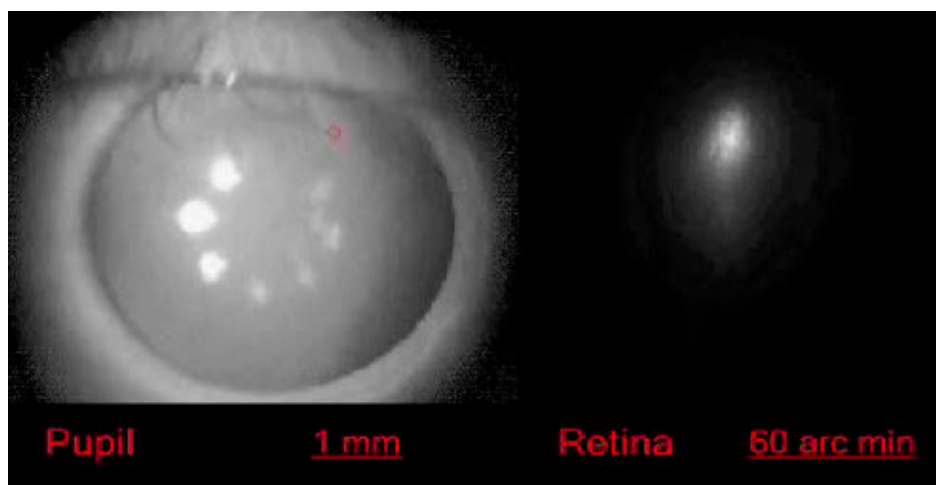
Movie 1. Pupil and retinal images as recorded during a typical measurement.

recordings of a typical run; The left side shows a video of the pupil as the entry beam scans discrete locations of the pupil and the right side shows the set of corresponding retinal aerial images as the beam moves across the pupil.

The illumination source was a diode laser coupled to an optical fiber (Schäfter + Kirchhoff) with a wavelength of 786 nm and a nominal output power of 15 mW. The use of infrared wavelength has some advantages over visible light and the results are equivalent to using visible light (except for defocus) within the accuracy of the technique (Llorente, Diaz-Santana, Lara-Saucedo, & Marcos, 2003). The laser was attenuated by means of neutral-density filters so that light exposure was at least one order of magnitude below safety limits (American National Standard Institute, 1993).

Pupils were dilated with one drop of tropicamide 1% before the measurement, and the subject was stabilized during the process by means of a dental impression. Pupil dilation was used to achieve pupil diameters of at least 6.5 mm, and to avoid fluctuations of accommodation (potentially important in the hyperopic group). All measurements were done using the line of sight as a reference. The subjects fixated foveally to the center of a cross displayed in the fixation channel, and the center of the pupil is aligned with respect to the optical axis of the system. The recommendations of the Committee for Standardization of the Optical Society of America (OSA) were followed regarding ordering and notation for Zernike coefficients (Thibos, Applegate, Schwiegerling, Webb, & Members, 2000).

Corneal aberrations

The technique for estimating corneal aberrations has been described in detail in previous publications (Barbero, et al., 2001; Marcos, Barbero, Llorente, & Merayo-Lloves, 2001): Placido disk corneal topography (Atlas Mastervue; Humphrey Instruments-Zeiss) was used to obtain height data of the anterior surface of the cornea. These data are processed by custom routines in Matlab (Matworks) and exported to an optical design software (Zemax V.9; Focus software), which performs a virtual ray tracing and computes the anterior corneal surface aberrations. The refractive indices used for the computations were those of the air and aqueous humor (1.3391) for a wavelength set to 786 nm, as in total aberrations measurements. Corneal wave aberration was described by a seventh-order Zernike polynomial expansion, following the OSA standard ordering and notation. Custom routines in Matlab were used to change the reference of the corneal aberrations from the corneal reflex to the pupil center to ensure common centration of the total and corneal wave aberration patterns, as has been described in detail in previous studies (Barbero et al., 2001; Marcos et al., 2001). Corneal wave aberrations were also computed for a 6.5-mm pupil. For convenience, we use the term "corneal aberrations" when we refer to the aberrations of the anterior surface of the cornea.

Internal aberrations were computed as the subtraction, term by term, of corneal aberrations from total aberrations. Internal aberrations account primarily for the contribution of the crystalline lens, because the posterior corneal surface aberrations in normal eyes is likely to be negligible (Barbero, Marcos, & Merayo-Lloves, 2002).

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 tropicamide.

Defocus and astigmatism were also estimated from the corresponding Zernike terms (Z_2^0, Z_2^{-2}, and Z_2^2) of the total aberration measurement, expressed in diopters (D). Because the aberration values were estimated from infrared measurements, we added the defocus difference (-0.78 D) between visible (543 nm) and infrared light (786 nm). This value was obtained experimentally (Llorente et al., 2003) and is close to the reported value of longitudinal chromatic aberration between these wavelengths (-0.82 D) (Thibos, Ye, Zhang, & Bradley, 1992).

When correction for spherical error was necessary during the measurement, the corresponding values in diopters of the focusing block and trial lenses were considered in the estimation of the final defocus.

We compared the refractive error spherical equivalent obtained from the autorefractor measurements to that estimated from the aberrometry in the 40 eyes. We found a good agreement between both types of measurements (coefficient of linear correlation r=0.97, and a slope of 0.9997). Autorefraction was shifted by -0.28 D on average with respect to the aberrometry refraction.

Results

Axial length and corneal shape

The axial length (AL) of hyperopic eyes (22.62 ± 0.76 mm) was significantly lower (*p*<.001) than the axial length of myopic eyes (25.16 ± 1.23 mm) (Figure 2A). Myopic eyes showed a statistically significant linear correlation of axial length with absolute spherical equivalent refractive error
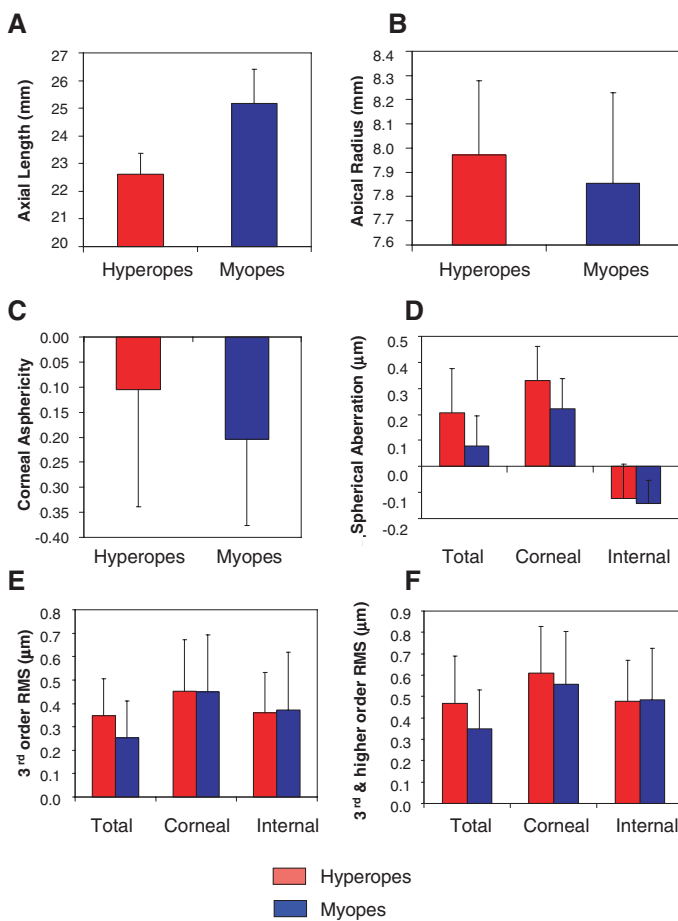

Figure 2. Axial length (A), corneal apical radius of curvature (B), corneal asphericity (C), total, corneal, and internal spherical aberration (D), third-order RMS (E), and third and higher order RMS (F), averaged across hyperopes (red) and myopes (blue). Error bars are SDs.

(*p*=.001, r= 0.57, slope =0.38 mm/D, intercept at 0 D=24.2 mm). Hyperopic eyes tended to shorten with increasing spherical equivalent but the correlation was not statistically significant within the sampled spherical equivalent refractive error (*p*=.25, r=−0.26, slope=−0.10 mm/D, intercept at 0 D=22.9 mm).

The apical radius of curvature of the cornea CR (Figure 2B) 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. The AL/CR was significantly (*p*<.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 refractive error spherical equivalent was also highly significant (*p*<.0001, r=−0.93, slope=−0.058D^{-1}, intercept at 0 D=3.02), and for myopes (*p*<.0001, r=0.87, slope= -0.07D^{-1}) and hyperopes (*p*<.0001, r=0.7171, slope= -0.04D^{-1}) alone. Corneal asphericity Q (Figure 2C) 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*=.054).

Optical aberrations

Figure 3 shows total, corneal, and internal wave aberration maps for three of the hyperopic (#H10, #H17, and #H16) and three of the myopic eyes (#M2, #M8, and #M6). Only third and higher order aberrations 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 spherical aberration pattern. The examples for hyperopic eyes show the case (eye #H10) of an internal map dominated by negative spherical aberration that partly compensates for the positive spherical aberration of the cornea, and the case (eyes #H17 and #H11) where total and corneal maps are quite similar, indicating a small role of the total internal aberrations (i.e., total aberration pattern dominated by the positive corneal spherical aberration). Myopic eyes #M4, #M7, and #M5 are representative of the general behavior in the group of myopes. Internal spherical aberration is negative, and partly balances the positive spherical aberration, resulting in a less positive total spherical aberration. Occasionally it may happen that the internal spherical aberration overcompensates for the corneal aberration, resulting in a slightly negative total spherical aberration (eye #M4).

Figure 2D shows the average total (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) spherical aberration for the hyperopic and the myopic groups, respectively, included in this study. We found that total and corneal spherical aberrations were significantly higher in the hyperopic group than in the myopic one (*p*=.005 and *p*=.004, respectively). However, internal spherical aberration was not significantly different (*p*=.62) between hyperopic and myopic eyes.
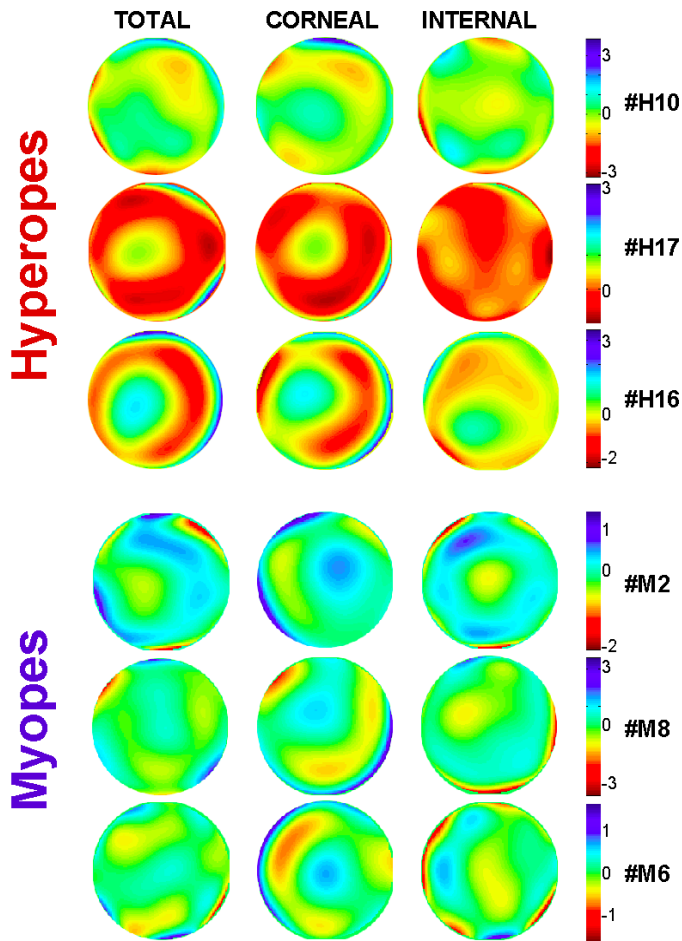
Figure 3. Total, corneal, and internal wave aberration maps for three of the hyperopic and three of the myopic eyes. Only third and higher order aberrations are represented.
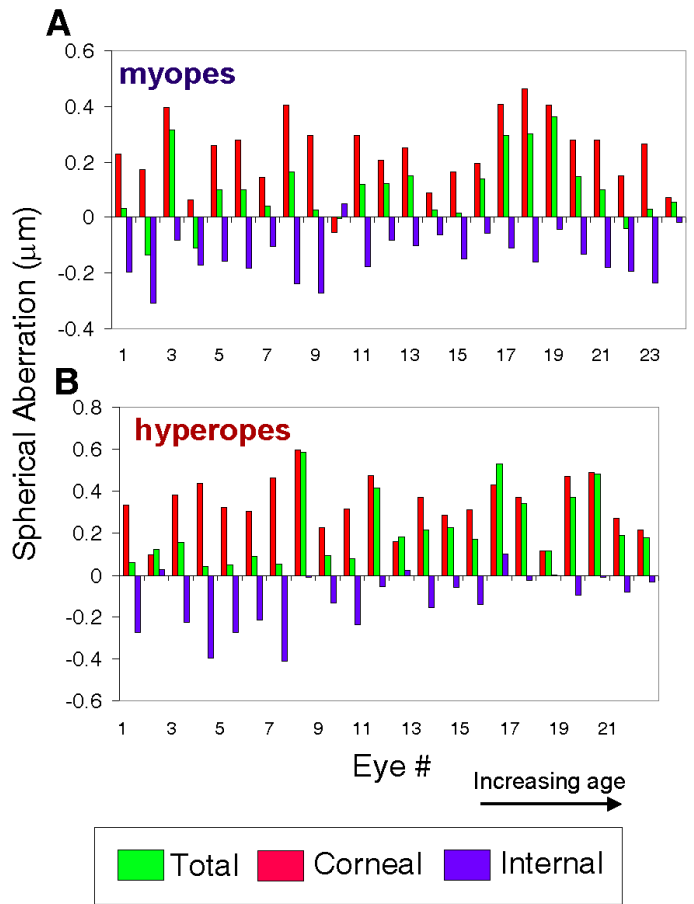

Figure 4. Corneal (red), total (green), and internal (blue) spherical aberration for myopes (A) and hyperopes (B). Eyes are ranked by increasing age. Ages ranged from 26 through 39 years in the myopic group and 23 through 40 years in the hyperopic group.

Only eyes ≤40 years were recruited for this study, and both groups were age-matched. However, we found age-related trends in the hyperopic group. Figure 4 shows the total (green), corneal (red), and internal (blue) spherical aberration for each eye sorted by age for the myopic (Figure 4A) and the hyperopic (Figure 4B) group. In the myopic group, there is no particular tendency with age: For most of the eyes, as previously shown, the internal spherical aberration is negative and compensates for the positive spherical aberration of the cornea. However, in the hyperopic group, this behavior is followed only by younger eyes (<30 years, n=11). The older eyes (≥30 years, n=11) in the hyperopic group showed an internal spherical aberration less negative (–0.04 ± 0.07 μm) than the internal spherical aberration of the younger eyes (–0.20 ± 0.14 μm), and this was statistically significant (p=.002). This results in a loss of compensation of corneal and internal aberration in older hyperopes. The same comparison was performed between young (<30 years, n=10) and old myopes (≥30, n=14), and we did not find statistically significant differences in the internal spherical aberration of these groups. If we compare similar age groups, we find a significantly higher inter-

nal (p=.004) and total (p=.002) spherical aberration (more positive) in the older hyperopic group than in the older myopic group. Internal aberration in the young hyperopic group (-0.20±0.14) tended to be more negative than in the young myopic group (-0.17±0.10), although it did not reach significant levels (p=.06).

Figure 4E shows the average total (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. Total third-order RMS was slightly higher in hyperopes than in myopes (p=.02), due to the contribution of the comatic terms. The RMS of horizontal and vertical coma was also significantly higher in hyperopes (p=.004), although when analyzed independently Z_3^1 and Z_3^{-1} are not significantly different across both groups of eyes. Average third and higher order RMSs for our hyperopic and myopic groups are shown in Figure 4F: total (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. Total third and higher order RMS was signifi-

cantly higher (p=.03) for the hyperopic group. Fifth and higher order RMS was not significantly different between both groups.

Discussion

In this study, geometrical parameters as well as optical aberrations of a group of myopic and hyperopic eyes were measured. Our study shows that differences are not limited to the well-known fact that hyperopic eyes are shorter than myopic eyes. We found that the differences in corneal shape between groups, which are in agreement with some previous studies, result in differences in corneal and total spherical aberration. In addition, we found age-related changes in the hyperopic internal aberrations, even in a small range of ages.

Corneal shape in myopes and hyperopes

As in previous studies (Carney et al., 1997; Sheridan & Douthwaite, 1989; Strang et al., 1998), we found that hyperopic eyes tend to be flatter than myopic eyes, although the variability is large in both groups and we did not find a statistically significant difference. A trend toward increased corneal asphericity in hyperopic eyes, compared with myopic eyes of the similar absolute refractive error spherical equivalent, is consistent with the increased corneal spherical aberration that we found in hyperopic eyes. To our knowledge, only three studies (Budak et al., 1999; Mainstone et al., 1998; Sheridan & Douthwaite, 1989) have reported corneal asphericity in hyperopic eyes, in comparison with myopic and emmetropic eyes. Sheridan and Douthwaite (1989;12 hyperopes and 23 emmetropes) and Mainstone et al. (1998; 25 hyperopes and 10 emmetropes) did not find differences in asphericities across groups. Budak et al. (1999) did not find a correlation between asphericity 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 (Carney et al., 1997; Horner et al., 2000), including ours (Marcos et al., 2002), found larger amounts of positive corneal spherical aberration and asphericity in high myopia. The present study shows larger amounts of spherical aberration in hyperopic than in moderately myopic eyes. The reasons for the corneal geometrical properties (radius of curvature and asphericity) leading to significant differences in spherical aberrations 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 spherical aberration in hyperopic eyes, total spherical aberration is significantly higher in our group of hyperopes than in a group of myopes with similar absolute refractive error and age.

Age-related aberration differences in myopes and hyperopes

As opposed to total and corneal spherical aberration, we did not find significant differences in the internal (i.e., primarily the crystalline lens) spherical aberration between our groups of myopes and hyperopes. However, despite the fact that inclusion criteria was an age less than 40 years, we found age-related differences in the hyperopic group, which are not present in the myopic group, as shown in Figure 4B. It seems fairly established that the positive spherical aberration of the cornea is balanced by the negative spherical aberration of the crystalline lens (Artal & Guirao, 1998). Artal et al. (2002) showed that this balance is disrupted with age. Several groups have reported changes of total spherical aberration as a function of age. Figure 5 represents data from different cross-sectional studies (Artal et al., 2002; Calver et al., 1999; Mclellan et al., 2001; Smith et al., 2001) showing the increase of spherical aberration with age resulting from a shift of the internal spherical aberration of the crystalline lens toward positive or less negative values. We have superimposed the myopic (blue) and hyperopic (red) eyes of our study. Total spherical aberration in myopic eyes does not correlate with age in the small range of ages of our study (p=.49). However, there is a marginally significant dependence of total spherical aberration with age in the hyperopic group (p=.06), with a higher slope than the average data from the literature.
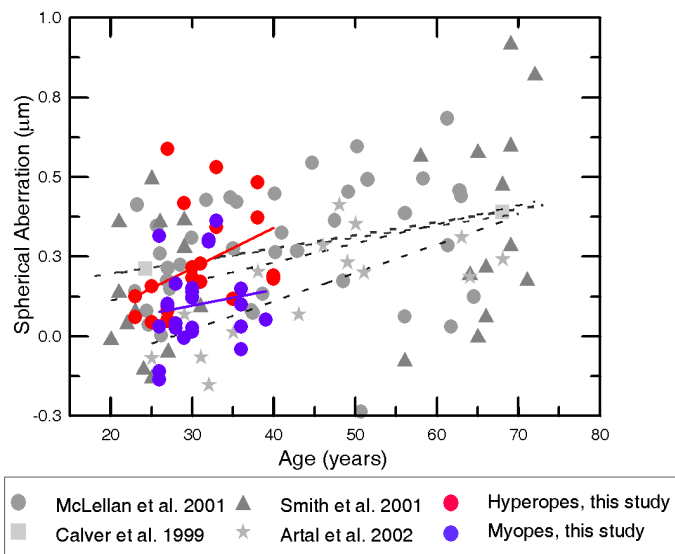

Figure 5. Spherical aberration of the eye in the hyperopes (red) and myopes (blue) of this study (6.5-mm pupil) as a function of age in comparison with the spherical aberration in aging studies from the literature [circles are data from Mclellan et al. (2001) for 7.32 mm; triangles are estimates from 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 spherical aberration. Marcos et al. (2002) showed that the spherical aberration balance was in fact well preserved in young myopes across a wide refractive error range. Both younger and older myopic groups show a 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 spherical aberration (56% on average), but the average compensation decreases to 14% in older hyperopes. In fact, because corneal spherical aberration is higher in hyperopes than in myopes, a more negative internal spherical aberration is required to achieve similar proportions of balance.

The negative spherical aberration 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 spherical aberration of the crystalline lens in myopes and hyperopes. Reports of changes of spherical aberration with accommodation have shown a shift toward less positive (or even negative) total spherical aberration with increasing accommodative effort (He, Burns, & Marcos, 2000). Changes in crystalline lens properties that accompany accommodation (increased power, but more likely changes in asphericity, and perhaps the distribution of refractive index) result in negative spherical aberration 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 from myopes and hyperopes. Our data showed that autorefraction measurements after tropicamide instillation were more positive (0.66 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 spherical aberration 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 spherical aberration 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 spherical aberration shifts significantly toward 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 5). 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 young hyperopes compared to young emmetropes aged 20 years, the former requiring reading glasses at an earlier age (Spierer & Shalev, 2003). A question remains whether the physical properties of the crystalline lens that lead to the development of presbyopia occur along with changes in the spherical aberration 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 (Dubbelman & Heijde, 2001; Koretz, Cook, & Kaufman, 1997) showed that the posterior and anterior surface of the crystalline lens become steeper with age. Dubbelman et al. (2001) also reported changes of asphericity 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 toward more positive spherical aberration with age, even without considering changes in the index of refraction (Marcos, Barbero, McLellan, & Burns, 2004). Changes in the refractive 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 & 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 spherical aberration.

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 emmetropization is visually guided (Rabin, Van Sluyters, & Malach, 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 & 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 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 spherical aberration is higher in hyperopic eyes than in myopic eyes, and a previous study showed that total spherical aberration 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 third and higher order aberrations occur in myopic eyes, these seem to be more prominent in high myopia (Marcos et al., 2002). It is interesting that even if the emmetropization 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.

Conclusions

We have shown some differences of structure and optical properties in hyperopic and myopic eyes. Myopic eyes, as previously reported, show a significantly higher axial length than hyperopic eyes. The AL/CR ratio is also higher in myopic eyes, although no significant difference in corneal radius has been found between both groups. Corneal asphericity tends to be less negative in hyperopic eyes (i.e., more spherical corneal shape), and as a consequence, the corneal spherical aberration is also higher in hyperopic than in myopic eyes. Total spherical aberration is also significantly higher in hyperopic eyes, although internal spherical aberration is not significantly different between both groups. Third and higher order aberrations were also slightly higher for the hyperopic group, due to the contribution of the comatic terms. We also found that total spherical aberration tends to increase with age at a faster rate in hyperopic than in myopic eyes, and so these eyes may show an earlier loss of the compensation of the corneal spherical aberration by the internal spherical aberration.

References

American National Standard Institute (1993). *American National Standard for the safe use of lasers, Standard Z-136.1-1993*. Orlando, FL: Laser Institute of America.

Artal, P., Berrio, E., Guirao, A., & Piers, P. (2002). Contribution of the cornea and internal surfaces to the change of ocular aberrations with age. *Journal of the Optical Society of America A, 19*, 137-143. [PubMed]

Artal, P., & Guirao, A. (1998). Contributions of the cornea and the lens to the aberrations of the human eye. *Optics Letters, 23*, 1713-1715.

Barbero S., Marcos S., Merayo-Lloves J., Moreno-Barriuso E. (2002). Validation of the estimation of corneal aberrations from videokeratography in keratoconus. *Journal of Refractive Surgery, 18*, 263-270. [PubMed]

Barbero, S., Marcos, S., & Merayo-Lloves, J. M. (2002). Total and corneal aberrations in an unilateral aphakic subject. *Journal of Cataract and Refractive Surgery, 28*, 1594-1600. [PubMed]

Bartmann, M., & Schaeffel, F. (1994). A simple mechanism for emmetropization without cues from accommodation or colour. *Vision Research, 34*, 873-876. [PubMed]

Budak, K., Khater, T., Friedman, N., Holladay, J., & Koch, D. (1999). Evaluation of relationships among refractive and topographic parameters. *Journal of Cataract and Refractive Surgery, 25*, 814-820. [PubMed]

Calver, R., Cox, M., & Elliott, D. (1999). Effect of aging on the monochromatic aberrations of the human eye. *Journal of the Optical Society of America A, 16*, 2069-2078. [PubMed]

Carkeet, A., Luo, H., Tong, L., Saw, S., & Tan, D. (2002). Refractive error and monochromatic aberrations in Singaporean children. *Vision Research, 42*, 1809-1824. [PubMed]

Carney, L., Mainstone, J., & Henderson, B. (1997). Corneal topography and myopia: A cross-sectional study. *Investigative Ophthalmology and Visual Science, 38,* 311-320. [PubMed]

Cheng, H., Singh, O., Kwong, K., Xiong, J., Woods, B., & Brady, T. (1992). Shape of the myopic eye as seen with high-resolution magnetic resonance imaging. *Optometry and Vision Science, 69,* 698-670. [PubMed]

Cheng, X., Bradley, A., Hong, X., & Thibos, L. (2003). Relationship between refractive error and monochromatic aberrations of the eye. *Optometry and Vision Science, 80,* 43-49. [PubMed]

Collins, M. J., Wildsoet, C. F., & Atchinson, D. A. (1995). Monochromatic aberrations and myopia. *Vision Research, 35,* 1157-1163. [PubMed]

Dubbelman, M., & Heijde, V. (2001). The shape of the aging human lens: Curvature, equivalent refractive index and the lens paradox. *Vision Research, 41,* 1867-1877. [PubMed]

Gee, S., & Tabbara, K. (1988). Increase of ocular axial length in patients with corneal opacification. *Ophthalmology, 1988,* 1276-1278. [PubMed]

Glasser, A., & Campbell, M. (1998). Presbyopia and the optical changes in the human crystalline lens with age. *Vision Research, 38,* 209-229. [PubMed]

Grosvenor, T., & Goss, D. (1998). Role of the cornea in emmetropia and myopia. *Optometry and Vision Science, 75,* 132-145. [PubMed]

Grosvenor, T., & Goss, D. A. (1999). *Clinical Management of myopia*. Boston: Butterworth-Heinemann.

Grosvenor, T., & Scott, R. (1994). Role of the axial length/corneal radius ratio in determining the refractive state of the eye. *Optometry and Vision Science, 71,* 573-579. [PubMed]

He, J. C., Burns, S. A., & Marcos, S. (2000). Monochromatic aberrations in the accommodated human eye. *Vision Research, 40,* 41-48. [PubMed]

He, J. C., Sun, P., Held, R., Thorn, F., Sun, X., & Gwiazda, J. E. (2002). Wavefront aberrations in eyes of emmetropic and moderately myopic school children and young adults. *Vision Research, 42,* 1063-1070. [PubMed]

Horner, D. G., Soni, P. S., Vyas, N., & Himebaugh, N. L. (2000). Longitudinal changes in corneal asphericity in myopia. *Optometry and Vision Science, 77,* 198-203. [PubMed]

Koretz, J., Cook, C., & Kaufman, P. (1997). Accommodation and presbyopia in the human eye: Changes in the anterior segment and crystalline lens with focus. *Investigative Ophthalmology and Visual Science, 38,* 569-578. [PubMed]

Koretz, J., & Handelman, G. (1986). The lens paradox and image formation in accommodating human lenses. *Topics in Aging Research in Europe, 6,* 57-64.

Llorente, L., Diaz-Santana, L., Lara-Saucedo, D., & Marcos, S. (2003). Aberrations of the human eye in visible and near infrared illumination. *Optometry and Vision Science, 80,* 26-35. [PubMed]

Mainstone, J., Carney, L., Anderson, C., Clem, P., Stephensen, A., & Wilson, M. (1998). Corneal shape in hyperopia. *Clinical and Experimental Optometry, 81,* 131-137. [PubMed]

Marcos, S., Barbero, B., Llorente, L., & Merayo-Lloves, J. (2001). Optical response to LASIK for myopia from total and corneal aberration measurements. *Investigative Ophthalmology and Visual Science, 42,* 3349-3356. [PubMed]

Marcos, S., Barbero, S., & Llorente, L. (2002). The sources of optical aberrations in myopic eyes. *Investigative Ophthalmology and Vision Science* [Abstract]*, 43,* 1510. [Abstract]

Marcos, S., Barbero, S., McLellan, J. S., & Burns, S. A. (2004). Optical quality of the eye and aging. In R. R.Krueger, R. A. Applegate, & S. M. MacRae (Eds.), *Wavefront customized visual correction: The quest for super vision II* (pp. 101-108). Thorofare, NJ: Slack Inc.

Marcos, S., Cano, D., & Barbero, S. (2003). The increase of corneal asphericity after standard myopic LASIK surgery is not inherent to the Munnerlyn algorithm. *Journal of Refractive Surgery, 19,* 592-596. [PubMed]

Mclellan, J., Marcos, S., & Burns, S. (2001). Age-related changes in monochromatic wave aberrations in the human eye. *Investigative Ophthalmology and Visual Science, 42,* 1390-1395. [PubMed]

Moreno-Barriuso, E., Marcos, S., Navarro, R., & Burns, S. A. (2001). Comparing laser ray tracing, spatially resolved refractometer and Hartmann-Shack sensor to measure the ocular wavefront aberration. *Optometry and Vision Science, 78,* 152-156. [PubMed]

Navarro, R., & Losada, M. A. (1997). Aberrations and relative efficiency of light pencils in the living human eye. *Optometry and Vision Science, 74,* 540-547. [PubMed]

Paquin, M., Hamam, H., & Simonet, P. (2002). Objective measurement of optical aberrations in myopic eyes. *Optometry and Vision Science, 79,* 285-291. [PubMed]

Porter, J., Guirao , A., Cox , I., & Williams, D. (2001). Monochromatic aberrations of the human eye in a large population. *Journal of the Optical Society of America A, 18,* 1793-1803. [PubMed]

Rabin, J., Van Sluyters, R. C., & Malach, R. (1981). Emmetropization: A vision-dependent phenomenon. *Investigative Ophthalmology and Visual Science, 20,* 561-564. [PubMed]

Rasooly, R., & BenEzra, D. (1988). Congenital and traumatic cataract: The effect on ocular axial length. *Archives of Ophthalmology, 106*, 1066-1068. [PubMed]

Schaeffel, F., & Diether, S. (1999). The growing eye: An autofocus system that works on very poor images. *Vision Research, 39*, 1585-1589. [PubMed]

Schwiegerling, J., & Snyder, R. W. (2000). Corneal ablation patterns to correct for spherical aberration in photorefractive keratectomy. *Journal of Cataract and Refractive Surgery, 26*, 214-221. [PubMed]

Sheridan, M., & Douthwaite, W. (1989). Corneal asphericity and refractive error. *Ophthalmic and Physiological Optics, 9*, 235-238. [PubMed]

Smith, G., Cox, M., Calver, R., & Garner, L. (2001). The spherical aberration of the crystalline lens of the human eye. *Vision Research, 15*, 235-243. [PubMed]

Spierer, A., & Shalev, B. (2003). Presbyopia among normal individuals. *Graefes Archive for Clinical and Experimental Ophthalmology, 241*, 101-105. [PubMed]

Strang, N., Schmid, K., & Carney, L. (1998). Hyperopia is predominantly axial in nature. *Current Eye Research, 17*, 380-383. [PubMed]

Thibos, L. N., Applegate, R. A., Schwiegerling, J. T., Webb, R. H., & Members, V. S. T. (2000). Standards for reporting the optical aberrations of eyes. *Vision Science and its Applications, OSA Trends in Optics & Photonics, 35*, 110-130. [PubMed]

Thibos, L. N., Ye, M., Zhang, X. X., & Bradley, A. B. (1992). The chromatic eye: A new reduced-eye model of ocular chromatic aberration in humans. *Applied Optics, 31*, 3594-3600.