

# Correlation Between Corneal and Total Wavefront Aberrations in Myopic Eyes

Michael Mrochen, PhD; Mirko Jankov, MD; Michael Bueeler, MS; Theo Seiler, MD, PhD

## ABSTRACT

**PURPOSE:** Corneal topography data expressed as corneal aberrations are frequently used to report corneal laser surgery results. However, the optical image quality depends on all optical elements of the eye, including the human lens. We investigated correlations between corneal and total wavefront aberrations and the relevance of corneal aberrations for representing the optical quality of the total eye.

**METHODS:** Thirty-three eyes of 22 myopic patients were measured using a corneal topography system and a Tscherning-type wavefront analyzer. Pupils were dilated to at least 6 mm in diameter. All measurements were centered with respect to the line of sight. Corneal and total wavefront aberrations were calculated up to the 6th Zernike order in the same reference plane.

**RESULTS:** Statistically significant correlations ( $P < .05$ ) between corneal and total wavefront aberrations were found for astigmatism (C3,C5) and all 3rd Zernike order coefficients such as coma (C7,C8). No statistically significant correlations were found for 4th, 5th, or 6th order Zernike coefficients. On average, all Zernike coefficients for corneal aberrations were larger than the Zernike coefficients for total wavefront aberrations.

**CONCLUSIONS:** Due to the lack of correlation between corneal and total wavefront aberrations in most of the higher order aberrations, measurement of corneal aberrations are of limited use for representation of the optical quality of the human eye, especially after corneal laser surgery. Corneal aberrations and optical elements within the eye are optically balanced. As a consequence, ideal

customized ablations must take both corneal and total wavefront aberrations into consideration. [*J Refract Surg* 2003;19:104-112]

Corneal laser surgery is currently shifting its paradigm from simply correcting spherocylindrical refraction to an optimization of the optical performance of the eye.<sup>1-3</sup> A considerable portion of imaging error in an eye is due to total wavefront and/or corneal aberrations. Therefore, customized ablations that correct total wavefront aberrations<sup>4</sup> or corneal aberrations<sup>5</sup> were recently introduced to refractive surgery.

The optical system of the eye consists of two main optical elements, the cornea and the lens. Although the geometric shape of the anterior and posterior surfaces of the cornea and lens are known to be aspheric<sup>6,7</sup>, these asphericity data are not implemented in many ablation profiles currently used in corneal laser surgery. Assuming the eye is a spherical optical system, higher order aberration may increase after refractive surgery since the shape of the corneal front surface has changed, without taking into consideration the optical and geometrical factors of the eye.<sup>8</sup>

Wavefront sensing provides detailed information on image quality at the retina of an individual eye, whereas corneal topography provides only shape information about the anterior front surface. Consequently, only wavefront sensing may deliver relevant preoperative and postoperative data to rate the quality and the result of a refractive surgery procedure such as laser in situ keratomileusis (LASIK).

The aim of this prospective study was to determine whether corneal aberrations may be representative of total wavefront aberrations in untreated eyes. Myopic eyes were selected because they are more frequently treated by corneal laser surgery than other types of ametropia. The measured data were analyzed to clarify the possible balance between corneal and total wavefront aberrations;

---

From the University of Zurich, Dept. of Ophthalmology, Zurich, Switzerland (all authors), the Departamento de Oftalmologia, Santa Casa de Sao Paulo, Brazil (Jankov), and the Swiss Federal Institute of Technology, Institute of Biomedical Engineering, Zurich, Switzerland (Mrochen and Bueeler).

Dr. Mrochen is a scientific consultant of WaveLight Laser Technology AG, Erlangen, Germany. This work was supported in part by the Swiss National Science Foundation and by a research grant from the University of Zurich.

Correspondence: Michael Mrochen, PhD, University of Zurich, Dept. of Ophthalmology, Frauenklinik Str. 24, CH-8091 Zurich, Switzerland. Tel: 41.1.255 4993; Fax: 41.1.255 4472;

E-mail: Michael.Mrochen@aug.usz.ch

Received: December 18, 2001

Accepted: September 20, 2002

findings are discussed with respect to relevance in corneal laser surgery.

### PATIENTS AND METHODS

Thirty-four myopic eyes of 22 patients scheduled for LASIK at Zurich University were enrolled in this prospective cohort study. Patients were eligible if they were at least 18 years of age, were free of ocular diseases, had a best spectacle-corrected visual acuity (BSCVA) of 20/20 or better, their spherical equivalent refraction was myopic, and manifest refractive cylinder was less than 3.00 diopters (D). Ten eyes were excluded from the study due to previous corneal laser surgery. Demographic and clinical data are listed in Table 1. Patient age ranged from 22 to 58 years (mean  $39 \pm 9$  yr). Slit-lamp microscopy showed no pathological alteration in any of the investigated eyes. Uncorrected visual acuity (UCVA), manifest refraction, BSCVA, auto refraction (Automatic Refractor/Keratometer model 599, Humphrey Instruments, Carl Zeiss, Jena, Germany), videokeratography, and wavefront analyzer data were obtained using standardized examination procedures with the systems described below. For corneal topography measurements and wavefront sensing, pupils were dilated to a diameter of at least 6 mm using tropicamide 1% (Mydriaticum Dispersa, Ciba Vision, Hettlingen, Germany).

### Corneal Topography

Anterior corneal topography was obtained with a placido disk videokeratoscope with customized software (Keratograph, Oculus, Wetzlar, Germany). The customized software provided an export of the corneal height data processed from a corneal image of the 22 rings, as used in this measuring device. Reproducibility and accuracy of videokeratographic measurements were tested using an artificial cornea provided by the manufacturer. Reproducibility was  $\pm 0.1$  D for a mean sphere of 44.18 D and  $\pm 0.01$  mm at a 6-mm-diameter for the root-mean-square surface error of 0.47 mm. The accuracy of the topography system was determined by means of conic surfaces made of polymethylmethacrylate (PMMA) (Ola Bengtsson. Surface analysis of local irregularities of the human cornea by corneal topography. Diploma thesis, Swiss Federal Institute of Technology, 2002) similar to the methods reported by Guirao and Artal.<sup>9</sup> All surfaces were made with a radius of 8.04 mm and asphericities of  $k = -0.8, -0.53, -0.3, -0.1,$  and  $+0.4$ . The test surfaces were determined by means of a surface profiling system. The accuracy was found to be

**Table 1**  
**Demography and Clinical Data of Study Patients**

	Mean $\pm$ SD	Median	Range
Age (yr)	$39 \pm 9$		22 to 58
UCVA*	$0.14 \pm 0.01$	0.01	
BSCVA†	$1.12 \pm 0.18$	1.20	
Manifest refraction (D)	Sph: $-4.41 \pm 2.76$ Cyl: $-0.84 \pm 0.71$		

\*Uncorrected visual acuity  
†Best spectacle-corrected visual acuity

better than 0.05 mm for all test surfaces for a 6-mm pupil. Reproducibility and accuracy of the topography device were calculated from five independent measurements. Here, the standard deviation for the total root-mean-square wavefront error (rms-wavefront error) was on average  $\pm 0.09$  mm at a pupil size of 6.0 mm in diameter.

Similarly, the anterior surface of each patient eye was measured five times. The height data of each single measurement were transferred to an analysis software program that averaged the height data and interpolated the Zernike coefficients up to the 6th order, as described below.<sup>9</sup> The topography system was centered onto the line of sight to achieve consistency in centration. All topography data were expressed with respect to this reference axis. The software included a mathematical algorithm for precise overlapping of the height data for averaging with respect to the reference axis. Data were accepted for averaging if measurements provided height data over a pupil area of at least 6.0 mm in diameter.

### Wavefront Sensing

Wavefront sensing was performed using the "Dresden Aberrometer" based on the principles of Tscherning aberrometry. Details of the measuring device have been published.<sup>10-12</sup> Basically, this ray tracing method uses the mathematical analysis of a retinal spot pattern grabbed by a video camera. From the deviations of the spot positions to their ideal position, the first derivative of the wavefront was calculated. Five independent measurements were performed, wavefronts were averaged, and the resulting mean wavefront was expressed in Zernike coefficients up to the 6th order.

Prior to measurement of patient eyes, calibration and reproducibility were tested by means of an artificial eye including several phase plates (WaveLight Laser Technologie AG, Erlangen, Germany) with defined wavefront aberrations. Reproducibility for a

total root-mean-square wavefront error of rms = 1.14 μm was 0.08 μm at a pupil size of 6 mm in diameter.

For both topography and wavefront measurements, a single measurement was accepted if the maximum deviation of the root-mean-square wavefront error did not differ more than 2.5 times the standard deviation from the mean value. Approximately one measurement per eye was discarded according to this criterion.

**Data Analysis**

Wavefront aberrations for the anterior cornea were computed by numerical fitting to a Zernike expansion:

$$W(x, y) = \sum_n C_n \cdot Z_n(x, y) \cdot R \tag{1}$$

with  $x = X/R, y = Y/R$  the normalized dimensions of the pupil varying from -1 to 1, regardless of the pupil radius  $R$ . Corneal wavefront aberrations were calculated as the difference in optical path between the chief ray and the marginal rays of the pupil. Total wavefront aberrations were calculated based on the deviations of the measured retinal spot locations from their aberration-free positions. Again, wavefront aberrations were computed by numerical fitting in terms of Zernike polynomials up to the 6th order.

The Zernike coefficients presented in our study must be divided by the appropriate normalization factor  $F_n$  and multiplied by the pupil radius to convert them into the Zernike representations proposed by the VSIA taskforce.<sup>13</sup> Here the normalization factors are determined by

$$F_n = \begin{cases} \sqrt{2(n+1)} & \text{if } n-2m \neq 0 \\ \sqrt{(n+1)} & \text{if } n-2m = 0 \end{cases} \tag{2}$$

where  $n$  is the order of the Zernike monomial and  $m$  is the frequency of the term.

The defocus  $C_4$  and astigmatism terms C3, C5, are used in conventional sphere (*Sph*) and cylinder (*Cyl*) powers and a cylinder axis as  $Sph / Cyl \times \alpha$ . The equations for these calculations are

$$C_4 = \frac{\sqrt{C_4^2 + C_5^2}}{R} \quad \alpha = \arctan\left(\frac{C_5}{C_4}\right) \quad \alpha = -\frac{1}{2} \arctan\left(\frac{C_5}{C_4}\right) \tag{3}$$

If  $C_5 \geq 0$ , then  $\alpha$  (degrees) must be changed according to  $\alpha = 90 + \alpha$  to obtain axis notation as used to report refraction data in ophthalmology. The signs of sphere (*Sph*) and cylinder (*Cyl*) are reversed to

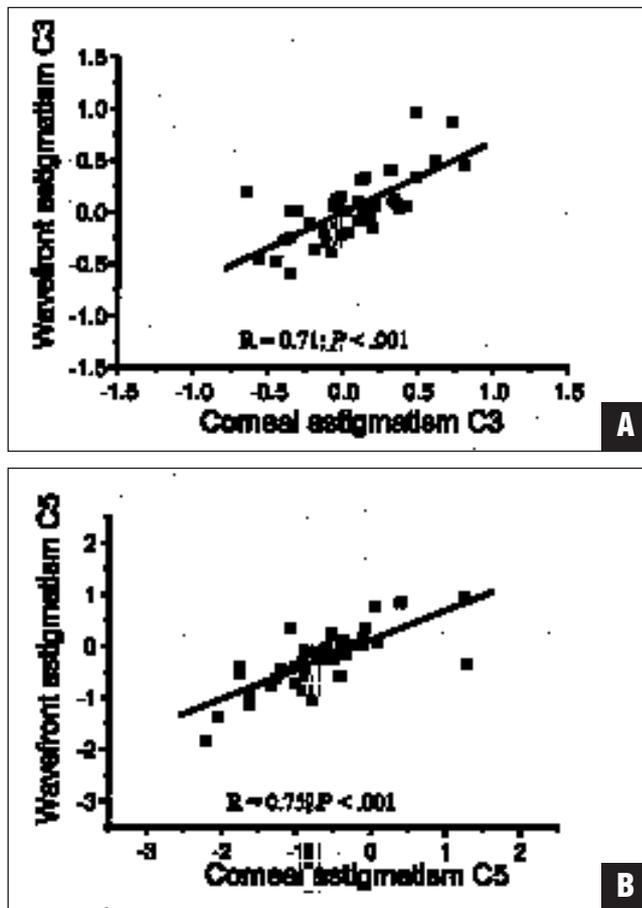


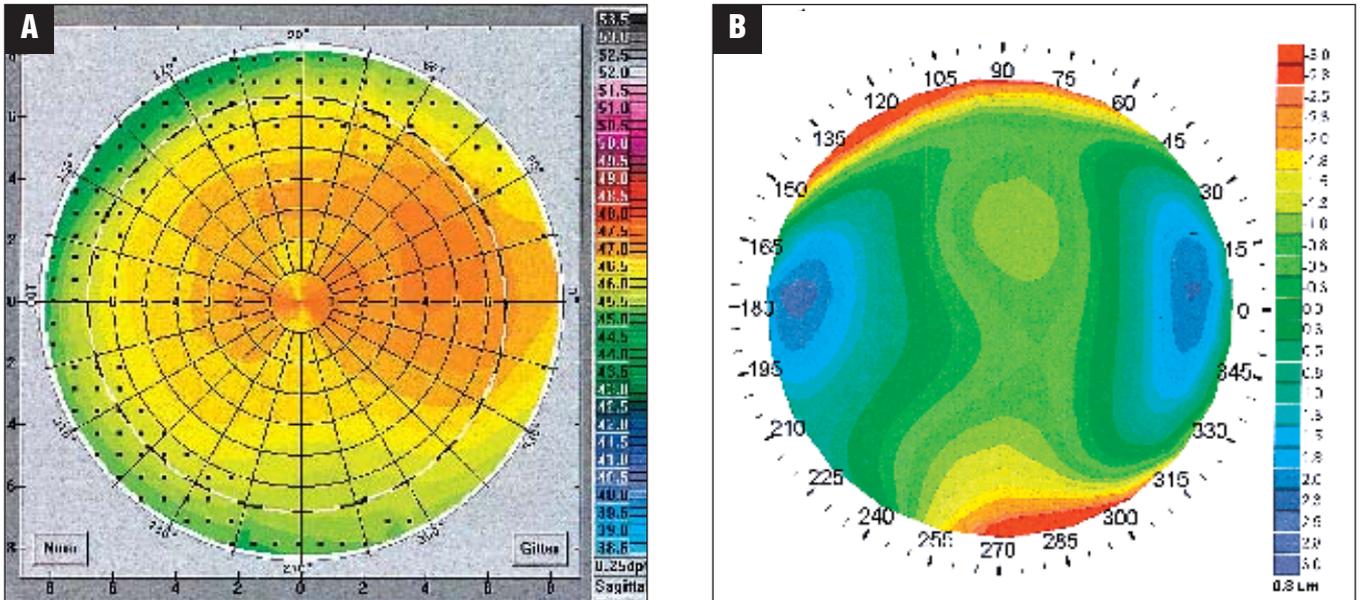
Figure 1. Correlation between Zernike coefficients for corneal and total wavefront astigmatism. A) C3: Astigmatism at 0°/90°; B) C5: Astigmatism at ±45°. All correlations were statistically significant with a significance level of  $P < .001$ . The correlation coefficients were  $R = 0.71$  for C3 and  $R = 0.75$  for C5.

obtain the best ophthalmic correction. Astigmatism differences between wavefront, topography, and manifest refraction were calculated on the basis of vector analysis.<sup>14</sup>

Corneal aberrations obtained from topography were correlated with total wavefront aberrations by means of a linear regression (Spearman rank correlation coefficient). A commercially available software package (Origin 6.0, OriginLab Corp, Northhampton, MA) was used for data analysis. From linear regression for each single Zernike coefficient the following conclusions can be drawn:

1. Where a significant correlation between the corneal and the total wavefront coefficient was found:

- a. A slope of  $m > 1$  indicates that the total optical error is greater than the cornea alone.
- b. A slope of  $m = 1$  indicates that the wavefront is created by the cornea alone.



**Figure 2.** A) Topography, and B) wavefront map of the eye that was excluded from the cohort of eyes because of lenticular astigmatism. Corneal astigmatism was -0.29 D at an axis of 5°. Astigmatism of the total wavefront was -1.88 D at an axis of 88°. The manifest cylinder was -2.00 D at an axis of 86°.

c. A slope of  $m < 1$  indicates that the corneal wavefront error aberration is compensated to some degree.

2. No significant correlation between total and corneal wavefront coefficients was found

a. The corneal aberrations are completely compensated by the optical aberrations of the intraocular structures.

b. The sensitivity of both measurement devices is too small for the determination of a correlation. This error increases with the order of the investigated Zernike mode.

**RESULTS**

Figure 1 represents the correlation between the Zernike coefficient C3 (0°/90° – astigmatism) and C5 (45° – astigmatism) for corneal and total wavefront aberrations. In both cases, the positive correlation  $R > 0.75$  was found to be statistically significant ( $P < .001$ ). The mean difference between the wavefront cylinder and the manifest cylinder was 0.27 D, whereas the mean difference between topography and manifest cylinder was 0.59 D. Four out of the 33 investigated eyes had a total wavefront cylinder larger than the corneal cylinder. One eye (1 patient) was excluded from the cohort of eyes used for the correlations because of an unexpected large lenticular astigmatism of -2.00 D, as demonstrated in Figure 2.

Figure 3 shows a similar but weaker correlation for 3rd order vertical coma C7 and horizontal coma

C8. The correlation coefficients were found to be  $R = 0.59$  and  $R = 0.67$  for the vertical coma C7 and horizontal coma C8, respectively. For both coefficients, the correlations between corneal 3rd order coma and the 3rd order coma of the total wavefront were statistically significant ( $P < .001$ ). In contrast, there was no statistically significant correlation ( $P = .07$ ) between the spherical aberration of the cornea and the spherical aberration of the total eye (Fig 4). All 4th to 6th order Zernike coefficients showed no significant correlation. The correlation coefficients and significance levels for all determined Zernike coefficients are listed Table 2.

The slope factors  $m$  between the corneal and total aberrations resulting from the linear correlations between corneal and total wavefront aberrations were found to be  $< 1.0$  for all Zernike coefficients (Table 2). Thus, the corneal aberrations are on average significantly larger than the total wavefront aberrations. This points toward a natural wavefront compensation of the corneal aberrations by the intraocular structures of the eye.

The correlation between the manifest and the wavefront spherical equivalent was determined to be  $Y = 1.04 + 0.1 D$  with a correlation coefficient  $R = 0.5$  and a significance level of  $P < .001$  for the study group. The correlations of the total wavefront defocus with the spherical aberration of the total wavefront ( $R = 0.16$ ;  $P = .33$ ) and the spherical aberration of the cornea ( $R = -0.26$ ;  $P = .09$ ) were not statistically significant; neither were the

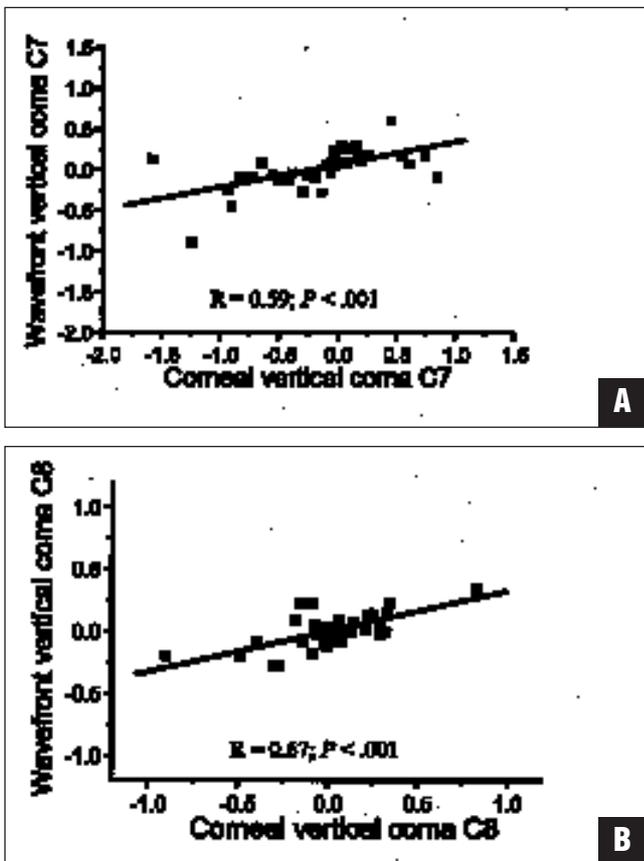


Figure 3. Correlation between Zernike coefficients for corneal and total wavefront coma. A) The correlation coefficient for the vertical coma C7 was  $R=0.59$  with  $P<.001$ ; B) Correlation coefficient for the horizontal coma C8 was  $R=0.67$  with  $P<.001$ .

correlations of the corneal defocus with the spherical aberration of the cornea ( $R=-0.01$ ;  $P=.96$ ) and the spherical aberration of the total wavefront ( $R=-0.29$ ;  $P=.06$ )

**DISCUSSION**

The main finding of this work was that astigmatism and 3rd order optical aberrations originate from corneal aberrations in most of the investigated eyes. In contrast, 4th order spherical aberration as well as all other 4th to 6th orders do not correlate with the aberrations of the anterior surface of the cornea. This indicates that in a normal myopic eye, intraocular structures may to a certain degree compensate for some of the higher order aberrations originated at the corneal front surface. In particular, the lack of correlation between corneal and total 4th order aberration (Fig 4) might be due to such an optical compensation mechanism.

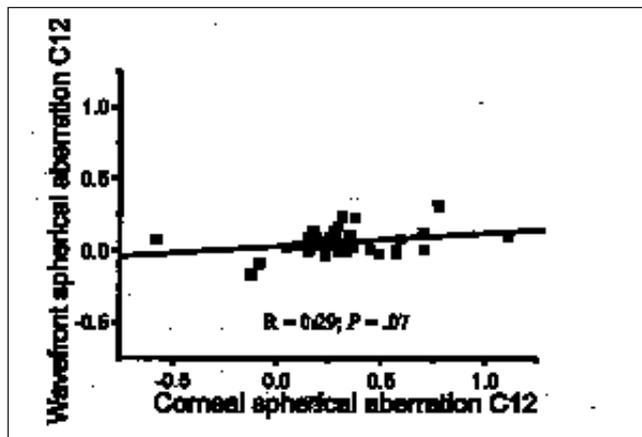


Figure 4. Spherical aberration C12 of the total wavefront as a function of corneal spherical aberration. The correlation was not statistically significant ( $P=.07$ ) with a correlation coefficient of  $R=0.29$ .

Polynomial (order)	Slope factor m	Correlation coefficient R	Significance level P
C3 Astigmatism (2nd)	0.68	0.71	<.001*
C5 Astigmatism (2nd)	0.58	0.75	<.001*
C6 3 – Foil (3rd)	0.14	0.35	.026*
C7 Coma (3rd)	0.28	0.58	<.001*
C8 Coma (3rd)	0.33	0.66	<.001*
C9 3 – Foil (3rd)	0.24	0.43	.006*
C10 4 – Foil (4th)	0.06	0.18	.28
C11 Astigmatism (4th)	0.06	0.16	.32
C12 Spherical aberration (4th)	0.01	0.29	.07
C13 Astigmatism (4th)	0.01	0.07	.69
C14 4 – Foil (4th)	0.08	0.27	.09
C15 5 – Foil (5th)	0.06	0.24	.14
C16 3 – Foil (5th)	0.03	0.19	.23
C17 Coma (5th)	0.24	0.15	.35
C18 Coma (5th)	0.09	0.46	.31
C19 3 – Foil (5th)	0.06	0.26	.11
C20 5 – Foil (5th)	-0.03	-0.25	.12
C21 6 – Foil (6th)	0.03	0.18	.28
C22 4 – Foil (6th)	0.06	0.06	.30
C23 Astigmatism (6th)	0.01	0.04	.82
C24 Spherical aberration (6th)	0.02	0.09	.60
C25 Astigmatism (6th)	0.01	0.03	.25
C26 4 – Foil (6th)	-0.03	-0.18	.27
C27 6 – Foil (6th)	-0.01	-0.07	.66

\*Statistically significant  $P<.05$

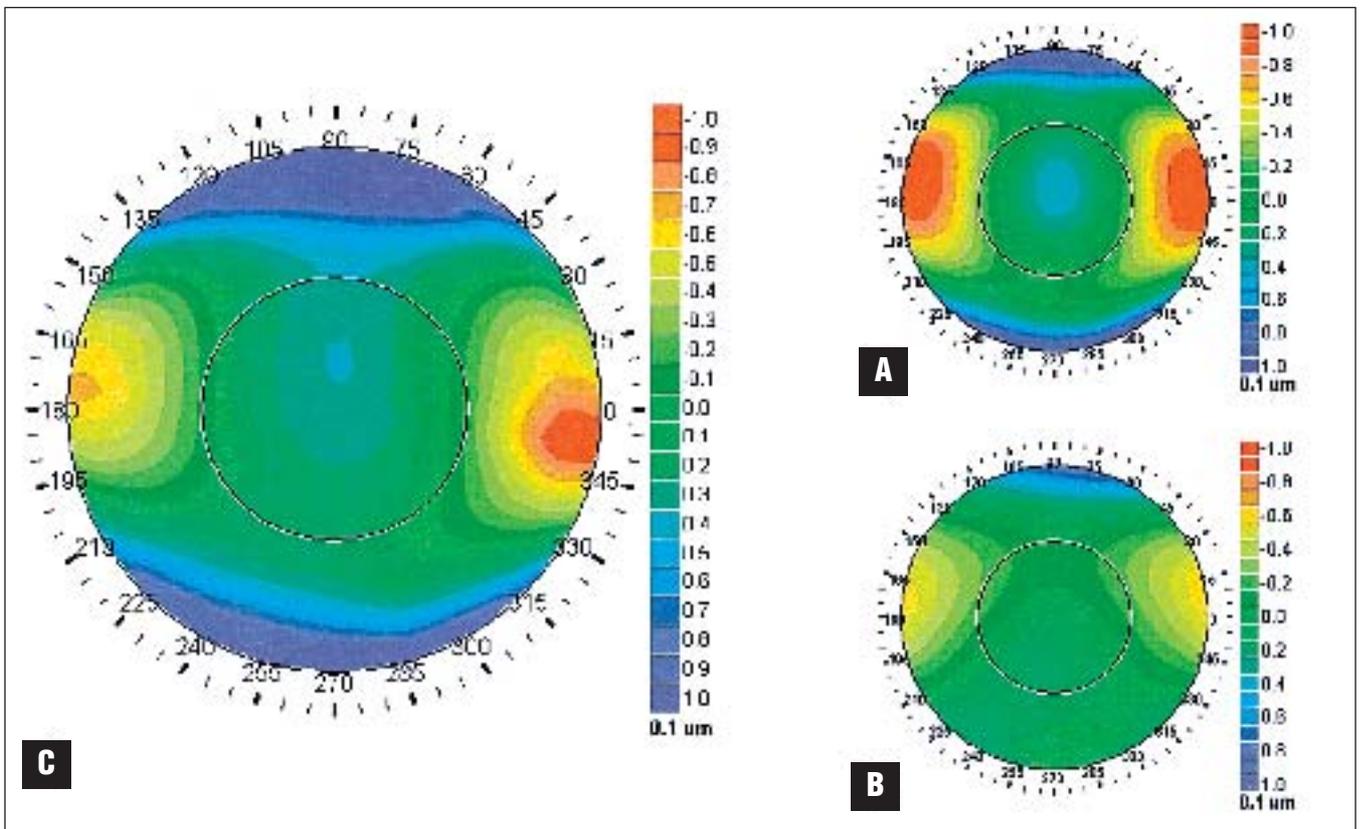
Our data demonstrate that higher order aberrations of most myopic eyes are composed of an individual mix of 3rd and 4th order aberrations. Furthermore, practically all higher order aberrations were confined to the 3rd and 4th Zernike orders. Since corneal and total wavefront aberrations beyond the 4th order contribute little to total ocular higher order aberrations, the detection of significant corneal aberrations above the 4th order may represent an abnormal condition. As an example, Schwiegerling and colleagues<sup>15</sup> measured 8th and 16th order aberrations in eyes that had undergone eight-incision radial keratotomy. One eye was excluded from the correlations because of unusually high lenticular astigmatism. This case demonstrates that the individual eye might have astigmatism or 3rd order aberrations, larger than the measured cornea aberrations originating from the intraocular structures.

From both a fundamental and clinical point of view, it is necessary to investigate the distribution of total wavefront aberrations in the normal population. A subjective method of measuring wavefront aberrations of the total eye has been described by Howland and Howland.<sup>16</sup> They concluded that spherical aberration is often of largely meridional character and that coma, an aberration hitherto regarded as unimportant in the eye, plays a dominant role in the wave equation at all pupil sizes. Porter and colleagues<sup>17</sup> used a modified Hartmann-Shack wavefront sensor to measure the monochromatic wave aberration in both eyes of 109 normal human subjects across a 5.7-mm pupil. They showed that most Zernike modes are relatively uncorrelated with each other across the population. Thus, even though there appears to be a random variation in the eye aberrations from subject to subject, many aberrations in the left eye were significantly correlated with their counterparts in the right. Consequently, the optics of the eye generally mirror symmetric in the left and right eye of the same person. In our study, the data are not large enough to demonstrate statistically relevant potential differences between left and right eyes. Further clinical studies should focus on this dependence to clarify the mirror symmetry of intraocular structures.

The fact that there is a good correlation between corneal and total aberrations for comatic terms indicates that coma is mostly of corneal origin. The lack of correlation between corneal and total spherical aberrations indicates a significant role of the crystalline lens, as suggested in previous publications. However, the results presented in earlier

studies demonstrate a variety of relationships between corneal and lenticular aberrations. Under certain circumstances, lenticular aberrations seem to compensate for corneal aberrations.<sup>18,19</sup> However, others report compounding or even adding corneal and lenticular aberrations.<sup>20</sup> Although these studies evaluated aberrations within a single meridian, Artal and Guirao<sup>21</sup> compared corneal and ocular aberrations across the entire pupil, based on video-keratoscopic and double-pass measurements. In all five of their subjects, the lens significantly compensated for the major corneal aberrations, with an average of 80% correction for cornea spherical aberrations and 50% correction for corneal coma. The results of the study presented by Smith and colleagues<sup>22</sup> demonstrated that the two sources of optical aberrations, relaxed lens and cornea, show spherical aberration of negative and positive value, respectively, thus leading to a lower level of spherical aberration for the eye as an optical entity. Artal and colleagues<sup>23</sup> reported on the relative contribution of optical aberrations of the cornea and the internal ocular optics, with the crystalline lens as the main component, to the overall aberrations in the eyes of young subjects. Here, the aberrations of both the cornea and internal optics were larger than for the complete eye, indicating that the first surface of the cornea and internal optics partially compensate for each other's aberrations, thus producing an improved image quality. All data presented in our study were consistent with previously presented data. The lack of correlations for 5th and 6th order aberrations, as found in our study, might suggest a significant amount of lens aberration. However, it is more likely that the corneal topography as well as the wavefront device were not accurate enough to provide information on possible compensation mechanisms for these Zernike modes. Also we must take into account the larger noise for the 5th and 6th order corneal aberrations, which reduce the predictability of correlations presented in this work.

The amount of total aberrations in the eye increases approximately linearly with age.<sup>24-27</sup> Larger aberrations in the older eye produce a more degraded retinal image than in younger counterparts. Artal and associates<sup>28</sup> analyzed the aberrations of the anterior cornea and the internal optics (17 subjects) considered as isolated systems. On average, the aberrations of the cornea increased moderately with age. However, the increment measured was too small to account for the increase in aberrations in the complete eye. The aberrations of the internal surfaces showed a larger variability



**Figure 5.** Wavefront maps of **A)** mean corneal front surface, **B)** mean total wavefront aberrations, and **C)** average difference of the total and corneal wavefront aberration.

with a tendency to increase in middle-aged and older subjects. Neither ocular component itself appeared to explain the change in aberrations in the entire eye. Thus, only a different coupling between corneal and internal aberrations in younger and older eyes could explain the optical deterioration of the eye with age.

Various groups have studied the increase of higher order aberrations after corneal laser surgery by corneal<sup>29-32</sup> and total wavefront measurements.<sup>33-35</sup> However, due to the lack of statistically significant correlations between cornea and wavefront aberrations (4th to 6th order), clinically relevant conclusions about the optical quality of a treated eye may not be drawn from topography measurements only. Nevertheless, corneal topography is currently the method of choice to determine changes at the anterior front surface due to ablation profile. Marcos and associates<sup>36</sup> investigated changes of corneal, total, and internal wavefront aberrations to evaluate outcomes in standard refractive surgery procedures. Their results show that a combination of corneal and total aberrations is necessary to understand individual surgical outcomes and their impact on

visual performance. In general, both corneal and total aberrations increased with surgery, but the particular increment depended on the individual subject. This is critical in any planned aberration-free procedure such as wavefront-guided LASIK, which cannot rely on the mean population response, but must be adapted to the individual patient. Again, this demonstrates the limitation of corneal topography as a guide for new refractive procedures and provides a strong endorsement of the value of ocular wavefront sensing for those applications.

In Figure 5, an example is shown using the mean corneal and total wavefront aberrations without defocus and tilt as well as the averaged difference between both. Here, the mean wavefront aberrations of the intraocular optical structure consists only of positive spherical aberration (more myopic in the pupil periphery) and astigmatism of approximately 0.50 D with an axis of 90°; the cornea has a systematic astigmatism of approximately 0.75 D with an axis of 0° and a negative spherical aberration (less myopic in the pupil periphery). These approximations were based on vector analysis. A large number of eyes have intraocular

astigmatism (lenticular astigmatism) on the order of 0.50 D.<sup>14,37-39</sup> The amount of corneal astigmatism is much higher than the amount of refractive astigmatism, indicating that lenticular astigmatism generally reduces the amount of refractive astigmatism. This might also explain the reduced slope  $m < 1$  for the correlation between corneal and total wavefront cylinder, as shown in Figure 1.

A subtraction of corneal aberrations from wavefront aberration is only allowed under specific conditions. The eye must be considered as an optical system of successively arranged coaxial refracting optical elements, each surface producing specific aberrations. The Gaussian image of a point object formed by the first surface serves as an object for the second surface, and so on. In addition, the exit pupil of the first surface is the image of the system entrance pupil formed by the second surface, and so on. Since one might calculate the aberrations of a surface at the exit pupil, the system aberrations are the sum of the peak values of the wavefront aberrations contributed by each surface. For example, if  $C7_i$  is the peak value of coma contributed by one of the optical elements, then

$$C7 = \sum_{i=1}^k C7_i \tag{4}$$

is the peak value of coma for an optical system consisting of  $k$  surfaces. Thus, wavefronts can be added or subtracted if they are calculated with respect to the same reference plane, such as the exit pupil.<sup>40</sup> Consequently, one might calculate the optical aberrations of the intraocular structures by subtracting the corneal aberrations from the total wavefront aberrations.

What conclusions can be drawn for refractive corneal laser surgery? Current laser surgery techniques aim to change the shape of the corneal front surface for correcting sphere and cylinder and also the higher order aberrations of the individual eye. However, spherical aberration of the total wavefront was found to be significantly higher in eyes after corneal laser surgery.<sup>33-35</sup> In particular, myopic corrections of more than -7.00 D demonstrate this effect<sup>8</sup> because ablation profiles ignore the balance between corneal and total wavefront aberrations. Such ablation profiles will alter the natural optical balance of the eye. As a consequence, this may lead to a significant increase in total wavefront aberrations after refractive procedures.

A theoretical description of the resulting increase in spherical aberration due to myopic correction is

given by Manns and colleagues.<sup>8</sup> In detail, they used an aspheric eye mode (Novaro eye model<sup>41</sup>) and ray tracing techniques. They concluded that corrections for axial myopia of -5.00 D or less induce primary spherical aberrations on the order of the preoperative values. Furthermore, myopic corrections of more than -5.00 D resulted in an almost exponential increase of the spherical aberration. Since little is known about the impact of an increase of spherical aberration on visual acuity under physiological conditions, one might speculate that wavefront-guided treatments or even standard corneal laser surgery should be limited to approximately -5.00 to -6.00 D in sphere in order to avoid a systematic increase in spherical aberration. On the other hand, it is still unclear how much spherical aberration is tolerated by the visual system before visual acuity under physiological conditions is reduced. Introducing customized ablations based on both corneal and total wavefront aberration might be the method of choice to overcome the undesired increase in spherical or other higher order aberrations. A practical solution was reported by Manns and coworkers.<sup>42</sup> They proposed explicit equations and an algorithm for the correction of spherical aberration and ametropia. Required input parameters can be derived directly from the patient's aberrometry and corneal topography data. A comparable method has already been applied in wavefront-guided treatments<sup>2,34,43</sup>, which assume the cornea is an aspheric surface with a corneal curvature of  $R=7.78$  mm and an average asphericity of -0.3.

The aim of modern corneal laser surgery should be to optimize the total wavefront aberrations of each individual eye. Preoperative consideration of corneal aberrations alone will result in incorrect assumptions for the optical performance of the total eye and a consequent misinterpretation of the optical quality of an individual eye. For the same reason, even customized laser treatments should always take the corneal front surface and the total wavefront aberrations into consideration. Further clinical studies on diagnostic corneal and total wavefront measurements are needed to open alleys for new treatment methods in refractive laser surgery.

REFERENCES

1. MacRae SM, Schwiegerling J, Snyder R. Customized corneal ablation and super vision. *J Refract Surg* 2000;16(suppl): S230-S235.
2. Mrochen M, Kaemmerer M, Seiler T. Wavefront-guided laser in situ keratomileusis: Early results in three eyes. *J Refract Surg* 2000;16:116-121.

3. MacRae S, Krueger RR, Applegate RA. Customized Corneal Ablations. The Quest for SuperVision. Thorofare, NJ: Slack, Inc; 2001.
4. Klein SA. Optimal corneal ablation for eyes with arbitrary Hartmann-Shack aberrations. *J Opt Soc Am A* 1998;15:2580-2588.
5. MacRae S, Schwiegerling J, Snyder RW. Customized and low spherical aberration corneal ablation design. *J Refract Surg* 1999;2:246-248.
6. Kiely PM, Smith G, Carney LG. The mean shape of the human cornea. *Optica Acta* 1982;29:1027-1040.
7. Fernandez V, Manns F, Zipper S, Sandadi S, Hamaoui M, Tahj H, Ho A, Parel J-M. Measurement of the topography of human cadaver lenses using the PAR corneal topography system. *SPIE Proceedings, Ophthalmic Technologies XI* 2001:113-118.
8. Manns F, Ho A, Parel J-M. Calculation of the primary spherical aberration of an eye model using paraxial ray-tracing with matrix optics. *SPIE Proceedings, Ophthalmic Technologies XI* 2001:57-65.
9. Guirao A, Artal P. Corneal wave aberration from videokeratography accuracy and limitation of the procedure. *J Opt Soc Am A* 2000;17:955-965.
10. Mierdel P, Wiegand W, Krinke H-E, Kaemmerer M, Seiler T. Measuring device for determine monochromatic aberrations of the human eye. *Ophthalmologie* 1997;6:441-445.
11. Mrochen M, Kaemmerer M, Mierdel P, Krinke H-E, Seiler T. Principles of Tscherning aberrometry. *J Refract Surg* 2000;16(suppl):S570-S571.
12. Mierdel P, Kaemmerer M, Mrochen M, Krinke H-E, Seiler T. Ocular optical aberrometer for clinical use. *J Bio Med Opt* 2001;6:200-204.
13. Thibos LN, Applegate RA, Schwingerling JT, Webb R. Report from the VSIA taskforce on standards for reporting optical aberrations of the eye. *J Refract Surg* 2000;16(suppl):S654-S655.
14. Holladay JT, Moran JR, Kezirian GM. Analysis of aggregate surgical induced refractive change, prediction error, and intraocular astigmatism. *J Cataract Refract Surg* 2001;27:61-79.
15. Schwiegerling J, Greivenkamp JW, Miller JM, Snyder RW, Palmer ML. Optical modeling of radial keratotomy incision patterns. *Am J Ophthalmol* 1996;122:808-817.
16. Howland HC, Howland B. A subjective method for the measurement of the monochromatic aberrations of the eye. *J Opt Soc Am A* 1977;67:1508-1518.
17. Porter J, Guirao A, Cox IG, Williams DR. Monochromatic aberrations of the human eye in a large population. *J Opt Soc Am A* 2001;18:1793-1803.
18. El Hage S, Berny F. Contribution of the crystalline lens to the spherical aberration of the eye. *J Opt Soc Am* 1973;63:205-211.
19. Tomlinson A, Hemenger R, Garriott R. Method for estimating the spherical aberration of the human crystalline lens in vitro. *Invest Ophthalmol Vis Sci* 1993;34:621-629.
20. Millodot M, Sivak J. Contribution of the cornea and lens to the spherical aberration of the eye. *Vis Res* 1979;19:685-687.
21. Artal P, Guirao A. Contributions of the cornea and the lens to the aberrations of the human eye. *Optics Letters* 1998;23:1713-1715.
22. Smith G, Cox MJ, Calver R, Garner LF. The spherical aberration of the crystalline lens of the human eye. *Vis Res* 2001;41:235-243.
23. Artal P, Guirao A, Berrio E, Williams DR. Compensation of corneal aberrations by the internal optics in the human eye. *Journal of Vision* 2001;1:1-8.
24. Oshika T, Klyce SD, Applegate RA, Howland HC. Changes in corneal wavefront aberrations with aging. *Invest Ophthalmol Vis Sci* 1999;40:1351-1355.
25. Calver RI, Cox MJ, Elliot DB. Effect of aging on the monochromatic aberrations of the human eye. *J Opt Soc Am A* 1999;16:2069-2078.
26. Guirao A, Gonzalez C, Redondo M, Geraghty E, Norrby S, Artal P. Average optical performance of the human eye as a function of age in a normal population. *Invest Ophthalmol Vis Sci* 1999;40:203-213.
27. McLellan J, Marcos S, Burns SA. Age-related changes in monochromatic wave aberrations of the human eye. *Invest Ophthalmol Vis Sci* 2001;42:1390-1395.
28. Artal P, Berrio E, Guirao A, Piers P. Contribution of the cornea and the internal surfaces to the change of ocular aberrations with age. *J Opt Soc Am A* 2002;19:137-143.
29. Martinez CE, Applegate RA, Klyce SD, McDonald MB, Median JP, Howland HC. Effect of pupillary dilation on corneal optical aberrations after photorefractive keratectomy. *Arch Ophthalmol* 1998;116:1053-1062.
30. Oliver KM, Hemenger RP, Corbett MC, O'Brart DP, Verma S, Marshall J, Tomlinson A. Corneal optical aberrations induced by photorefractive keratectomy. *J Refract Surg* 1997;13:246-254.
31. Oshika T, Klyce SD, Applegate RA, Howland HC, el Danasoury M. Comparison of corneal wavefront aberrations after photorefractive keratectomy and laser in situ keratomileusis. *Am J Ophthalmol* 1999;127:1-7.
32. Oliver KM, O'Brart DPS, Stephenson CG, Hememger RP, Applegate RA, Tomlinson A, Marshall J. Anterior corneal optical aberrations induced by photorefractive keratectomy for hyperopia. *J Refract Surg* 2001;17:406-413.
33. Seiler T, Kaemmerer M, Mierdel P, Krinke H-E. Ocular optical aberrations after photorefractive keratectomy for myopia and myopic astigmatism. *Arch Ophthalmol* 2000;118:17-21.
34. Mrochen M, Kaemmerer M, Seiler T. Clinical results of wavefront-guided LASIK at 3 months after surgery. *J Cataract Refract Surg* 2001;27:201-207.
35. Moreno-Barriuso N, Merayo Lloves J, Marcos S, Navarro R, Llorente G, Barbero S. Ocular aberrations before and after myopic corneal refractive surgery: LASIK-induced changes measured with laser ray tracing. *Invest Ophthalmol Vis Sci* 2001;42:1396-1403.
36. Marcos S, Barbero S, Llorente L, Merayo-Lloves J. Optical response to LASIK surgery for myopia from total and corneal aberration measurements. *Invest Ophthalmol Vis Sci* 2001;42:3349-3356.
37. Budak K, Khater TT, Friedman NJ, Holladay JT, Koch DD. Evaluation of relationships among refractive and topographic parameters. *J Cataract Refract Surg* 1999;25:814-820.
38. Hugger P, Kohnen T, LaRosa FA, Holladay JT, Koch DD. Comparison of changes in manifest refraction and corneal power following photorefractive keratectomy. *Am J Ophthalmol* 2000;129:68-75.
39. Holladay JT, Lynn M, Waring GO III, Gemmill M, Keehn GC, Fielding B. The relationship of visual acuity, refractive error, and pupil size after radial keratectomy. *Arch Ophthalmol* 1991;109:70-76.
40. Mahajan VN. Optical Imaging and Aberrations - Part I Ray Geometrical Optics. *SPIE Optical Engineering Press*; 1998.
41. Navarro R, Santamaria J, Bescos J. Accommodation-dependent model of the human eye with aspherics. *J Opt Soc Am A* 1985;2:1273-1281.
42. Manns F, Ho A, Parel J-M, Culbertson W. Ablation profiles for wavefront-guided correction of myopia and primary spherical aberration. *J Cataract Refract Surg* 2002;28:766-774.
43. Mrochen M, Krueger RR, Bueeler M, Seiler T. Aberration sensing and wavefront-guided laser in situ keratomileusis: Management of decentered ablations. *J Refract Surg* 2002;18:418-429.