Wavefront Aberrations in Eyes With Acrysof Monofocal Intraocular Lenses

Prema Padmanabhan, MS; Geunyoung Yoon, PhD; Jason Porter, PhD; Srinivas K. Rao, FRCSEd; Roy J, MSc; Mitalee Choudhury, BS

ABSTRACT

PURPOSE: To characterize and measure the ocular aberrations in eyes implanted with monofocal intraocular lenses (IOLs) and to study any correlation between postoperative aberrations and surgical factors.

METHODS: A Tscherning aberroscope was used to measure the wavefront aberrations of 62 eyes that had undergone phacoemulsification with the implantation of foldable monofocal Acrysof MA60BM IOLs (Alcon Laboratories Inc, Ft Worth, Tex). The Zernike coefficients, measured with a pupil diameter of 6 mm, were compared with those of a normal dataset of 82 eyes of healthy young myopes.

RESULTS: Spherical aberration (Z_4^0) was the most predominant higher order aberration, with a mean value of 0.37 ± 0.16 μm. A statistically significant linear relationship was noted between the magnitude of postoperative spherical aberration and the dioptric power of the IOL. The mean spherical aberration was 33 times more in the pseudophakic group than in normal young myopic eyes. The other major higher order aberrations were trefoil (Z_3^{-3}) with a mean of -0.13 ± 0.22 μm and vertical coma (Z_3^{-1}) with a mean value of -0.11 ± 0.23 μm. On average, the root-mean-square of higher order aberrations in pseudophakic eyes was 2.1 times that in a normal population of young myopic eyes.

CONCLUSIONS: Eyes that undergo cataract surgery with monofocal IOL implantation suffer from significant higher order aberrations. The optical design of the IOL is most likely responsible for the increase in spherical aberration, the magnitude of which is a function of the dioptric power of the IOL. [*J Refract Surg*. 2006;22:237-242.]

Phacoemulsification, with the implantation of a foldable intraocular lens (IOL), has become the most popular technique for cataract surgery.[1] The small self-sealing incision has reduced surgically induced astigmatism.[2] The continuous curvilinear capsulorrhexis has increased the surgeon's ability to ensure a stable centration of the IOL. Precision in biometry and improvements in calculation of IOL power have enhanced the predictability of desired postoperative results. All of these optical and biomechanical factors are responsible for the qualification of cataract surgery as a "refractive procedure."

Until recently, the term "refractive procedure" has been used solely for spherocylindrical corrections. We now know that optical imperfections other than spherocylindrical refractive errors influence visual function.[3-5] The introduction of wavefront sensors into clinical practice has given the clinician a powerful tool to measure and examine these aberrations and thereby describe retinal image quality in more definitive terms.[6]

Most IOLs marketed today have better optical quality than that of a healthy crystalline lens.[7-10] However, inserting IOLs of better optical quality does not directly translate to having optimum optical performance once inside the human eye.[11-13] This discrepancy can be explained by the fact that, in the laboratory, the optical quality of the IOL is tested as a single unit, whereas the optical quality of the entire eye is mainly governed by both the cornea and the IOL. Artal et al[14,15] have shown that aberrations in the young cornea can be partially compensated by lenticular aberrations, resulting in an eye that has better overall optical quality than either two components alone. For this reason, inserting an optically "perfect" IOL into

From Medical & Vision Research Foundation, Tamil Nadu, India (Padmanabhan, Rao, J, Choudhury); and the Center for Visual Science, University of Rochester, Rochester, NY (Yoon, Porter).

The authors have no financial or proprietary interest in the materials presented herein.

Correspondence: Prema Padmanabhan, MS, Cornea Service, Sankara Nethralaya, 18 College Rd, Chennai 600 006, Tamil Nadu, India. Tel: 91 44 28271616; Fax: 91 44 28254180; E-mail: drpp@snmail.org

Received: March 28, 2005

Accepted: April 25, 2005

the eye will not yield a perfect overall system, devoid of aberrations. Rather, the ideal IOL should contain aberrations that are equal in magnitude and opposite in sign to those inherent in an individual's cornea.

Other possible causes for a suboptimal optical performance of an IOL implanted into an eye could be due to decentration of the IOL and possible changes in corneal shape induced by the cataract wound.

Clinical studies on the visual acuity and contrast sensitivity of patients with monofocal or multifocal IOLs have been performed.[16,17] These, however, are measures of both the optical and neural processes of vision and do not directly describe the optical performance of the IOL. Artal et al[18] used the double-pass measurements of the modulation transfer function (MTF) in eyes implanted with IOLs. Although the MTF is a good metric of retinal image quality, wavefront aberration may be a more complete description of optical quality as it contains phase information as well.[12] The optical aberrations of eyes implanted with an IOL were only recently measured in vivo by Miller et al[19] in 11 patients using the Shack-Hartmann sensor and by Barbero et al[12] in 9 eyes using the laser ray tracing technique. It is hoped that the present study, with its relatively larger data set of 62 eyes, will add statistical value to the observations made. Although Miller et al[19] and Barbero et al[12] observed an increase in positive spherical aberration in eyes with IOLs, Barbero et al[12] showed that spherical aberration increased as a function of the IOL power. The present study also demonstrates a similar relationship and extends this relationship by providing a mathematical relationship between the postoperative spherical aberration and the power of the IOL.

The aims of the study were 1) to characterize and measure the ocular aberrations in eyes implanted with IOLs, and 2) to study any correlation between postoperative aberrations and surgical factors.

PATIENTS AND METHODS

This study analyzed 62 eyes from patients diagnosed with cataract aged between 40 and 74 years who underwent phacoemulsification with implantation of a foldable hydrophobic acrylic IOL (Acrysof MA60BM; Alcon Laboratories Inc, Ft Worth, Tex) through a self-sealing 4.1-mm frown incision between the 10 and 11 o'clock meridians. The power of the IOLs ranged from 10.5 to 26.0 diopters. Eyes with any known ocular pathology (other than cataract) or previous ocular surgery were excluded from the study. Eyes that suffered any complication during surgery, including the loss of an intact capsulorrhexis or a tear in the posterior capsule, were also excluded. The study was approved by the institutional review board and an informed consent was obtained from all patients.

The ALLEGRETTO WAVE Analyzer (WaveLight Laser Technologies AG, Erlangen, Germany) was used to measure each patient's wave aberration. Measurements were taken 2 weeks after surgery, when the eyes were believed to have attained refractive stability. A laser diode (wavelength of 532 nm) was used to produce a collimated bundle of light, which was then split into a group of parallel rays by means of a mask with a regular matrix of small apertures. The retinal image of the spot pattern was photographed by a charged couple device camera.

The coordinates of the geometric centers of all imaged retinal spots were determined by image processing software and computed by numerical fitting to a Zernike expansion. The Zernike coefficients provided by the aberrometer were converted to the notation recommended by the Optical Society of America (OSA) standard committee,[20] using the normalization factors provided by the manufacturers. The 62 eyes analyzed in this study included 31 right eyes and 31 left eyes. The signs of all modes with odd symmetry about the y-axis were negated in the left eyes to allow all eyes to be analyzed together. Measurements were made with a pupil diameter of at least 6 mm. Only well-centered images were chosen for analysis. Zernike coefficients through the 6th order were measured and the root-mean-square (RMS) wavefront error of each order was calculated. Higher order aberrations included the 3rd through 6th order aberrations.

These coefficients were compared with those of a normal dataset of 82 eyes of healthy young myopes aged 19 to 48 years (mean 26.6±4.8 years) with refractive errors ranging from −0.75 to −8.50 D who attended our refractive surgery clinic.

RESULTS

Figure 1 shows the mean values of all Zernike coefficients from 3rd to 6th order, across a 6-mm pupil with error bars for the postoperative pseudophakic eyes. The 1st and 2nd order aberrations have been deleted. The most predominant aberrations that were statistically significantly greater than zero were spherical aberration (Z_4^0) measuring 0.37±0.16 µm ($P \leq .001$), trefoil (Z_3^{-3}) measuring −0.11±0.23 µm (P=.001), and vertical coma (Z_3^{-1}) measuring −0.13±0.22 µm ($P < .001$).

Figure 2 shows the corresponding RMS values of each order and the overall higher order RMS error in this group of pseudophakic eyes. The RMS of 3rd order measured 0.44±0.25 µm and 4th order measured 0.45±0.23 µm. The RMS of total higher order aberrations was 0.67±0.34 µm.

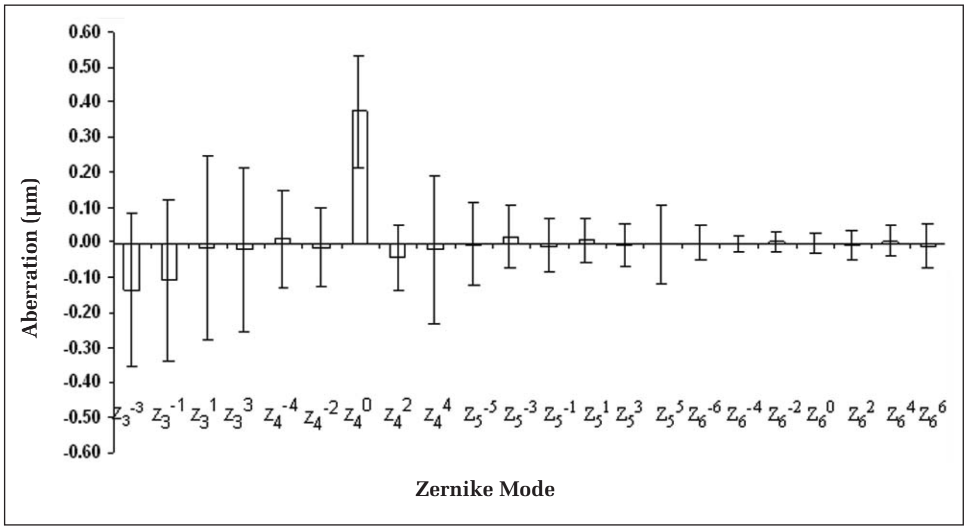

Figure 1. Mean coefficient of wavefront error in Zernike modes (3rd to 6th order) in eyes with monofocal IOL (pupil diameter=6 mm). Error bars represent one standard deviation from the mean value.

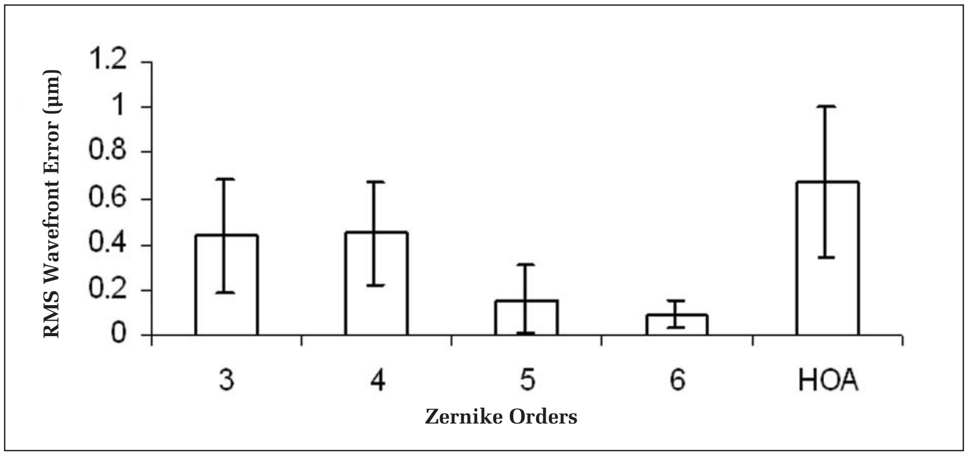

Figure 2. Root-mean-square (RMS) wavefront error of 3rd to 6th order and total higher order aberrations (HOA) in eyes with monofocal IOLs (pupil diameter=6 mm).

The mean coefficient of aberration of each Zernike mode was compared with its corresponding mode from the normal dataset of 82 myopic eyes (Fig 3). Those that showed a statistically significant difference were vertical coma (−0.11±0.23 μm in pseudophake and 0.009±0.16 μm in myope, P=.001), spherical aberration (0.37±0.16 μm in pseudophake and 0.01±0.10 μm in myope, $P\leq.001$), and secondary astigmatism (0.04±0.1 μm in pseudophake and 0.01±0.06 μm in myope, $P\leq.001$). Among those, spherical aberration showed the biggest difference (33 fold).

Corresponding differences in the RMS values of the 3rd to 6th order and total higher order aberrations are shown in Figure 4. The differences in each of the four radial orders and in the total higher order aberrations showed statistical significance. The RMS of total higher order aberration in the pseudophakic group was 0.67±0.34 μm compared to 0.32±0.11 μm in the normal myopic dataset ($P\leq.001$), representing a 2.1-fold increase.

A regression analysis (Fig 5) showed a statistically significant linear relationship between the magnitude of the postoperative spherical aberration Z_4^0 and the dioptric power (P) of the IOL ($P<.05$) despite inter-subject variability. This relationship could be mathematically represented by the equation:

$$Z_4^0\,(\mu m) = (0.011 \times P) + 0.128 \text{ (r value 0.30).}$$

DISCUSSION

The optical quality of IOLs was poorly specified until the late 1970s when reports by Dunn[21] and Olson et al[22] drew attention to the need for minimum acceptable optical standards. Dunn[21] introduced the concept of "resolution efficiency" or resolved spatial frequency, expressed as the number of line pairs per millimeter, as a percentage of the theoretical maximum attainable cut-off spatial frequency.

In 1984, the American National Standards Institute adopted the 3-bar target test and set standards for the limiting resolution of IOLs, which corresponded to 60% resolution efficiency in air.[9] The resolution efficiency was revised in 1994 to be 70% in a cell contain-

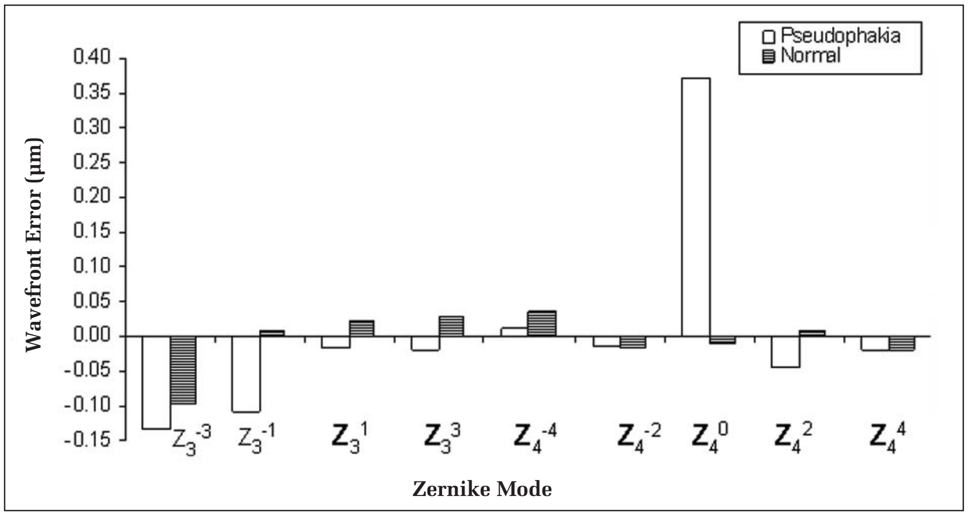

Figure 3. Comparison of mean coefficient of wavefront error of individual Zernike modes (Z_3^{-3} to Z_4^4) in pseudophakic eyes with normal myopic dataset (pupil diameter=6 mm). Age of pseudophakes = 40 to 74 years and age of normal myopes = 19 to 48 years.

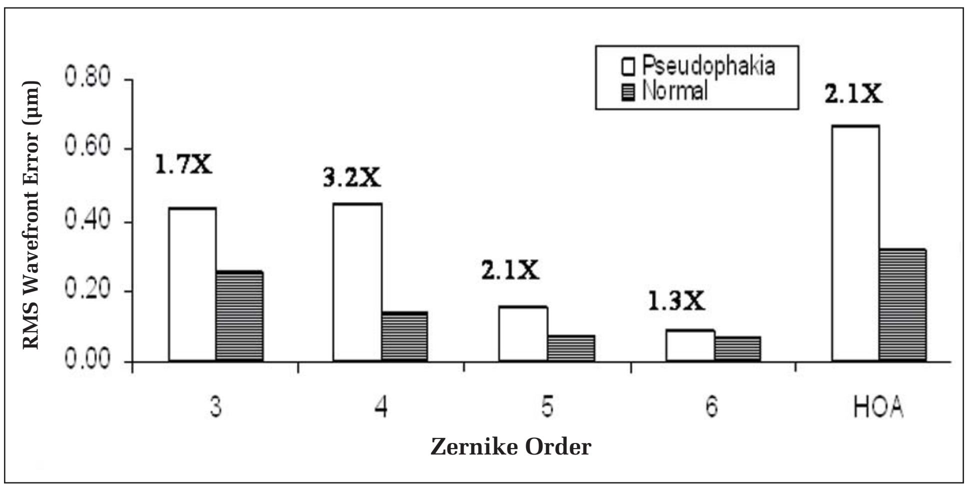

Figure 4. Comparison of RMS wavefront error of 3rd to 6th order and total higher order aberrations (HOA) between pseudophakic eyes and normal myopic eyes (pupil diameter=6 mm). Numerals indicate how many times more the magnitude of one is compared to the other.

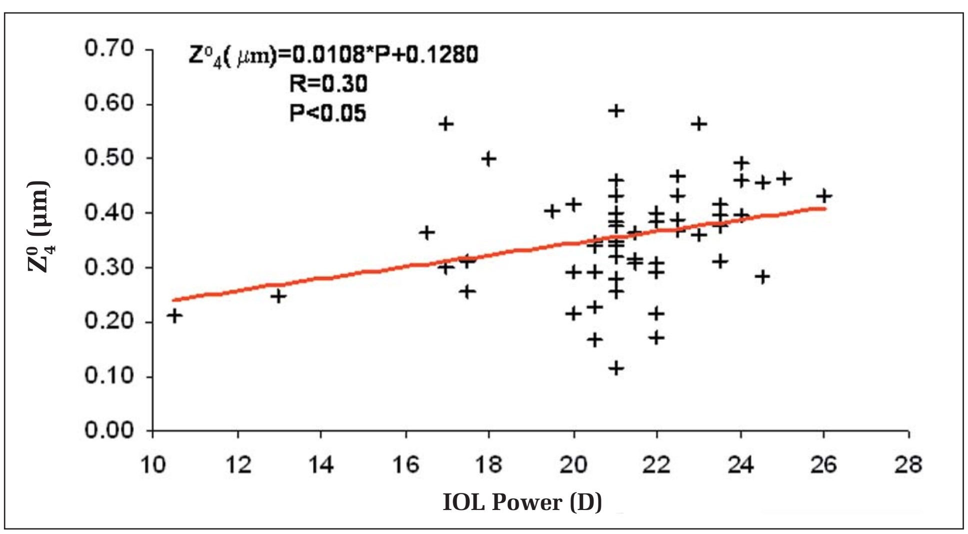

Figure 5. Regression analysis illustrating the relationship between the postoperatively measured value of spherical aberration (Z_4^0) and the power of the IOL (P) in pseudophakic eyes. The equation is: $Z_4^0 = (0.011 \times P) + 0.128$.

ing a liquid with a refractive index of 1.336.[10] With modern methods of measuring image quality, MTF curves could be generated as well. Inter-laboratory testing has shown that MTF measurements using a model eye have better repeatability and reproducibility than the 3-bar target test.[9] The commonly applied criterion of 60% resolution in air corresponds to 0.43 MTF units at 100 lines/mm in a model eye. All IOLs marketed today are expected to meet these criteria but unfortunately do not account for the effects of spherical aber-

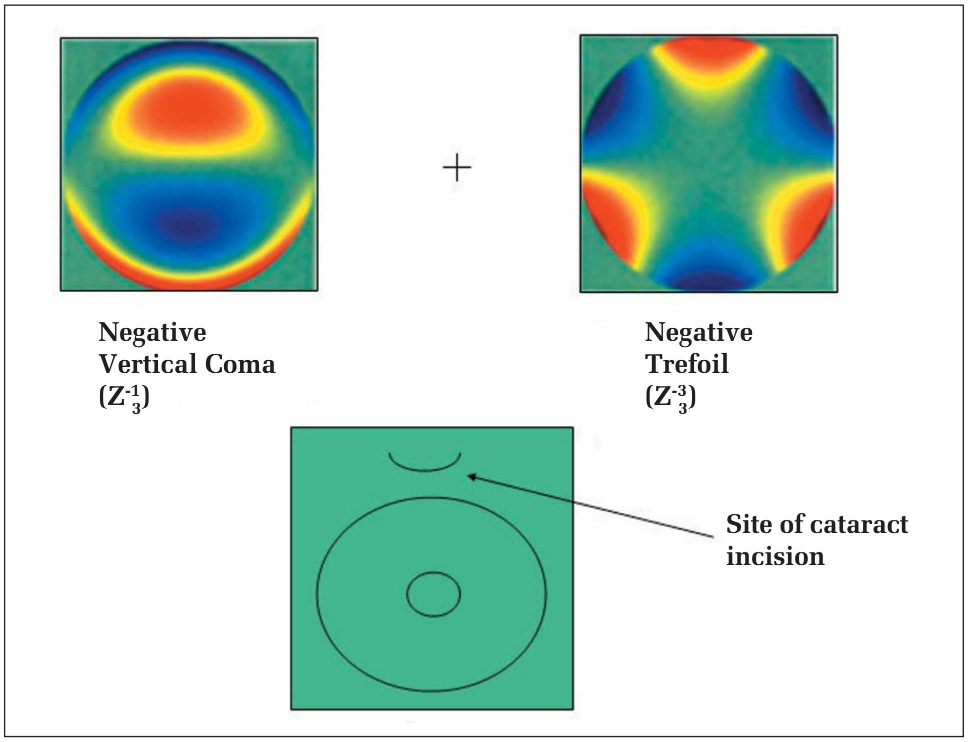

Figure 6. A phase advanced portion of the wavefront, formed when adding negative vertical coma (Z_3^{-1}) to negative trefoil (Z_3^{-3}), is located at the top portion of the pupil. The site of the cataract incision is in a similar location and could be responsible for the large magnitudes of these two aberrations observed in our pseudophakic eyes.

ration. However, this study showed that the spherical aberration in eyes implanted with an IOL is significant, and would, theoretically, profoundly affect the MTF, especially for large pupil diameters.

On the basis of theoretical models, Atchison[16] suggested that convex-plano IOL geometry (ie, convex surface towards the cornea) minimized optical aberrations. A biconvex geometry was found to be acceptable but the plano-convex design (with the convex surface facing the retina) was found to perform poorly. More recently, Uchio et al[23] calculated the spherical aberration of different spherically surfaced IOLs using a computer ray tracing system. They found that biconvex lenses, which had a more curved posterior surface, produced more spherical aberration than those with a more curved anterior surface. Intraocular lenses with a lower refractive index would need to be thicker and, with increasing powers, would need to have steeper curvatures and therefore would be expected to induce higher degrees of spherical aberration. In short, the magnitude of spherical aberration in an eye after cataract surgery with IOL implantation would be determined by the design (geometry), material (refractive index), and power (curvature) of the IOL. All 62 eyes in this study had IOLs of the same optical design and refractive index. The only variable was the power of the IOL and a regression analysis showed a statistically significant linear relationship between the amount of spherical aberration (Z_4^0) and the power of the IOL (P) in the pseudophakic eye, which could be represented mathematically as: Z_4^0 (µm) = $(0.011 \times P) + 0.128$.

We did not measure corneal and internal aberrations separately and therefore cannot assess the distribution of the aberrations between the cornea and the IOL. Past studies have shown that there are no significant differences in corneal aberrations between eyes that have undergone cataract surgery (a conventional extracapsular cataract surgery with a rigid polymethylmethacrylate IOL through a large limbal incision) and an age-matched, pre-cataract surgery group.[11] One would expect a small scleral tunnel incision to produce fewer changes in the cornea. This could imply that the most obvious source of the large spherical aberration observed in our pseudophakic eyes must be the IOL. This is most likely because of the geometric design of its optic and because it does not counteract the effect of the spherical aberration produced by the cornea, as the normal crystalline lens does. The Acrysof MA60BM is a biconvex lens with its posterior surface having a steeper convexity than its anterior surface. The higher the dioptric power, the greater the posterior convexity of the optic. The diameter of the optic is 6.0 mm and the hydrophobic acrylic of which it is made has a refractive index of 1.55.

Barbero et al[12] measured the total and corneal aberrations in nine eyes after a small incision cataract surgery with a foldable IOL implantation. The total higher order RMS wavefront error measured 2 months after surgery in their study was 0.62±0.18 µm (5-mm pupil). In our study, the total higher order RMS error

2 weeks after IOL implantation was 0.67±0.33 µm (6-mm pupil), which correlates well with the results of Barbero et al.

Higher order aberrations in our dataset of pseudophakic eyes were 2.1 times larger than in young myopic eyes. It is well known that optical aberrations increase with age[24] and comparisons of aberrations following cataract surgery with aberrations in a younger population of normal eyes could be misleading. Although it would have been ideal to compare postoperative aberrations to preoperative values within the same patients, there is considerable difficulty in obtaining wavefront measurements in eyes with a cataractous lens due to scatter and lens opacities. We did not have a dataset of normal healthy eyes in the same age group as that of the pseudophakic eyes, and therefore could not make such an age-matched comparison among our own population.

However, if racial differences are ignored, the results of other studies on patients of similar age groups as our own could be extrapolated to provide an estimate for the types of aberrations indicative of normal, healthy eyes in the same age range. Artal et al[24] recorded an average higher order RMS wavefront error of 0.7 µm for a 6-mm pupil. The higher order aberrations in our pseudophakic eyes for a 6-mm pupil (mean RMS of 0.67±0.34 µm) were not statistically significantly different from the higher order RMS values for the normal, similarly aged, healthy eyes reported by Artal et al. This observation is in agreement with similar conclusions by Barbero et al.[12]

This study showed a significant negative mean value for vertical coma (Z_3^{-1} = −0.11±0.23 µm) and trefoil (Z_3^{-3} = −0.13±0.22 µm) in the pseudophakic eyes 2 weeks after cataract surgery. Combining these two aberrations into a single wavefront profile, one would notice the phase-advanced portion of the wavefront to correspond to the site of the cataract incision wound (Fig 6). Further studies on the effect of varying sites and sizes of incisions on aberrations may be required to improve our understanding of such possible associations.

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