Cataract surgery and optimal spherical aberration: as simple as you think?

Shamrozé Khan,* BSc, OD; Guillermo Rocha,† MD, FRCSC

ABSTRACT • RÉSUMÉ

This paper reviews the optics of higher-order and spherical aberrations and discusses aspheric intraocular lenses, attempting to address 2 questions that, despite an abundance of information, remain unanswered: what amount of ocular spherical aberration has been correlated with optimum visual performance, and for what final amount of spherical aberration should the cataract surgeon aim? Finally, the paper briefly reviews recent publications and makes suggestions for future studies in the area.

Cet article revoit l'optique des aberrations de haut degré et sphériques et traite des lentilles intraoculaires asphériques, cherchant à résoudre 2 questions qui demeurent sans réponse malgré l'abondance de l'information : Quel est le degré d'aberration sphérique oculaire qui a été mis en corrélation avec la performance visuelle optimale et quel degré définitif d'aberration sphérique le chirurgien de la cataracte doit-il viser ? Enfin, l'article fait une brève revue des publications et présente des suggestions d'études éventuelles sur le sujet.

The eye-care profession's advancement from cataract couching to phacoemulsification is proof that the route to achieving perfect vision is always changing. We first thought that perfect vision could be achieved by maximizing quantitative vision, associating "perfect" with the Snellen 20/20 line or equivalent on a high-contrast visual acuity chart. This left unexplained, however, the patient who finished his or her perfect recitation of the 20/20 line with "but it's not clear," indicating that some aspect of vision still needed to be addressed.

When studies began to show that, despite their excellent visual acuity, patients could demonstrate poor visual performance in the high-contrast and ideal lighting conditions of the examination room[1] and that performance on qualitative rather than quantitative vision testing was a truer indicator of visual functioning in the real world,[1] the eye-care profession became sensitive to the importance of not only vision quantity but also vision quality.

Given this understanding that both quantity and quality needed to be improved for perfect vision, the only unknown became the limits to which these elements could be improved. Modern technological advances, research publications, and clinical experience have shed some light on this ambiguity; the best possible quantity and quality of vision are now commonly associated with a visual state referred to as "super vision."

Super vision assumes flawless ocular optics. Nonetheless, super visual acuity is still limited to a value only slightly better than 20/10.[2,3] This is because the images of objects beyond a certain acuity level fall on too few photoreceptor cells to be accurately sampled. The objects are reconstructed by the brain with a considerable amount of guesswork on behalf of the neural system. Thus the highest potential acuity of the perfect eye remains fixed somewhere between 20/12 and 20/5.[3]

In terms of vision quality, super vision is much more promising. When vision is limited by only diffraction and chromatic aberration, as it would be in the perfect eye, the range of object sizes (spatial frequencies) over which brightness differences (contrast) can be perceived greatly increases, even at larger pupil sizes.[2] The ideal visual system is created: one that can tell light from dark regardless of object size, illumination, and pupil diameter.

How does one achieve this kind of vision in patients? Since the potential to manipulate visual acuity is capped by our retinal anatomy, the eye-care profession may have more success in providing patients with faultless vision by addressing quality of vision and the factors, both optical and neural, that keep the eye from being a diffraction-limited system. A perfect example of this approach is the use of aspheric intraocular lenses (IOLs) to correct the increase in spherical aberration that occurs, along with other higher-order aberrations, with age.[4,5]

This paper reviews the optics of higher-order and spher-

From *the University of Waterloo School of Optometry, Waterloo, Ont., and the Illinois College of Optometry, Chicago, Ill.; and †Brandon Regional Health Centre, University of Manitoba, Brandon, Man., and the University of Ottawa Eye Institute, Ottawa, Ont.

Originally received Oct. 30, 2007. Revised July 1, 2008
Accepted for publication July 15, 2008
Published online Oct. 24, 2008

Correspondence to Guillermo Rocha, MD, GRMC Vision Centre, Medical Centre Building, Suite 20, 144-6th St., Brandon MB R7A 3N2; rochag@westman.wave.ca

This article has been peer-reviewed. Cet article a été évalué par les pairs.

Can J Ophthalmol 2008;43:693–701
doi:10.3129/i08-152

ical aberrations and discusses aspheric IOLs, hoping to address 2 questions that so far remain unanswered: what amount of ocular spherical aberration has been correlated with optimum visual performance, and for what final amount of spherical aberration should the cataract surgeon aim? Finally, the paper briefly reviews recent publications and makes suggestions for further studies in this area.

OCULAR ABERRATIONS, HIGHER-ORDER ABERRATIONS, AND THE NEED TO CORRECT THEM

In the ideal eye, all rays of light emerging from an object, regardless of their direction of travel or point of entry into the pupil,[2] will oscillate the same number of times before coming to a sharp focus at the same spot on the retina in unison. As a result, the image formed at the neural system will be an exact replica of the source object in terms of size (spatial frequency), contrast (modulation), and location (phase). The ability of the visual system to translate an object into an identical image is known as the optical transfer function, 2 important features of which are phase and modulation transfer.[3] Ocular aberrations are imperfections of the ocular media, changes in the refractive index, and misalignments of elements of the eye, which prevent perfect optical transfer from being realized. They are a special kind of refractive error.

Ocular aberrations are categorized as monochromatic or chromatic (Fig. 1).[3] An infinite number of monochromatic aberrations exist in the eye, and these are organized into numerical orders labeled first, second, third, etc., to infinity. The first-order and second-order aberrations are referred to as lower order. Lower-order aberrations describe the ametropias and astigmatism (i.e., those refractive errors that can easily be addressed by rotationally symmetric modes of correction such as spherocylindrical techniques). Aberrations that fall above the second order are referred to as higher-order aberrations and are much more difficult to correct. The higher the order, the more complex and numerous are the aberrations. Those in odd-numbered orders are considered rotationally asymmetric (e.g., trefoil); conversely, those aberrations in even-numbered orders are symmetric (e.g., tetrafoil).

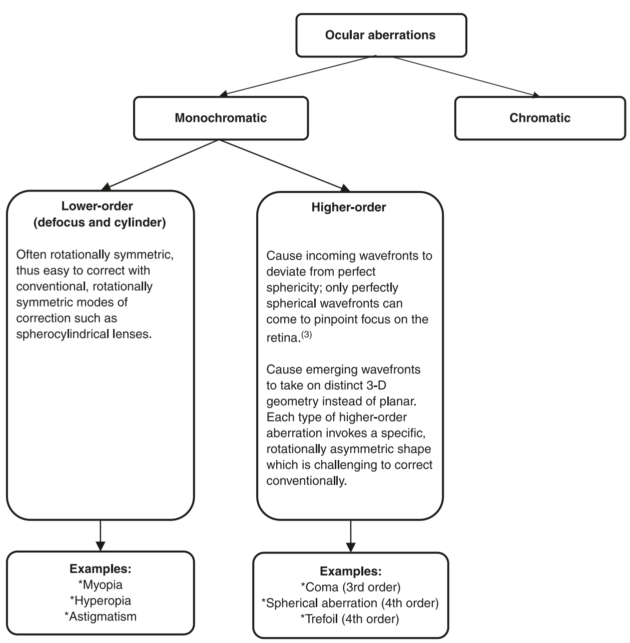

Fig. 1—Simplified classification of ocular aberration. Ocular aberrations are imperfections in the ocular media, changes in refractive index, and misalignments of the ocular media, which prevent rays of light that emerge from an object from coming to a sharp focus together at the same point on the retina, regardless of their direction of travel or point of entry into the pupil.

An infinite number of higher-order aberrations exist, although the eye-care profession deals with relatively few; these have been given common names. One such naming set is the Zernike polynomial system, a mathematical system that describes each higher-order aberration by geometric shape. For example, "coma" is the Zernike polynomial term for one of the third-order aberrations, and the term "spherical aberration" is the Zernike polynomial term for one of the more significant fourth-order aberrations. The quantity of each Zernike polynomial is often reported in micrometres, e.g., "the proportion of coma in the system averaged +0.0352 µm." The concept of a higher-order aberration imparting a shape can best be understood by visiting the model of the perfect eye.

An object at infinity will project parallel light rays. A perpendicular line drawn through these light rays is referred to as the wavefront of incoming light and is considered perfectly flat. Upon encountering the ideal eye, this wavefront is refracted into a spherical wavefront, which in turn converges to pinpoint focus on the retina. When the situation is reversed, such that the point of light on the retina becomes the point source, an emergent wavefront, which is also perfectly flat, is created. Flat wavefronts and resultant pinpoint retinal foci only serve to benefit the optical transfer function.

Higher-order aberrations affect these planar wavefronts in 2 main ways. First, they cause an incoming, converging wavefront to deviate from perfect sphericity. This is an issue because only perfectly spherical wavefronts can focus as perfect points on the retina.[3] Second, higher-order aberrations cause an emerging wavefront to take on a distinctly 3-dimensional, nonplanar geometry. Since this geometry is often rotationally asymmetric, it is difficult to offset with conventional glasses and contact lenses. Because an infinite number of higher-order aberrations exist in the eye, the final 3-D emergent wavefront is a combination of all the errors contributed by each of these higher-order aberrations. The mathematical term "root mean square" (RMS) describes how much the final curved wavefront deviates from a flat baseline. This value can be considered an average of all the higher-order aberrations in the system. Note that since the RMS calculation involves a squaring function, it can only be considered an indicator and not an exact computation of how much aberration exists in a system.

Furthermore, it provides no information about how much of each higher-order aberration is present.

Higher-order aberrations have devastating consequences on the optical transfer function; decreased contrast is one such effect. While lower-order aberrations affect our contrast sensitivity for high spatial frequencies alone, higher-order aberrations have negative effects on all spatial frequencies. In other words, contrast sensitivity is affected at all levels with increasing high-order aberrations. This effect is exacerbated by increasing pupil size, even when the aberration is as little as 0.50 D.[2] Subjectively, higher-order aberrations manifest as complaints of haloes and glare around lights. For these reasons, higher-order aberrations warrant correction.

It should be noted that the true significance of higher-order aberrations is not completely understood. Although known to be visually devastating if present in large amounts, higher-order aberrations correlate poorly with functional vision when present in low numbers.[6] In one study of 70 eyes with super vision, the RMS value was 0.334 µm,[7] indicating a significant amount of aberration (although not which kind). Nonetheless, the correction of higher-order aberrations is warranted to improve, at the very least, contrast sensitivity.[8]

Traditionally, the correction of higher-order aberrations has fallen on the shoulders of the refractive surgeon. With the use of wavefront-sensing aberrometers, the patient's emergent wavefront of light is mapped out and compared with the flat plane that emerges from the perfect eye. The surgeon then adapts his or her ablations to (*i*) offset but not correct aberrations that already exist[9] and (*ii*) decrease the amount of higher-order aberrations induced on altering the prolate shape of the cornea during refractive surgery. An obvious advantage of higher-order aberration manipulation during refractive surgery is that this approach addresses the full gamut of wavefront errors, be they rotationally symmetric or not. The downfall is that refractive surgery is neither requested by nor warranted for every patient, hence the need for alternative modes of correction.

SPHERICAL ABERRATION AND THE EYE

Of all the higher-order aberrations, why is the eye-care profession so interested in spherical aberration and its effects on human vision? To answer this question, one must understand the world of geometric optics as well as that of human ocular anatomy.

Spherical aberration is a fourth-order higher-order aberration referring to the inability of a spherical surface to refract all rays of incoming light equally. Light rays traveling closer to the optical axis (central rays) are refracted less than peripheral ones and so come to a focus at a different point than the latter. When a spherical surface focuses peripheral rays in front of the central point, the inaccuracy is referred to as positive spherical aberration. If the peripheral rays come to a focus behind the central point, the term negative spherical aberration is used. The result is an image that is smeared or spread out on the retina instead of coming to a focus at a single sharp point.

Let us translate this situation to the human eye. The 2 main spherical refractive surfaces, and hence sources of spherical aberration in the human visual system, are the crystalline lens and the cornea. The lens produces negative spherical aberration,[10] and the cornea contributes positive aberration to the system. Regardless of the positive or negative sign, both of these systems are detrimental to the modulation transfer function (aberration means error, after all).[4] Extensive study of the wavefronts of the anterior cornea, the internal structure of the eye, and the eye as a whole indicate that the spherical aberration of the lens and cornea serve to balance one another out, resulting in a total amount of ocular spherical aberration that is far less than the spherical aberration of the cornea alone.[4] Ocular anatomy has adapted in other ways to combat the effects of spherical aberration: the creation of further negative spherical aberration upon accommodation[10] and the development of an ellipsoid cornea as opposed to a spherical one are 2 examples.

The radius of curvature of the cornea changes with time to render the anterior cornea more spherical than ellipsoid, adding more positive spherical aberration to the anterior corneal system.[11] Between the ages of 32 and 45 years, even more significant changes occur in the surface curvature and refractive index of the lens,[10,12] inducing positive spherical aberration. Not only is the compensatory mechanism between cornea and lens compromised but also the lens now adds to the positive spherical aberration of the cornea.

Interest in spherical aberration has grown because one might correlate the age-associated decline in vision quality[13] with the increase in ocular spherical aberration. Is this fair? Looking at Fig. 2, perhaps partly.

In Fig. 3, from the blur created by spherical aberration on the retina one can understand how this type of refractive error might have such a detrimental effect on contrast sensitivity. The central portion of the blur circle shows a fairly high-intensity distribution, meaning that a substantial proportion of rays are in focus at the correct location on

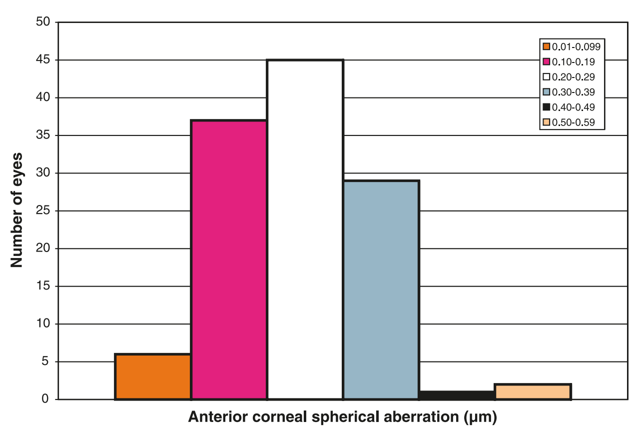

Fig. 2—Frequency of distribution of anterior corneal spherical aberration in our study population.

the retina. The surrounding area of blur is representative not only of rays focusing in front of or behind the retina but also at variable focal lengths. This continuum of foci[3] has 2 major effects on vision: the first is that it creates a halo of light that surrounds bright objects, resulting in serious complaints from some patients; and the second is that it creates a significant spread of blur around every object such that the blur around 1 adds to the blur around the next. This is commonly referred to as the "packing phenomenon" and decreases contrast as a whole. In fact, Applegate et al.[2] propose that the contrast of the retinal image could be improved 12-fold if spherical aberration alone were corrected in an eye with a 6 mm pupil.

One might ask why the focus has been on correcting spherical aberration over all other higher-order aberrations. While some other important aberrations, such as coma, do increase with age, none have been as strongly correlated with age as has spherical aberration.[11] As well, various studies have shown that while most higher-order aberrations exist to some extent in most individuals, few are present in amounts significantly greater than zero. The consistent exception to this rule is spherical aberration,[11,14] which remains the main aberration of the cornea.[15]

The desire to negate the positive spherical aberration of the cornea has led to several important inventions. Dietze and Cox[16] provide an interesting review of aspheric contact lenses. A new generation of IOLs has also emerged. The AMO Tecnis Z9000 (Advanced Medical Optics, Santa Ana, Calif.) offers a lens with an aspheric anterior surface that also contributes –0.27 µm of negative spherical aberration to the system. The aspheric AcrySof IQ (Alcon Inc, Fort Worth, Tex.) contributes –0.19 µm of negative spherical aberration upon implantation. Last, the SofPort AO from Bausch & Lomb (Bausch & Lomb Inc, Rochester, N.Y.), with prolate anterior and posterior surfaces, contributes none at all and is considered a neutral aspheric lens.

Although the literature is rife with information about these IOLs, studies still need to address one important issue. If each of these lenses offers the cataract surgeon a different amount of negative spherical aberration, or even none at all, each will affect the patient's overall aberration profile differently. Are all acceptable? An investigation follows.

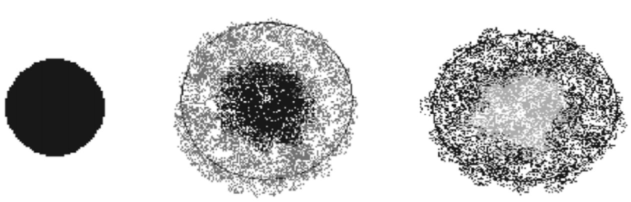

Fig. 3—The first picture represents zero error in the visual system and thus an image sharply in focus at the retina. The next 2 represent blur circles created when spherical aberration is present such that all incoming rays of light do not focus at the same location on the retina. The darker centre and lighter surround represent positive spherical aberration (peripheral rays focus in front of the central point), and the final picture represents negative spherical aberration (central rays come to a focus in front of peripheral).

Relation between the cornea and the IOL

The average amount of anterior corneal spherical aberration in the population has been reported to be +0.270 µm.[17] Wang et al.[18] recently published their finding of an average of 0.280 (SD 0.086) µm. We conducted a pilot study to determine the average amount of anterior corneal aberration in a sample population of our clinic. Anterior corneal topography was conducted on 120 eyes from 6 different age groups (20 eyes per age group, a total of 87 patients) using the Humphrey Atlas Corneal Topographer (Carl Zeiss Meditec Inc, Oberkochen, Germany). The subjects included refractive and cataract surgery candidates, as well as patients from general practice. These are unpublished observations made to confirm the feasibility of reproducing clinical studies in a standard cataract practice. The inclusion criteria for each eye and scan were based on that of Wang et al.:[18]

- a manifest refractive sphere between –3.00 DS and +3.00 DS inclusive;
- refractive and corneal cylinder less than or equal to DC;
- no history of ocular surgery or injury;
- no corneal pathology; and
- absolutely no missing data within the central 6 mm of the topography.

The topographical data for each eye individually were then input into the CT View program (Sarver and Associates Inc, Carbondale, Ill.). The program generates a higher-order aberration profile consisting of all third-order to sixth-order aberrations found to be present in that anterior cornea from the topographical data. The amount of each third-order to sixth-order aberration is given as a Zernike polynomial in micrometres (e.g., –660.273 µm of coma, +0.255 µm of spherical aberration). A total of 28 Zernike polynomials are therefore computed.

Of the 28, our interest was in the spherical aberration Zernike. The average amount of spherical aberration per aberration profile was computed for each age group (Table 1). The average amount of spherical aberration in patients aged from 50 to 79 years (i.e., those most likely to be cataract patients) was +0.252 (SD 0.104) µm. We computed the average amount of spherical aberration in our total population to be +0.243 (SD 0.089) µm (range 0.0737–0.578 µm) (Fig. 3). While the ocular higher-order aberrations in general

Table 1—Average amount of spherical aberration per age group

Age group (20 eyes in each)	Average amount of spherical aberration, µm (SD)
20–29	+0.22 (0.07)
30–39	+0.21 (0.05)
40–49	+0.26 (0.07)
50–59	+0.22 (0.08)
60–69	+0.29 (0.08)
70–79	+0.24 (0.13)
Average	+0.24 (0.09)

showed great variability in the population,[18–20] the amount of corneal spherical aberration seemed fairly stable with age. These findings are in agreement with previous studies.[4,18]

On the basis of the reported population average of +0.270 µm of anterior corneal spherical aberration, the cataract surgeon can expect to leave a patient with 0 µm, around +0.10 µm, or +0.270 µm of residual aberration depending on which of the Tecnis, IQ or SofPort IOLs are implanted. It is unlikely that all 3 amounts of aberration will provide the patient with the same vision; it is more likely that 1 of these amounts will be more ideal than the others. The approach in this paper is to identify this optimal amount of spherical aberration by investigating which of the aspheric IOLs has brought patients the closest to the ultimate goal: super vision.

What is the optimum amount of ocular spherical aberration?

Is it zero?

The Tecnis Z9000 was deliberately designed to negate all of the positive spherical aberration of the cornea[17] and does so effectively upon implantation.[21,22] The published data on the implantation of the Tecnis Z9000 have indirectly provided us with insight into the impact that removing all ocular spherical aberration might have on human vision. Does it leave patients with super vision?

The decision to leave the patient with zero ocular spherical aberration comes from more than just the reasoning that the less error there is in our visual system the better. The age at which visual performance is thought to be at its maximum, that is the closest to the state of super vision that the human eye will ever be, is age 19 years. Interestingly, this is the age at which the spherical aberration of the internal optics of the eye completely neutralizes that of the anterior cornea[23] (–0.17 µm in the lens vs +0.17 µm in the cornea). Although it is unlikely that this balance between the cornea and the lens is solely responsible for the peak visual performance at age 19 years, it is reasonable to assume that we would be one step closer to exceptional vision by eliminating all ocular spherical aberration. Does the literature validate this assumption?

The vast majority of studies conclude that implanting a lens that eliminates all spherical aberration from the visual system will not improve visual acuity any more than a conventional IOL. Both leave the cataract patient with equally improved, excellent best corrected visual acuity.[24–26] If anything, visual acuity may improve more quickly following implantation of an aspheric lens.[25] A few studies, such as the one from Mester et al.,[21] report a significantly better visual acuity result with the Tecnis versus a conventional spherical lens. Even then, the best visual acuity attained with the Tecnis in that study was 20/13, not the 20/8 and better that has come to be defined as super vision. Bellucci et al.[27] also showed a significant improvement in visual acuity following implantation of the Tecnis Z9000, but this was only 3 letters better than the acuity of patients who received the spherical IOL.

The Tecnis Z9000 has a much more dramatic effect on contrast sensitivity and thus on quality of vision and daily functioning than it does on visual acuity. Remember that the visual ideal is to be able to distinguish between bright and dim or light and dark under all possible lighting conditions regardless of object size. Put more scientifically, the ultimate goal is to provide patients with improved contrast sensitivity at varying spatial frequencies not only in photopic conditions but in mesopic conditions as well. Does leaving the eye with zero spherical aberration by means of the Tecnis Z9000 bring us closer to this goal? The findings can be summarized as follows.

For the most part, both the aspherical intraocular and conventional spherical lens will improve the patient's mean contrast sensitivity function from presurgical values. While both improve contrast sensitivity under photopic conditions,[21,25] the aspheric lens is more likely to improve contrast at a larger range of spatial frequencies.[21,25] The most significant improvements are around 6.0 cycles per degree[12] and higher.[24–27] Peak improvements at these spatial frequencies, particularly at the 6.0 cycle per degree mark, have long been considered clinically significant. Since they correlate strongly with functional and pilot vision,[28] these spatial frequencies are considered to be the most clinically useful at which to have any improved contrast.[27]

Under mesopic conditions, the results are even more promising. Of all the IOLs tested, only a few, including an acrylic IOL, had a positive impact on the mesopic contrast sensitivity function.[21,25] The Tecnis outshone the conventional lens, particularly at higher spatial frequencies,[26,27] 1 study reporting a 100% improvement in contrast sensitivity at 18 cycles per degree with the Tecnis as compared with a 50% increase at the same spatial frequency with a conventional IOL.[25] In other studies, the differences were more significant at lower spatial frequencies.[12,24,26] Since the Tecnis may provide superior night vision, it has been touted as a safer option for elderly patients who drive at night. This claim can be confidently backed by a study by Kershner,[25] who showed that out of 3 IOLs investigated the Tecnis was the only one to improve contrast sensitivity at all spatial frequencies when tested under mesopic conditions hampered by glare. The improvement ranged from 9% at lower spatial frequencies to 100% or better at high spatial frequencies such as 18 cycles per degree.[25] Other studies show improvements at only the higher spatial frequencies.[26]

While many positive findings do exist in the literature, there is little consistency about the exact spatial frequencies and lighting conditions under which the Tecnis definitely improves contrast. Furthermore, in only 1 study[26] did the Tecnis perform better than a conventional IOL in terms of improving contrast sensitivity at more than 2 spatial frequencies and in all lighting conditions, including photopic and mesopic conditions with glare. One reason for the variability among studies is that most of them compared the Tecnis with conventional lenses, which differ from it in other ways than just anterior surface design. To eliminate this confounding factor, Ricci et al.[29] compared the effect of Tecnis Z9000 implantation with that of its parent lens, the CeeOn Edge 911 (Advanced Medical Optics). The only way in which these 2 lenses differ is that the anterior surface of the Tecnis has a prolate design, whereas the CeeOn's is spherical. Furthermore, the study measured low contrast letter acuity as opposed to contrast sensitivity; the former measures acuity under different contrast situations whereas the latter tests only the patient's threshold for recognition. The study showed that the removal of all spherical aberration left patients with significantly better low contrast visual acuity under all contrast levels than did the conventional lens, except for at 100% contrast. These results were elucidated following mydriasis, highlighting the benefits of reducing spherical aberration when the pupil is dilated, such as in night driving.

How is it possible for the Tecnis to have such a positive effect on contrast? This can be attributed to the clarity of the retinal image that is created when aberrations are minimized. In fact, 1 study reported the retinal image to be 40% sharper following implantation of an aspheric lens.[25] Other studies have used objective techniques such as ray tracing to show that the Tecnis improves individual modulation transfer functions,[30] though their data are not as convincing as some of the contrast sensitivity studies described earlier.

The evidence strongly supports the removal of all spherical aberration from the visual system. It is important to note that all the aforementioned studies compared the Tecnis Z9000 against a conventional spherical IOL. Conventional spherical IOLs, while still beneficial in their own right, have been shown to introduce positive spherical aberration of up to 0.92 D[21] into the visual system themselves.[22,29] In this light, the purported advantages of eliminating all spherical aberration from the visual system may be slightly exaggerated, given that visual performance following implantation of the Tecnis has been compared with visual performance following implantation of a lens that probably induced positive spherical aberration into the system. Furthermore, even though the results of the studies differ in terms of precisely which spatial frequencies and under which lighting conditions the elimination of spherical aberration may be useful, they share 1 common theme: the most benefit will be derived under mesopic conditions. While it would be a huge advantage to provide patients with the ability to tell the difference between brightness levels in the dark, as Mester aptly puts it: "So far, we are on the way to an 'owl eye' (improved vision under nighttime conditions) instead of an 'eagle eye' or 'super' vision."[21]

So, although there is still no question as to whether using an aspheric IOL may prove beneficial for cataract patients, it is also apparent that zero spherical aberration does not automatically bless a patient with super vision. How does leaving them with residual spherical aberration compare?

Is a smaller, residual amount of positive spherical aberration ideal?

While it makes sense that the retinal image will be more defined and contrast sensitivity improved by removing all error from the visual system, the picture is not that simple. Some have hypothesized that there are some benefits to errors in the visual system.[14] For example, inherent blur leaves the patient less susceptible to the effects of chromatic aberration[31] and defocus.[30]

Levy et al.[7] studied individuals who already had super vision (which they defined as uncorrected visual acuity better than or equal to 20/15) and investigated their optics. Specifically, the team set out to prove that patients with super vision actually had low levels of higher-order aberrations, as one might expect. The results were surprising, in that the average amount of spherical aberration in the 35 subjects was determined to be +0.110 (SD 0.077) µm, far from zero. One might discard these results on the basis that the sole criterion for super vision in the subjects was a supernormal visual acuity, but the mean age of the subjects, 24.3 years, should be taken into consideration. There is powerful evidence in the literature to suggest that the best human contrast sensitivity is experienced from ages 20 to 30 years, as opposed to the single age of 19 years, as proposed by supporters of total spherical aberration elimination. A study by Amesbury and Schallhorn[32] confirms the results of Levy et al.,[7] also finding a small amount of positive spherical aberration in naval pilots who have been shown not only to have exceptional visual acuity but to have exceptional contrast sensitivity as well.[33]

How can ocular aberrations be present in excellent visual performance? Perhaps, as Applegate et al.[34] suggest, higher-order aberrations are more complex than we originally thought. In its paper researching the interactions among different higher-order aberrations, the team showed that having certain combinations of higher-order aberrations is actually less detrimental than eliminating other higher-order aberrations altogether.[35] In essence, higher-order aberrations may indeed serve a purpose within the eye and may even have evolved to be beneficial to the person. Furthermore, the most convincing data for the negative effect of higher-order aberration on vision come from situations in which the amount of higher-order aberrations are particularly high, such as in irregular corneas, as opposed to the smaller amounts that are found in the normal population.[7] Studies have also shown that the RMS unit is a poor predictor of visual acuity[35] and that low amounts of higher-order ocular aberration do not automatically lead to phenomenal visual performance.[6] Furthermore, the mean amount of spherical aberration in the internal optics of the eyes is –0.145 (SD 0.094) µm according to Wang et al.[19] Although it is impossible to differentiate between the individual contributions of the posterior cornea, lens, and gel-like refractive media to this total, one might safely assume that the total spherical aberration of the AcrySof IQ mimics the natural lens at –0.19 µm.

Are supernormal visual attributes recreated if we target a residual spherical aberration of +0.10 µm? This could be achieved by implanting the AcrySof IQ lens from Alcon (inherent amount of spherical aberration close to –0.19 µm).

The only published study to include the AcrySof IQ comes from Rocha et al.,[36] who showed that while the AcrySof IQ outshone competitor spherical lenses, the only truly significant effect was at 1 low spatial frequency under mesopic test conditions.

In a recent study,[37] Beiko hypothesized that targeting +0.10 µm of spherical aberration would leave patients with significantly improved contrast sensitivity regardless of whether the Tecnis or the IQ was used. Implanting the Tecnis into a small, select group of patients with +0.37 µm of anterior corneal spherical aberration, he found improvements in contrast sensitivity in both photopic and mesopic conditions, particularly in the latter. Implanting the IQ into a general group of patients with average anterior corneal spherical aberration close to the +0.27 µm population average, Beiko found very similar improvements in contrast sensitivity. When zero residual spherical aberration was achieved, the improvements in contrast sensitivity were not as good. This information leads us to believe that it is not the lens one implants but the targeted amount of residual aberration that will lead to improved visual performance. It proves how important it is to know the amount of spherical aberration with which super vision is correlated. Additionally, it implies that targeting a specific amount of spherical aberration in a general group of patients gives the same results as targeting that amount in a specially selected cohort.

Is a negative amount of spherical aberration ideal?

Some suggest leaving the patient with around –0.10 µm of spherical aberration following aspheric IOL implantation. This practice is not based on evidence that negative spherical aberration would provide better overall vision. On the contrary, the purported benefits of leaving a patient with some negative spherical aberration are confined to near vision only.[23] This concept can be better understood by revisiting Fig. 3. In negative spherical aberration, the central portion of the blur circle comprises mainly central light rays and thus a stronger power in comparison with the periphery. On viewing a near object, pupillary miosis brings the central portion of the blur circle into clearer focus and thus achieves higher power, emulating an addition at near vision.[23] A residual amount of negative spherical aberration may therefore be most useful to a presbyope desiring a decreased dependence on corrective near additions. The caveat is that the quality of the image may not be as clear as it might otherwise be. Little information regarding the effectiveness of this technique has been published.

Other considerations

Decentration

Holladay et al.[17] reported that the Tecnis Z9000 would provide significant improvements to the contrast sensitivity function only if decentred less than 0.40 mm and tilted less than 7° once implanted in the eye. These values probably err on the higher side of caution for the experienced surgeon. The tolerances of Holladay et al. may also be more restrictive than necessary, since they come from testing situations that include monochromatic light and minimized aberrations. The real world presents the system with polychromatic light and other inherent ocular aberrations, making the eye much less sensitive to strict performance tolerances.

Nonetheless, some studies report decentration and tilt as high as 0.7 mm and 7.8° respectively.[38] Even small amounts of decentration of IOLs can have detrimental effects on the modulation transfer function. Upon decentration, IOLs induce higher-order aberrations such as coma and astigmatism.[39,40] Aspheric IOLs will have the most negative effect on contrast sensitivity compared with even a conventional spherical IOL at as small as 0.5 mm of decentration. The greater the inherent amount of spherical aberration of an IOL, regardless of positive or negative, the stronger is this effect.

Given this information, one might question the benefit of implanting a lens with inherent spherical aberration (i.e., the Tecnis or the IQ) when even mild decentration can have such a detrimental effect on a patient's wavefront profile. This question becomes even more relevant when one considers that the chances of altering a patient's higher-order aberration profile to an amount significantly lower than his or her corneal aberration before surgery may be as low as 50% regardless.[40] Since Bausch & Lomb's SofPort does not affect contrast sensitivity at all upon decentration,[39] this may be reason enough to implant this aspheric lens before any other.

Effects of pupil size

Several studies have shown an increase in higher-order aberration with increasing pupil size.[41,42] This information was the basis for designing aspheric lenses that would reduce spherical aberration more significantly than a conventional IOL at pupil sizes of 4 mm or more. According to a recent study by Kasper et al.,[43] this is indeed true. The Tecnis Z9000 lowered spherical aberration significantly at all pupil sizes up to and including 6 mm.

Interestingly, this effect was only obviously significant at pupil sizes of 5 and 6 mm, and just barely significant at pupil sizes below these numbers. Furthermore, a significant decrease in the total higher-order aberration profile was only significantly better over the conventional lens at a 6 mm pupil size. These findings are thought-provoking for two reasons. First of all, we are brought back to the fundamental question of whether, since spherical aberration really is only a small piece of the higher-order pie, its correction is worthwhile if it will affect this profile at only larger pupil sizes.[16] Second, for what percentage of the elderly population will these lenses truly be useful given senile miosis? For the subject population in Kasper et al.'s study, the average pupil diameters of the groups of patients implanted with the aspheric lens and with the conventional spherical lens were 4.90 mm and 5.03 mm, respectively, in the darkest of testing conditions and accounted for approximately only one half of all subjects. In another study designed to investigate average pupil diameter with age it was determined that for a median age of 69 years the average pupil size in total darkness was 5.5 mm. In more realistic, dim conditions it was just over 4 mm.[44]

Suitability for all

With no clear-cut answer yet as to which of the aspheric IOLs will leave patients closest to a state of super vision, opting to leave the patient with no ocular spherical aberration or a residual amount of positive or negative aberration is, for now, a matter of personal choice. Regardless of whether the surgeon prefers one of these end-points over the other, it would be impossible to have a go-to lens that meets the needs of every patient presenting for cataract surgery (Table 2). For example, a surgeon might prefer to use the Tecnis on the basis of the belief that the elimination of all spherical aberration in the visual system would be beneficial to the patient. This lens would leave all of the surgeon's patients who have +0.27 µm of anterior corneal spherical aberration with no spherical aberration at all. Now imagine that the same surgeon implants the Tecnis into the eyes of a patient who has had refractive surgery for either hyperopia or myopia. In the case of the former, the patient would now be left with a significant amount of negative spherical aberration, as hyperopic laser correction induces negative spherical aberration itself. In the case of the myope, the patient would likely be left with a residual blur of positive spherical aberration. Even if the patient had untouched corneas, there is so much variability in the possible amount of anterior corneal spherical aberration (as shown by our and other studies[20,41]) that the ideal would be to have a slew of aspheric IOLs from which to choose, let alone 3. The best approach remains to calculate the spherical aberration of each cornea and to then pick the lens that brings the patient closest to the targeted amount of spherical aberration. We are still waiting, however, for this to become the norm in clinical practice.

Conclusion

The potential to increase quality of vision by reducing the amount of ocular aberration is a reasonable goal to pursue, and hybrid cataract and refractive surgery remains an effective way of doing so. While aspheric IOLs do have the potential to decrease the total spherical aberration of the eye, this effect may be compromised by factors that include decentration, patient variability, and pupil size, to name a few. Further investigation is also needed to determine how much spherical aberration is ideal for the human visual system.

Studies comparing the 3 aspheric IOLs against each other as opposed to against spherical IOLs, when the benefits of an aspheric lens are obvious, are crucial. The effect of each aspheric lens on total wavefront aberration, high contrast visual acuity, low contrast visual acuity, and grating contrast sensitivity should be evaluated under a variety of lighting conditions. Ideally, follow-up should be up to 6 months to 1 year, the time it supposedly takes the brain to adapt completely to changes in the optical system.

Last, increased spherical aberration is not the sole reason for decreased functional vision with age, and one must remember that the quest for super vision will always be hampered by more complicated and important optical[45] and neural factors over which the eye-care profession has little control … so far.

Table 2—Proportion of study patients qualifying for 1 of 3 aspheric intraocular lenses by targeted level of residual ocular spherical aberration

	Patients reaching targeted amount of spherical aberration (%)		
Spherical aberration targeted (µm)	Tecnis	IQ	SofPort
0 (SD 0.05)	35	~41.7	0
0.10 (SD 0.05)	~11.7	35	~10.8
–0.10 (SD 0.05)	~41.7	10	0

The authors have no proprietary interest in any aspect of this article.

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Key words: cataract, super vision, spherical aberration, aspherical intraocular lenses