The Aspheric Cornea, Spherical Aberration, and Intraocular Lenses: Considerations for Surgical Management

BY JOHN LLOYD, MD, FRCSC, DABO, REEM ALNABULSI, MD, AND MICHAEL WAN, MD

The cornea is the main refractive surface of the eye. The prolate shape of the cornea plays a role in maintaining the optimum total spherical aberration (SA) of the eye by neutralizing the negative SA of the lens. As we age the lenticular SA shifts in the positive direction while the corneal SA remains the same, making the total ocular SA more positive. SA of the eye is directly proportional to the Q coefficient that represents the corneal aspheric shape. In order to replace the natural lenticular SA after senile cataract surgery, aspheric lenses with different amounts of inherent SA have been developed. The evidence supporting the use and benefits of these lenses is controversial with many limitations. Despite limited evidence, most of the existing studies show that aspheric lenses give better contrast sensitivity and lower higher-order aberrations (HOAs) as well as SAs postoperatively. The outcomes are dependent on many factors such as the preoperative HOAs and SAs, decentration/tilt, pupil size and the surgically induced HOAs. Superior outcomes were demonstrated when the preoperative HOAs and SAs were measured when choosing an aspheric intraocular lens (IOL) to target zero postoperative SA. This issue of Ophthalmology Rounds will review the SA of the eye, its relation to the image quality and how it changes with aging, IOL implantation, and corneal surgery. Furthermore, the theory behind developing aspheric IOLs and the evidence available to demonstrate their benefits over spheric lenses will be summarized.

The cornea is prolate in shape with flatter periphery and steeper centre. The shape of the cornea is important as it influences the spherical aberration (SA) of the cornea and therefore the total SA of the optical apparatus. Maintaining a balance between the lenticular and corneal SAs is important for optimal vision quality. Changes in the shape of the cornea following laser-assisted in situ keratomileusis (LASIK) surgery or age-related changes in the lens can disturb the natural balance of the SA of the ocular system. This can lead to halos, glare, starburst and other visual defects. SA may be an important consideration for customizing the implantation of an intraocular lens (IOL) following cataract extraction.

Basic Optical Consideration: SA and Its Relation to Corneal Asphericity

SA is a higher fourth-order aberration that is produced by a difference between the central and the peripheral power of a refracting surface so that light rays passing through the periphery (marginal rays) are bent differently than those passing through the paraxial area, which leads to rays focusing at more than one point. SA is positive when the
Peripheral rays focus in front of the paraxial rays (Figure 1) while negative when the opposite happens. The aspheric shape of the cornea can be approximated as a conic section. In mathematics, conic sections are formed by the intersection of a plane with a cone (Figure 2). Conic sections are described by a number of coefficients, which are all different ways of describing the curvature of the conic section and can be converted mathematically. Table 1 describes the relationships.

An ellipse is described by the equation \( \frac{x^2}{a^2} + \frac{y^2}{b^2} = 1 \). If \( a > b \) then the ellipse has its major (longer) axis along the horizontal and is called prolate. Figure 3A shows the curvature decreasing as we move away from the apex. When \( b > a \), the opposite occurs and this is termed oblate (Figure 3B). If we consider the visual axis to be the horizontal, then the cornea has a prolate configuration. The term “p” is defined as \( \frac{b^2}{a^2} \) and represents how much the curvature varies from a circle (in which \( a = b \), and therefore \( p = 1 \)). The asphericity term “Q” is simply defined as \( p - 1 \). Doing this adjusts the scale so that \( Q = 0 \) describes a spherical (circular) surface. The result is that negative Q values are prolate and positive ones are oblate, with the special cases of \( Q = -1 \) being a parabola and \( Q < 1 \) being a hyperbola.

Knowing the corneal asphericity measurements in a population is helpful for customized laser ablation and contact lens fitting. Altering the corneal asphericity by targeting a more negative Q value may be useful in presbyLASIK. Further elaboration on the calculation of the Q value and on eccentricity \( (e) \) are beyond the scope of this paper. Interested readers are referred to the excellent review article by Calossi.

A spherical refracting surface has positive SA. When a surface is aspherized, giving a non-zero Q value, the change in Seidel SA at the aspheric surface is determined by an aspheric aberration contribution factor \( (k) \), which was defined by Hopkins and Welford (Table 2). The total SA of the eye comes from the cornea, lens, and retina; however, more than 95% arises from the anterior corneal surface as it is the main dioptric power of the eye. The SA is directly proportional to the Q value and is inversely proportional to the apical radius of curvature.

In the human cornea, a Q value of -0.53 would be predicted to give 0 SA, which is sometimes referred to as a “perfect” prolate ellipsoid. Average corneal Q values have been found to be -0.26, predicting a positive SA of +0.19 \( \mu \)m; however, actual measured SA has been found to average around +0.27 \( \mu \)m. This discrepancy arises because the true corneal shape is more complex than a simple radius of curvature and a Q value can predict. Therefore, there is no easy way to convert from a Q value to the SA, and measurement of SA is best performed by a topographer who has Zernicke analysis.

In a young eye, the measured SA of the crystalline lens is about -0.26 \( \mu \)m, which acts to neutralize the average corneal SA (+0.27 \( \mu \)m) over a

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\begin{array}{|c|c|c|c|}
\hline
\text{p} & \text{Q} & \text{e} & \text{e}^2 \\
\hline
\text{p} & 1 + \text{Q} & 1 - \text{e}^2 & 1 - \text{e}^2 \\
\text{Q} & \text{p} - 1 & -\text{e}^2 & -\text{e}^2 \\
\text{e} & \sqrt{1-p} & \sqrt{-\text{Q}} & - \\
\text{e}^2 & 1 - \text{p} & -\text{Q} & \text{e}^2 & - \\
\hline
\end{array}
\]

p defines how much curvature varies from a circle; Q represents asphericity, \( Q = 0 \) is a circle; \( e \) is eccentricity and \( e^2 \) represents the index of asphericity. Reproduced from Calossi A. J Refract Surg. 2007;23(5):505-514 with permission of SLACK Incorporated.
increase the depth of perception.\textsuperscript{25-27} Furthermore, as the SA is rotationally symmetric, it can balance or offset other types of higher-order aberrations (HOAs).\textsuperscript{28} Some studies claim that individuals with excellent visual performance (20/12) have an average of +0.2 µm of positive SA when measured over the 5.7-mm pupil diameter and thus SA is the only HOA that has non-zero mean value.\textsuperscript{29-32} It has even been postulated in one report that the increase in positive SA over age is the natural way of the eyes to compensate for the lost accommodation that happens in presbyopia.\textsuperscript{28} However, the subjects in these studies were aged 22–70 years while the best visual performance is known to be at age 19, making these conclusions debatable.\textsuperscript{14,30,31} Holladay argued that near-zero SA around the age of 19 is the ideal SA for the eye, which should be the target SA post-operatively, especially in younger individuals.\textsuperscript{14}

The optimum SA after senile cataract surgery for best image quality has yet to be determined.\textsuperscript{3} Some simulation studies have concluded that the best visual performance was associated with variable degrees of residual SA in different eyes. In the majority, the ideal residual SA was found to be slightly negative, ranging from (0.0 to -0.1), assuming the second-order aberrations are fully corrected.\textsuperscript{33-40} This can be especially true in pseudophakic presbyopic patients needing better near vision, which is helped by a residual negative SA as the pupil constricts during accommodation (stronger central power).\textsuperscript{14} The available aspheric lenses (SA ranging from 0.00 to -0.27)\textsuperscript{41} have been designed to neutralize the natural average amount of corneal SA present in the non-operated population.\textsuperscript{42}

As previously mentioned, studies of postoperative LASIK patients have shown that myopic ablation induces additional positive SA and hyperopic negative SA, with larger degrees of ametropia causing larger shifts.\textsuperscript{3,43} With the target postoperative SA ranging

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Table 2: Hopkins and Welford definition of aspheric aberration contribution factor ($\kappa$)

| $\Delta S_1 = \kappa = C^3 Q h^4 (n'-n)$ |

| where: |
| $\Delta S_1 =$ the change in spherical aberration |
| $\kappa =$ the aspheric aberration contribution factor |
| $C =$ the curvature = $1/r$ |
| $Q =$ the asphericity coefficient |
| $h =$ the height of the marginal ray |

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As previously mentioned, studies of postoperative LASIK patients have shown that myopic ablation induces additional positive SA and hyperopic negative SA, with larger degrees of ametropia causing larger shifts.\textsuperscript{3,43} With the target postoperative SA ranging
from (0.00 to -0.10), only 20% of the patients who underwent refractive surgery in one study could achieve such a target with the current range of aspheric IOLs. This suggests that measurement of post-LASIK SA may be necessary to determine the suitability of these patients for the current aspheric IOLs. Since SA measurements are not readily available to many cataract surgeons, avoiding negative SA aspheric IOLs in post-hyperopic LASIK patients is the simplest way to take this fact into consideration.

**Aspheric IOL Implantation**

Many factors can influence the clinical outcome of an aspheric IOL implantation. These include decentration, tilt, preoperative corneal HOAs, surgically induced HOAs, inherent SA of the lens, postoperative defocus and astigmatism, and pupil size (senile miosis). In addition, the time at which the patient is assessed postoperatively plays a role as the neural adaption of the brain to the new vision may take 3–12 months.

Numerous papers compared the outcomes of aspheric and spherical lenses in terms of postoperative HOAs, visual acuity, and photopic and mesopic contrast sensitivities. However, few of these studies assessed the preoperative corneal HOAs or the SA to optimize the postoperative SA, which is a significant limitation to the available evidence on the benefits of these lenses. Moreover, many of the conclusions were based on computer simulation testing where the visual axis is at the center of the pupil, which is not the case in the human eye. In most of these clinical trials, no statistically significant difference in best-corrected visual acuity (BCVA) was found between spherical and aspheric IOLs. Two studies, however, found significantly better BCVA outcomes with the aspheric lens. When photopic and mesopic contrast sensitivity were evaluated, the results depended mostly on the spatial frequency at which the contrast sensitivities were analyzed. Most of the studies found that aspheric lenses give better contrast sensitivity compared to spherical lenses, mainly in dim light and larger pupil size. As well, the majority of studies that examined HOAs postoperatively found that HOAs are lower in eyes with aspheric lenses as compared to spherical ones, while all studies that examined SA postoperatively found the SA to be significantly lower in eyes implanted with aspheric lenses. On the other hand, Negishi et al found no statistical difference between pre- and postoperative SA or HOAs, which may be explained by the surgically induced HOAs. Packer, Chandra, and Lian targeted zero SA postoperatively through the measurement of the preoperative corneal topographic SA. They were able to demonstrate the feasibility of this method and showed better outcomes compared to studies that did not consider the preoperative SA.

A recent large meta-analysis of all the available randomized, controlled trials comparing the HOAs postoperatively with aspheric versus spherical multifocal IOLs confirmed that aspheric IOLs did result in less HOAs particularly SA.

**Conclusion**

The SAs of the lens and cornea balance each other in the natural young eye. When this balance is lost because of lenticular aging or cataract extraction with inappropriate IOL implantation, or when the SA of the cornea changes following refractive surgery, the vision quality drops as a result of halos, glare, and starburst formation despite 20/20 vision on visual acuity testing. For a cataract surgeon, it is important to keep in mind the preoperative SA of the eye and any history of refractive surgery when choosing a standard IOL versus an aspheric one, which will influence the postoperative vision quality.

Many factors other than the SA contribute to the vision quality postoperatively. These include lower order aberrations, pupil size, tilt/decentration, the preoperative HOAs and the induction of new aberrations following surgery. Based on the current available evidence, aspheric lenses are either better or at least similar to spherical lenses.

As the rotationally symmetrical SA may balance other HOAs as the eye ages, this complex interaction needs further exploration, and should be considered in future studies when conclusions are drawn regarding the optimal SA. Attempting to measure the preoperative corneal SA in order to implant a “matching” aspheric IOL appears in some studies to have merit, but the benefit is not so substantial that the general ophthalmologist need rush out to buy specialized instruments to do so.
Dr. Lloyd is a staff ophthalmologist at the Sunnybrook Health Sciences Centre and the Kensington Eye Institute, and is the medical director of the Downtown LasikMD surgicentre, Toronto, Ontario. Dr. Alnabulsi is a PGY3 resident, Department of Ophthalmology and Vision Sciences, University of Toronto, Toronto, Ontario. Dr. Wan is a staff pediatric ophthalmologist at The Hospital for Sick Children, Toronto, Ontario.

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