Spherical Aberration: The Next Frontier

Only by understanding the math can ophthalmologists target the ideal correction for their patients.

BY JACK T. HOLLADAY, MD, MSEE

Spherical aberration is the property of a single spherical surface to refract rays too strongly as one moves from the center of the pupil peripherally compared with the paraxial (central) focus (Figure 1). The image formed when spherical aberration is present causes a halo (or blur) around the paraxial image (Figure 2). The terminology is the same in an optical system with multiple surfaces such as the human eye, which has four refracting surfaces (the anterior/posterior cornea and the anterior/posterior crystalline lens). If the system has more optical power away from the optical axis, toward the periphery, there is *positive* spherical aberration. If the opposite is true, then it is *negative*. Spherical aberration is radially symmetric, meaning that all semimeridians are identical and have the same ray-tracing diagram as if it were the only aberration in the system.

This article analyzes spherical aberration mathematically in order to identify the optimal amount to target for the human eye.

THE MATHEMATICS OF ASPHERIC SURFACES AND SPHERICAL ABERRATION: THE ANTERIOR CORNEA

Biological single surfaces are rarely spherical. More often they are aspheric, as are the surfaces of the cornea and crystalline lens. Some of the simplest aspheric surfaces are referred to as *conic sections*, because they can be created by taking a section of a cone. If we allow these surfaces to have a toric apex (astigmatism), then the resulting surfaces are hyperboloid, paraboloid, prolate ellipsoid, spheroid, and oblate ellipsoid. Each of these surfaces can be determined by three variables: horizontal and vertical apical radii (R_{xz} and R_{yz}) and an asphericity quotient (Q-value) in a three-dimensional Cartesian coordinate system (X, Y, and Z).

Equation 1.

$$Z = c \mp c^{*}\sqrt{\left(1-\frac{X^{2}}{R_{xz}c}-\frac{Y^{2}}{R_{yz}c}\right)}$$

where Equation 2.

$$R_{SEQ} = \frac{2R_{xz}R_{yz}}{R_{xz}+R_{yz}} \quad \& \quad c = \frac{R_{SEQ}}{(1+Q_{SEQ})}$$

Table 1 shows the values of Q and their corresponding surfaces. Figure 3 provides a cross-section (two-dimensional plot) of these surfaces.

Figure 4 illustrates a colored ray tracing of a spherical surface. The *longitudinal spherical aberration* (LSA') is the difference between the marginal focus (L'_m) and the paraxial focus (L'_p) along the optical axis. *Transverse spherical aberration* (TSA') is the height of the marginal ray at the paraxial focal plane.

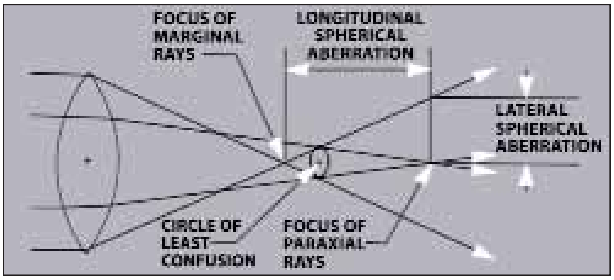

Figure 1. This diagram of positive spherical aberration illustrates longitudinal and lateral spherical aberration.

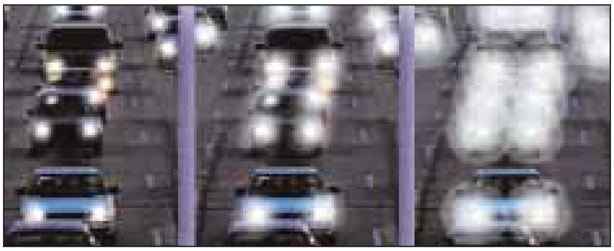

Figure 2. Spherical aberration is perceived as halos around lights that cause the symptoms of glare. Increasing amounts of spherical aberration create larger halos.

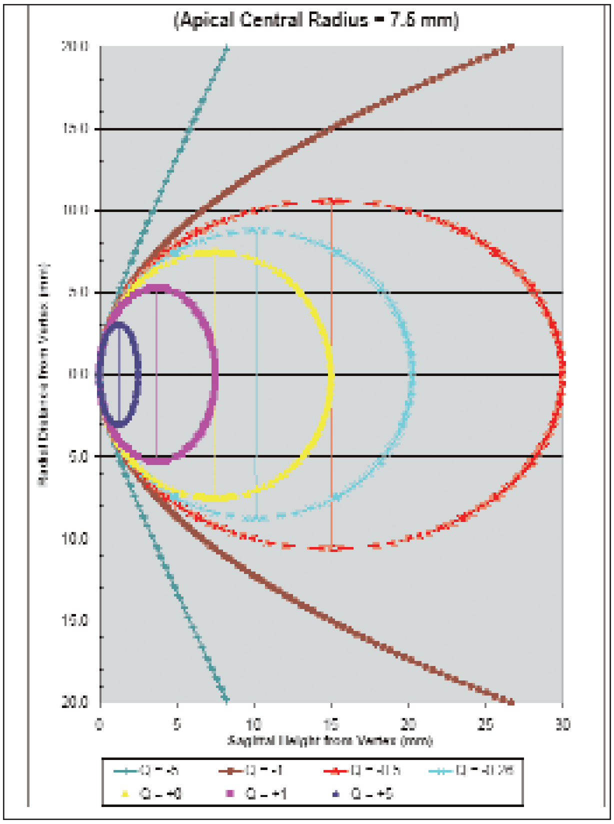

Figure 3. These conicoids have various Q-values. Blue (Q = +5) is an oblate ellipsoid, magenta (Q = +1) is an oblate ellipsoid, yellow (Q = 0) is a sphere, aqua (Q = -0.26, mean human cornea) is a prolate ellipsoid, red (Q = -0.50) is a prolate ellipsoid, brown (Q = -1) is a paraboloid, and green (Q = -5) is a hyperboloid.

Written as formulas, it is

Equation 3a. $LSA' = L'_m - L'_p$

Equation 3b. $TSA' = H' = (LSA')\tan U'_m$

where U'_m is the slope of the marginal ray after refraction. When the marginal ray intercept is anterior to the paraxial focus, the spherical aberration is positive. If posterior to the paraxial focus, it is negative.

TABLE 1. Q-VALUES AND THEIR CORRESPONDING SURFACES

Q-Value	Surface
Q < -1	Hyperboloid
Q = -1	Paraboloid
-1 < Q < 0	Prolate ellipsoid
Q = 0	Spheroid
Q > 0	Oblate ellipsoid

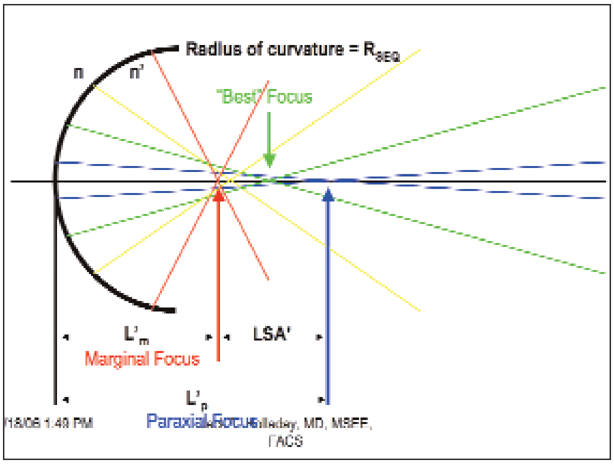

Figure 4. This diagram of positive spherical aberration shows marginal focus (L'_m), paraxial focus (L'_p), and longitudinal spherical aberration (LSA'). When only primary (third-order spherical aberration) is present, the best focus is midway between the marginal and paraxial foci.

The longitudinal spherical aberration can also be expressed as a series

Equation 4. $LSA' = a\,Y^2 + b\,Y^4 + c\,Y^6 + \ldots$

where the first term is referred to as *third-order LSA*, the second term as *fifth-order LSA*, etc., and the *a* is the coefficient of the third-order term, the *b* is the coefficient of the fifth-order term, etc. In most simple optical systems, including the normal human eye, it is rare to have more than third-order LSA, so the first term is all that is used clinically. In optical design, the term *zonal* SA_z is used. Instead of the marginal ray, it is customary to use a ray of height that is 0.707 of the marginal ray (Y_m) such that the areas inside and outside this diameter are equal. The resulting equations for third-order LSA are

Equation 5a. *Marginal Third-Order*

$$LSA'_m = aY_m^2$$

Equation 5b. *Zonal Third-Order*

$$LSA'_z = a\frac{Y_m^2}{2}$$

where

$$a = \frac{LSA'_m}{Y_m^2}$$

When only third-order spherical aberration is present, the "best" focus (circle of least confusion) is midway between the paraxial focus and marginal focus (one half of LSA_m). If third- and fifth-order spherical aberration are present, then the best focus moves to three quarters of LSA_m.

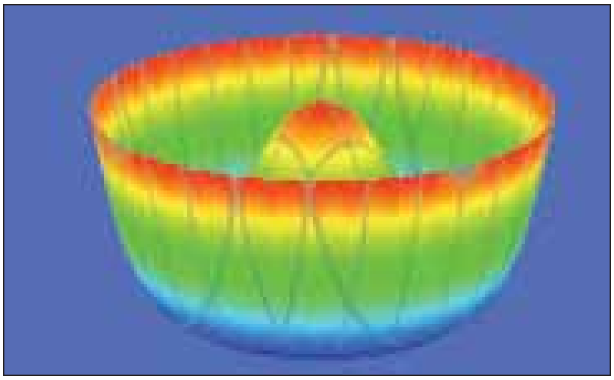

Figure 5. The surface of the Z(4,0) Zernike term for primary (third-order) spherical aberration is shown.

The spherical aberration may also be described using wave aberration form, which expresses the aberration of the wave at the refracting surface.

Equation 6.

$$W = w_4 Y^4 + w_6 Y^6 + w_8 Y^8 + \dots$$

Similar to Equation 4, the wave aberration for third-order spherical aberration is the first term, fifth-order spherical aberration is the second term, etc. For an aspheric surface, the primary spherical aberration (third-order) may be determined with the following equation[1]:

Equation 7.

$$w_4 = \frac{\frac{n'}{L'_m}\left(\frac{1}{L'_m} - \frac{1}{R_{SEQ}}\right)^2 - \frac{n}{L}\left(-\frac{1}{L} + \frac{1}{R_{SEQ}}\right)^2}{8} + \frac{Q_{SEQ}(n'-n)}{8R^3_{SEQ}}$$

where *n* is the index of refraction of the media of the object, *n'* is the index of refraction of the media of the image, *L* is the distance to the object, and *L'* is the distance to the image from the vertex of the surface for the marginal ray.

A number of observations can be made when looking at this equation. The first term (divided by eight) is the spherical aberration of a spherical surface, and the second term (after the plus sign) is the additional term necessary to describe the primary spherical aberration of an aspheric surface with a Q-value of Q_{SEQ}. In this equation, the primary spherical aberration coefficient is a proportional Q-value (as Q becomes more positive, the spherical aberration increases) and inversely related to the apical radius (as the apical radius decreases or K-reading increases, the spherical aberration increases). For any single object and apical spheroequivalent radius, there is a spheroequivalent Q-value that will give zero primary spherical aberration (note: this is only true for a single object at a given distance, not for an object at any other distance).

If we want to find the surface that has no spherical aberration for any object and image, the optical path difference must be the same for any rays traced through the system at height Y and must satisfy the following two-dimensional equation (Y and Z as defined in Equation 1 with X = 0):

Equation 8.

$$n'\sqrt{Y^2 + (L'\ \ Z)^2} + n\sqrt{Y^2 + (Z\ \ \ L)^2} - n'L'\ \ nL$$

Equation 8 is a form of the famous Descartes equation. Unfortunately, for all objects at any distance, the aspheric surface is not a conic section, so none of the aforementioned conic surfaces (Equation 2) can eliminate spherical aberration for *any* object at *any* finite distance. If the object is at infinity, then the formula reduces to the simple equation

Equation 9.

$$Q = -\frac{n^2}{n'^2}$$

This equation shows that, for an object at infinity, the negative of the ratio of the anterior index of refraction and squared divided by the posterior index of refraction squared is the perfect Q-value (conic surface) to eliminate spherical aberration. For the cornea, the index of refraction is 1.376, and the anterior medium is air. The ideal asphericity for the anterior surface of the cornea to eliminate spherical aberration for a distant object would therefore be a prolate ellipsoid with

Equation 10. ***Q= - (1.000^2/1.376^2) = -0.528.***

Several investigators have shown that the mean Q-value of the anterior cornea over a 6-mm zone is -0.260 (0.00 to -0.50) with a wide variance.[2] The normal human cornea with a Q-value of -0.260 has less positive spherical aberration than a sphere (Q = 0), but it is rarely free of spherical aberration (Q = -0.53). An important clinical point is that, even if the anterior cornea did have a Q-value of -0.528, it would only be free of spherical aberration for an object at infinity. An object at any distance other than infinity will result in spherical aberration.

Another common method of describing a wavefront aberration over a circular pupil with radius ρ is the Zernike polynomials. They are easily related to the classical aberrations, but two terms are required for aberrations that are not rotationally symmetric such as astigmatism and coma. Such terms are decomposed into an x and a y component, but they can be easily combined into one term with a single magnitude and orientation.

The term for primary (third-order) spherical aberration is given by the following Zernike polynomial:

Equation 11.

$$Z(4,0) = 5^{1/2}(6\rho^4 - 6\rho^2 + 1)$$

All of the Zernike terms above Z(0,0) have an average value of zero, and all terms are orthogonal and therefore mutually exclusive. Because each term has an average value of zero over the entire surface, the reference plane of zero (Figure 5 where zero is green) is not the paraxial focus but the best focus (circle of least confusion), as seen in Figure 4. For positive spherical aberration, the paraxial focus would be hyperopic (posterior to the best focus), and the marginal focus would be myopic (anterior to the best focus).

If we use the mean keratometric power of the human cornea (43.86D, yielding a radius of curvature of 7.695mm [keratometric index of refraction = 1.3375]), the mean human Q-value of -0.26, and the corneal stromal index of refraction of 1.376, the calculated primary spherical aberration using the Zernike transform Z(4,0) is +0.189µm for a 6-mm–diameter zone on a virgin cornea. We can also look at the spherical aberration as the change in refractive power on the cornea, which is much more familiar to the clinician.

Figure 6 is the topographic refractive power map of the conic anterior surface of the average human cornea with a central radius of 7.695mm (K-reading = 43.86D) and a Q-value of -0.26 with a stromal index of refraction of 1.376. The increase in refractive power is shown by warmer colors. At a 3-mm radius from the center (6-mm diameter), the additional refractive power equals +1.00D or +1.00D of marginal spherical aberration. The paraxial focus (L'_p) in media 1.376 is 28.1604mm, the marginal focus at 3mm (L'_m) is 27.5741, and the difference (LSA') is +0.586mm (+586µm). We see that, for the average anterior aspheric surface of the human cornea, the spherical aberration has a wavefront Z(4.0) of +0.189µm, a refractive power spherical aberration of +1.00D, and a longitudinal spherical aberration of +586µm—three different ways of describing the same amount of spherical aberration.

Unfortunately, using the actual topographic height data, these values are approximately 30% less than the actual measured, average, virgin, human, anterior corneal spherical aberration Z(4,0), which has been shown to be +0.270µm.[3,4] The refractive power spherical aberration is +1.42D, and the longitudinal spherical aberration is +837µm.

Recent studies explain the cause of this disparity and demonstrate that the conic with apical radii and Q-values (Equations 1 and 2) do not exactly reflect the true shape of the cornea, especially after corneal refractive surgery.[5-8] As a result, the K-reading and Q-value should never be used to determine the spherical aberration Z(4,0) term, because significant errors will occur.

Topographers such as the OPD Scan (Nidek, Inc., Fremont, CA) and the Pentacam (Oculus Optikgeräte GmbH, Wetzlar, Germany) calculate the Zernike terms for the topographic examination and display a report of these values. Most topographers do not have this feature in their software and require separate software programs such as VOL-CT (Sarver and Associates, Inc., Carbondale, IL) that take exported examinations from the topographers, import the information into VOL-CT, and then compute all of the Zernike terms and many other parameters. Unfortunately, this is the only accurate method available to clinicians today for most topographers that allows the exact calculation of the spherical aberration for choosing the correct aspheric IOL after cataract surgery.

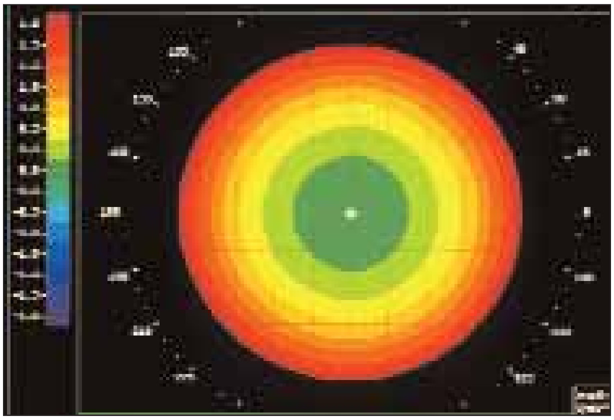

Figure 6. Shown is a refractive power map of the anterior surface of the corneal aspheric model with a central radius of 7.695mm (K-reading = 43.86D), a Q-value of -0.26, and a stromal index of refraction of 1.376. The increase in refractive power is shown by warmer colors. At 3mm from the center, the additional refractive power equals +1.00D.

With newer instruments such as the Pentacam and Visante OCT (Carl Zeiss Meditec, Inc., Dublin, CA) that are not Placido ring based, the central zone of the cornea is no longer a scotoma, and data are measured all the way to the center. These instruments have shown that the normal cornea is flatter in the central 2mm, becomes steeper from 2 to 4mm, and then begins to flatten beyond 4mm. To accurately represent the true corneal shape measured with these newer instruments, the simple ellipsoid is not adequate, and we must use a figured ellipsoid. It differs from the standard ellipsoid given in Equations 2 and 3 in that the Q-value is not a constant but an equation that varies as one moves radially from the center of the cornea. If we compute the apical radii and keep them constant, the Q-value usually gets more negative from the normal cornea's center to its periphery. A simple second-order polynomial is sufficient to describe this change.

Equation 7. $Q=a+b\rho+c\rho2$, ***where*** $\rho2 = X2 + Y2$ and ρ is the radial distance from the center (apex). To use the

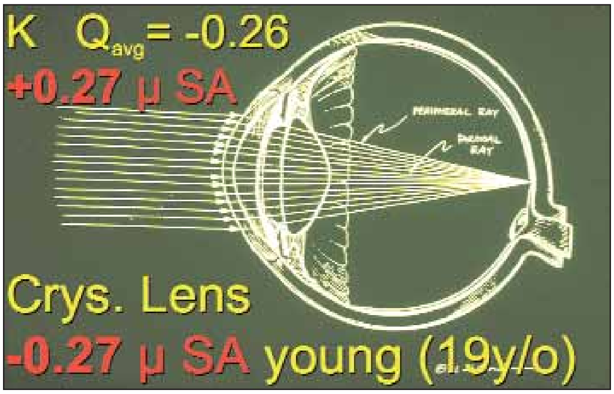

Figure 7. The ocular spherical aberration (entire eye) is nearly zero young in life (approximately 19 years of age), because the negative spherical aberration of the crystalline lens is almost equal and opposite to the positive spherical aberration of the cornea.

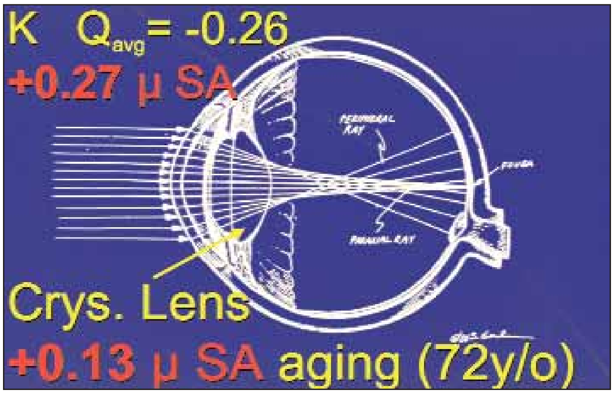

Figure 8. The human cornea and crystalline lens both have positive spherical aberration later in life due to the progressive increase in spherical aberration of the crystalline lens with age.

figured ellipsoid, we would therefore need five variables (R_{xz}, R_{yz}, a, b, and c): two principal apical radii for astigmatism and three coefficients for the Q-value as a function of the radial distance from the center, compared with only three for the standard conic surface. An excellent measure of the quality of the fit of any surface to the actual height data is the root mean square (RMS) error of the fit. The difference in the actual height data from the cornea and the height of the model surface is determined at each point. The difference at each point is then squared, the mean value of the sum of all of the squares is determined, and the square root of this value is calculated. A fit with an RMS error of < 0.5µm is excellent and represents a true fit.

OCULAR SPHERICAL ABERRATION: THE ENTIRE EYE

Studies measuring ocular (entire eye) spherical aberration agree on two findings. First, there is a great deal of variation in ocular spherical aberration at any age. Second, the average ocular spherical aberration is nearer to zero when people are around 15 to 20 years of age than when older. The *ocular spherical aberration* is the sum of the spherical aberration from the four refracting surfaces of the eye (the anterior/posterior cornea and the anterior/posterior crystalline lens).

Studies have demonstrated that the cornea has a stable shape throughout life in the absence of anterior corneal disease such as dry eye or anterior membrane dystrophy.[9] As mentioned earlier, the average spherical aberration of the anterior cornea is +0.270µm over a 6-mm zone. Glasser and Campbell have shown in vitro that the spherical aberration of the crystalline lens increases (from negative to positive) as a function of age.[10] Two more recent in vivo studies[11,12] have shown that the ocular spherical aberration is lowest in people aged 15 to 20. The variation is wide, however, and the trends of spherical aberration versus age only explain between 5% and 12% of the data. These statistics are similar to refractive error, color vision, contrast sensitivity, etc.

The best performance is around 19 years of age rather than older, but, even at that age, most people have spherical aberration that will likely become more positive as they grow older. Figure 7 is a ray-traced diagram with the ocular spherical aberration (entire eye) nearly zero at around 19 years of age, because the negative spherical aberration of the crystalline lens is almost equal and opposite to the positive spherical aberration of the cornea. Figure 8 depicts the spherical aberration in the aging human eye, where the cornea and crystalline lens both have positive spherical aberration.

IDEAL SPHERICAL ABERRATION IN THE HUMAN EYE

Knowing that the ocular spherical aberration is nearly zero when the eye is at its peak performance does not necessarily prove that zero is the ideal target, especially as people age. Some proposed concepts about spherical aberration are erroneous. Two fallacies are that the depth of focus increases with positive spherical aberration and that these changes naturally and beneficially reduce the effects of presbyopia on the quality of near vision.

First, the term is *spherical aberration*. By definition, an *aberration* reduces the quality of the ocular image. It is true that some aberrations are worse than others. For example, Huber[13] demonstrated better distance vision with similar amounts of with- versus against-the-rule astigmatism, and Sawusch and Guyton[14] demonstrated that against-the-rule astigmatism was better for near vision. The observations are true and relate to the Arabic alphabet. There are more vertical than horizontal strokes in the 26 letters of the English alphabet. Leaving the vertical line of the Conoid of Sturm on the retina therefore allows people to recognize more letters and explains the seemingly paradoxical results from Huber and Sawusch and Guyton.

Several researchers have demonstrated with image simulation how, together, certain higher-order aberrations can provide clearer images than lower amounts of other aberrations.[15-19] Additionally, McClellan et al have shown that we do not perceive chromatic aberration (rainbows of at least 1.50D around white light), because they are balanced by achromatic higher-order aberrations in the eye.[20] All of these observations and explanations are true and underscore the complex interplay of parameters in the eye that result in our excellent vision.

Spherical aberration does not increase depth of focus. Figure 9 depicts the pencil (fan) of rays passing through a 6-mm aperture, coming into focus, and then passing out of focus. Of note, the aspheric IOL (no spherical aberration in the system) brings rays into a single point of focus, whereas the spherical IOL with spherical aberration does not (forms a blurred circle of least confusion). The only difference between these two lenses is at the best focus, where the aspheric surface comes to a single point and the spherical lens does not. At ±0.50D and beyond, the pencil of light is the same diameter in both the spherical and aspheric IOLs with corresponding, equally blurred circles. There is no difference in the depth of focus, only the clarity of best focus.

The same comparison can be made between a +20.00D conoid aspheric indirect ophthalmoscopic lens and a spherical +20.00D lens from the trial lens set. The aspheric indirect lens creates a much clearer image than the spherical trial lens, because it eliminates spherical aberration. If there were any increased depth of focus due to the spherical aberration of the spherical lens or any other perceived improvement, we would all be using the $5 spherical trial lens and not the $300 aspheric conoid lens.

In fact, plus or minus spherical aberration yields a blurred halo around the image, and no spherical aberration yields the best possible image. In presbyopia or pseudophakia with an aspheric monofocal IOL, it may actually be desirable to have negative spherical aberration (rays in the periphery bend less than paraxial rays, thus resulting in more power centrally than peripherally). The reason is the synkinetic reflex when viewing an object at near. When an object is brought close to the eye, the synkinetic reflex includes convergence, accommodation, and miosis of the pupil. If negative ocular spherical aberration is present, then the power of the eye increases and makes the near image clearer when the pupil constricts. The negative spherical aberration when the pupil constricts still creates a halo, but the near vision with presbyopia is better. With positive spherical aberration, when the pupil constricts, the power centrally is weaker and actually reduces the quality of the image at near.

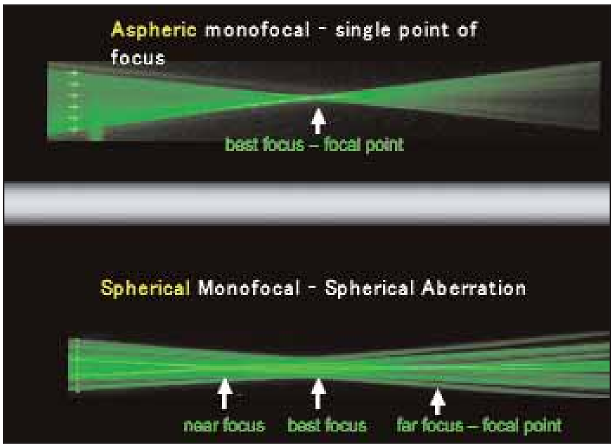

Figure 9. The light's path through different IOLs is visualized by projecting a monofocal, green (550-nm) light bundle through a lens positioned in water.

Suggestions that residual positive spherical aberration when the pupil constricts is beneficial refer to population-based studies or Top Gun pilots who have an average of +0.1µm. Referring to these studies is misleading, because the average age of the subjects is between 35 and 45 years.[21] These individuals have excellent vision, but the quality of their vision was better when they were 19 years old and their spherical aberration was nearer to zero. Also, if the RMS value rather than the coefficient of the spherical aberration is used, it is always positive and only relates to the magnitude and not the sign (positive or negative) of the aberration. The target of zero still provides the best result.

Also, we must carefully consider clinical studies comparing spherical aberration and the quality of contrast sensitivity function, macular threshold testing, etc. If other higher-order aberrations are present in the cornea, then any conclusions about spherical aberration and quality of vision are suspect, unless the other aberrations are also analyzed independently.[13-18]

In addition, if pseudophakic patients are left slightly myopic (-0.25D), uncorrected contrast sensitivity function or macular threshold studies may actually show better results with slightly positive spherical aberration. In mesopic or photopic conditions, the average size of the pupil is between 3 and 4mm, and the central part of the aperture is slightly hyperopic, balancing the mild myopia. If the patient's minimal myopic refraction is corrected, zero spherical aberration will always give the best results, provided there are no other higher-order aberrations present to confuse the issue. If all parameters of testing are controlled properly, zero will always yield the best quality of vision. If the magnitude of the positive and negative spherical aberration is equal, they will also perform the same. The only difference will be improved near vision with negative spherical aberration due to the constriction of the pupil as described earlier. Pablo Artal, PhD, has confirmed these findings clinically in his laboratory.[22]

Excimer laser surgery has also confirmed these findings. Standard hyperopic treatments induce negative spherical aberration versus positive spherical aberration with myopic treatments. If patients are emmetropic with presbyopia, the hyperopes with negative spherical aberration will have better near vision than their myopic counterparts with positive spherical aberration. The negative value is also the basis of presbyopic LASIK and Near Vision CK (Refractec, Inc., Irvine, CA), which produces an exaggeratedly prolate cornea with negative spherical aberration.

What is the optimal ocular spherical aberration we should target with aspheric IOLs and corneal ablation? From the material already presented in this article, it should be clear that we should target zero spherical aberration in the young individuals with no presbyopia who are scheduled for LASIK or PRK. Because they can accommodate, they will derive no benefit from the introduction of negative spherical aberration. In the presbyope or pseudophake with little or no accommodation, negative spherical aberration may be beneficial if they want to depend less on readers. If they are not bothered by using reading glasses, then zero spherical aberration is still the best target.

Several clinical studies have demonstrated improved quality with reduced ocular spherical aberration for aspheric IOLs after cataract surgery.[23-33] They have determined the improvement in contrast sensitivity to be approximately 0.3 log units (3dB) or 40% to 50% improved retinal image contrast. These results are predictable because modern small-incision cataract surgery introduces minimal new corneal aberrations and the optical qualities of IOLs' surfaces far surpass those of the cornea. Measuring the corneal spherical aberration over a 6-mm zone and matching this value with the aspheric IOL with the closest negative spherical aberration is the correct approach. If the surgeon cannot make an exact match, leaving the patient slightly negative is the best choice.

Unlike cataract surgery, unfortunately, modern corneal refractive surgery often introduces aberrations into the optical system when changing the refractive properties of the eye (primarily sphere and cylinder). The causes include nonhomogeneity of the excimer beam, reduced tension of the corneal collagen fibers in the LASIK flap, biomechanical changes of the cornea, and epithelial healing and remodeling. Although these factors are much harder to control and predict than cataract surgery, further research will realize the full benefits of ocular and topographic wavefront-guided treatments and result in the improvement of all aberrations, not just sphere and cylinder.

Another consideration that we cannot ignore, when looking at outcome measures such as visual acuity and contrast sensitivity function, is that our visual system includes an optical, sensory, and computer processor. The last of these compares the retinal image to stored images and also enhances the quality of the image. This neural adaptation has both a rapid and a long-term phase. The latter extends from 3 months to 1 year and is present whether the optical changes improve or degrade the retinal image.

Multifocal IOLs, which reduce the contrast of the image by 30% and are associated with halos, show that fewer than 1% of patients notice or are bothered by these effects by 1 year postoperatively. The same is true when the optical system is improved. In the original studies of the Tecnis aspheric IOL, Mester et al[30] and others[34] showed that the contrast sensitivity function continued to improve from 3 months to 1 year as the brain adjusted to the improved image. The point is that studies performed before the 1-year mark, when the optical system has been altered, do not necessarily reflect the patient's final outcome.

CONCLUSION

Our refractive surgical goal should be to eliminate or at least reduce all of the optical aberrations of the eye, including spherical aberration. We should remember, however, that it may take 6 to 12 months of neural adaptation for the patient to fully appreciate and exhibit improvement in subjective measures such as visual acuity and contrast sensitivity function. Older presbyopic patients may benefit from a small amount of residual negative spherical aberration in order to achieve better unaided near vision and depend less on readers—a similar compromise as with modern diffractive and refractive multifocal IOLs. Finally, there is no benefit to leaving any positive spherical aberration in the optical system, because it degrades the image and reduces patients' near vision as their pupils constrict. ■

Jack T. Holladay, MD, MSEE, is Clinical Professor of Ophthalmology at Baylor College of Medicine in Houston and President of the Holladay LASIK Institute in Bellaire, Texas. He is a consultant to Advanced Medical Optics, Inc., and Nidek, Inc. Dr. Holladay may be reached at (713) 668-7337; (713) 668-7336 fax; holladay@docholladay.com; or on the Internet at http://www.docholladay.com.

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