Phacoemulsification, Laser Cataract Surgery and Foldable IOLs

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CHAPTER 30

Effect of the Shape Factor on the Quality of Images in Eyes Corrected with IOLs

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R Fuentes, C González, F Mateos, E Villegas

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INTRODUCTION

In November, 1949 Dr. Ridley implanted the first ever intraocular lens (IOL). As a result of the operation there was a refraction defect of -24 (+6) 30°. In order to analyze this result, we must consider the circumstances in which the surgical operation was carried out. Firstly, at that time the mechanical and optical properties of materials such as polymethylmethacrylate (PMMA) were not known as they are today. Secondly, the design of the lens was a copy of the crystalline lens, making implantation difficult, whereas modern lenses have a very different design. Thirdly, the surgical instruments that we have nowadays were not available then, for example, at that time there were no surgical microscopes. In 1951, Dr. Ridley presented the results of his operation at an ophthalmological congress in Oxford. The medical profession showed its disapproval and went as far as to say that such an operation should never have been performed. Nowadays, there are millions of people with implanted IOLs of different types, geometry, shape and size.

Enormous progress has been made in this field. Both the design of the lenses and surgical techniques have improved to such an extent that nowadays the operation takes only about 15 minutes and is carried out under local anesthetic with the patient sedated. This means that the patient is able to leave the hospital just a few hours after the operation, and the risks associated with a general anesthetic are avoided.

In this chapter the latest advances made in the field of IOLs from a geometrical optics point of view are discussed, giving examples of how specific cases, mainly those involving high myopia, are being treated.[1]

Furthermore we will analyze the image quality of pseudophakic eyes with IOLs in high myopia applying geometric optics [transverse spherical aberration (TA) and transverse chromatic aberration (TCA)], and wave optics [(polychromatic modulation transfer function (MTF)].[2,3]

GEOMETRY OF INTRAOCULAR LENSES

There are two basic aspects of an IOL. On the one hand, there is the optic zone, of which we need to consider the diameter, thickness, shape and radii of curvature. On the other hand, there are the haptics whose size, geometry and shape must be taken into account since they determine the zone where the lens will be implanted as well as the possible side effects of the lens being "off center" or inclined together with the possible effects of aberrations.

Figure 30.1 shows an example of an IOL that clearly demonstrates the way in which this type of lens has developed.

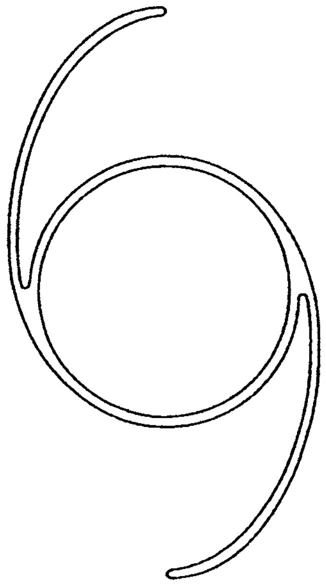

FIGURE 30-1. Intraocular lens (IOL) design

The design has become ever simpler, the lens lighter, and the haptics' configuration is such that they prove a minimum hindrance in the zone of union and to their insertion in the eye. This geometry prevents the lens from rotating, inclining or moving off center.

It should be emphasized that the geometry of the haptics is crucial when the lens is inserted, and contact with the cornea must be avoided at all times.

CLASSIFICATION OF INTRAOCULAR LENSES

Depending on the implant site, these lenses can be classified as: anterior chamber lenses, posterior chamber lenses and anterior chamber lenses for high myopia.

According to the optical way in which they work, they can be classified as: refractive monofocal lenses, refractive bifocal lenses, aspheric lenses and diffractive bifocal lenses. Fig.30.2 shows the optical way in which a diffractive bifocal lens works. In theory, diffractive lenses show a large amount of chromatic aberration, however, this has not been demonstrated clinically.

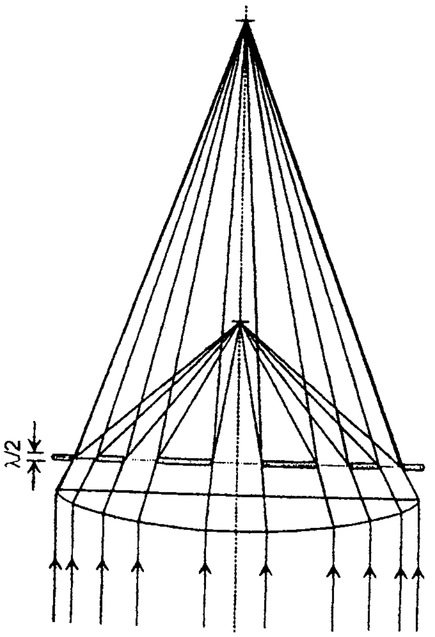

FIGURE 30-2. Way in which a diffractive bifocal intraocular lens (IOL) works

FUNCTION

An important point to discuss is the need to implant IOLs as an alternative to other corrective systems. Corrective ophthalmic lenses have the disadvantages of variations in the size of the retinal image, restriction of the visual field and prismatic effects since they are usually very high power systems.

The use of contact lenses poses a problem when the eyes have undergone surgery, and there is a lack of tears. This is usually the case with elderly people who moreover have difficulty in putting the lenses every day.

In the case of intraocular lenses, no variations in the size of the image occur, and they also act as a barrier between the aqueous humor and the vitreous humor, thereby, maintaining the ocular structure. Nevertheless, we must not forget that a surgical operation is involved.

MATERIALS

The material to be used in an implant must be biocompatible, have a high transmittance in the visible spectrum zone, and a refractive index that may be varied in order to control the geometry of the design.

Basically PMMA is the material used, although in some cases (HEMA) is chosen for its high biocompatibility and the case with which it polymerizes.

POWER CALCULATION FORMULAS

Precision is very important in the power calculation of IOLs since normally, the objective is for the patient to have a specific postsurgical refraction, or even be emmetropic. The precision depends on three factors: (i) biometric data (axial length, corneal power), (ii) precision of the manufacturer's quality control of the IOLs' power, and (iii) the precision of the formulas used to calculate the required power. In a survey carried out in 1990,[5] 35 percent of the surgeons consulted stated that they believed the power calculation formula to be the most imprecise factor in the power calculation of IOLs.

There are two groups of calculation equations.[6] The first is made up of statistical type calculation equations based on the calculation of the linear regression of the numerical adjustment made. These empirical or regression formulas are a function of the axial length, corneal power and a specific constant for each type and brand of IOL. These equations are commonly used clinically due to the fact they are easy to use and are established on the majority of biometers. The most commonly used is the Sanders-Retzlaff-Kraff (SRK) which has been shown to be very accurate from a statistical point of view. However, in the case of high myopia, some calculation errors are seen using this equation.

The other group of equations correspond to the evaluation of the IOL implant power based on the principles of geometrical optics. These theoretical formulas are a function of the axial length, corneal power and desired depth of the anterior chamber. These equations do not produce errors, however, there are a great number of them, differing mainly in the approximations used in their development.

Possibly the most important parameter in IOL power calculation equations is the depth of the anterior chamber. There are innumerable models and statistical studies available to evaluate this parameter[7,8] and the one chosen depends on the individual surgeon and the surgical technique used.

Figure 30.3 shows just some of the different equations that exist together with a wide variety of terminologies used. It can therefore be said that these equations are personal and specific to the population studied in order to develop them. The most commonly used equation is the BK which gives excellent results. Nevertheless, most of these equations usually give rise to errors when the corneal power of axial length differs

Theoretical formulas

1. **R.D. Binkhorst**

$$D = \frac{1336\,(4r-a)}{(a-d)\,(4r-d)}$$

2. **Colenbrander**

$$F_L = \frac{N_1}{l-v-0.00005} - \frac{N_1}{\frac{N_1}{F_c} - v - 0.00005}$$

3. **Eyodorov-Galin-Linksz**

$$D_p = \frac{n-aD_c}{(a-k)\left(1-\frac{k}{n}D_c\right)}$$

4. **R. Binkhorst Extendida**

$$D = \frac{1336(4R-\{L+0.25-0.0517\})}{\{(L+0.25-0.0517)-C\}\,(4R-C)}$$

5. **Shammas**

$$P = \frac{1336}{L-0.1-(L-23)-C-0.05} - \frac{1}{\frac{1.0125}{K} - \frac{C+0.05}{1336}}$$

Symbols used in the formulas:

	keratometry radius	keratometry power	thickness of the cornea plus depth of anterior chamber	axial length	power of the IOL
RD Binkhorst	r		d	a	D
Colenbrander F_L		F_c	v	l	
F–G–L, D_p		D_c	k	a	

Regression formulas

1. Formula SRK

$$Dp = A - 2.5\,A_l - .9\,K$$

D_p = Implant power to obtain emmetropia
A = Constant
A_l = Axial length in mm
K = Preoperative keratometry

FIG. 30–3. Different equations used to calculate intraocular lens (IOL) power

greatly from normal values. To be precise, high axial myopia needs to be given special treatment since many of the equations found in the literature give rise to significant errors. For example, the SRK-II[9] is a modified version of the SRK, and its parameters have been corrected so as to adapt it to the case of high myopia.

An alternative to optical-geometrical methods for power calculations is the use of the matrix method to obtain accurate calculation equations for all types of eyes. In this way, we have obtained the following equation[10]

$$P_7 = \frac{n_8(1-\delta_6P_5)a - n_8n_4\delta_6c - l'(aP_5+n_4c)}{l'(a-\delta_6P_5a-n_4c\delta_6)} \qquad (1)$$

Where

P_7 = power of the second surface of the IOL
n_8 = refractive index of vitreous humor
δ_6 = reduced thickness of the IOL
P_5 = power of first surface of the IOL
n_4 = refractive index of aqueous humor
l' = distance between the second surface of the IOL and the retina
a and c = coefficients related to the refraction and translation matrices used in the calculation.

Once P is calculated using Equation 1, we can find the IOL power P_L from the equation:

$$P_L = P_5 + P_7 - \delta_6P_5 + P_7 \qquad (2)$$

Moreover, the power of different types of lenses with different radii of curvature can be calculated, so that we can determine the shape factor of each lens in order to subsequently relate it to the quality of the image desired.

ABERRATIONS OF INTRAOCULAR LENSES

Just like any other type of lens, IOLs can have all kinds of chromatic and monochromatic aberrations. However, if the implanted IOL is correctly oriented with respect to the visual axis and has exactly the power necessary to focus near the fovea, the spherical aberration is the most important aberration to be considered and is the one that mostly affects the vision of the human eye.[11] For this reason, it is the aberration which has been studied most and the aim is to compensate for it at all times.

There are two possible IOL design principles—to minimize the spherical aberration of the whole eye[12] or to obtain the same spherical aberration as in phacic eye.[11]

With regard the second criterion, Jalie[11] found that the IOL shape which most closely reproduces the average spherical aberration of the natural eye is planoconvex with the plane surface facing the cornea (convex plane, X = –1) for IOL powers ranging from + 15.94 to 17.98D.

However, Wang and Pomerantzeff[12] found that the shape factor which minimized spherical aberration of the whole eye was X = –0.52 (an unequal biconvex lens) for IOL powers—+19.4, +18.77, +19.17 and +19.61D.

On the other hand, Smith and Lu[13] found that for corneas with asphericities less negative than about –0.512, the spherical aberration of the eye as a whole is minimized with a planoconvex IOL with the curved surface facing the cornea (planoconvex, X = +1). Atchison's research[14] supports the use of a planoconvex IOL.

All these studies were carried out using general models of emmetropic theoretical eyes, except for the Atchison study[14] in which he also analyzed six ametropic eyes with refractive errors of approximately +10, +5, +2D (hypermetropia) and –2, –5, –10D (myopia). Nevertheless, in all cases the IOL power was positive. However, there do exist certain cases of highly myopic eyes in which when the image focal length of the cornea is less than the axial length of the eye, a negative IOL power is needed to achieve emmetropia.[1]

Some experimental studies[15,16] have been published on the optical quality modulation transfer function—(MTF) of the eyes implanted with IOLs by using a double-pass method. In these studies, the optical performance of different types of bifocal IOL are compared with that of conventional monofocal IOLs. However, the optical performance of different types of monofocal IOLs are not compared.

Another recent study shows the use of MTF measurements to provide a standard test of minimum optical quality of positive intraocular lenses[17] using a water cell with plane entrance and exit windows. The results show that a meniscus-shaped lens gives an MTF that is significantly worse than the biconvex and planoconvex lenses.

Other studies show that in an emmetropic eye, diffraction and chromatic aberration are the factors that mostly affect image quality and therefore visual acuity.[18–22]

LN Thibos[20] designed a reduced model which predicts experimental values for chromatic aberration with a good degree of accuracy. However, this model is made up of only one refractive surface and cannot therefore be used to directly analyze the influence of any variation introduced in the eye on ocular chromatic aberration.

A real eye has aspheric surfaces, and the refractive indices of the ocular media depend on the wavelength. Furthermore, recent studies indicate that the human eye uses chromatic aberration to extract valuable directional information about "defocus" and to drive the accommodation response.[23]

For these reasons, it is of utmost importance to analyze diffraction and chromatic aberration together with spherical aberration in a theoretical pseudophakic eye model which more closely mimics a real eye.

In the pseudophakic eye, the total spherical aberration is the result of the contributions of the cornea and of the IOL. The amount of spherical aberration caused by the IOL depends mainly on the position of the object relative to the IOL and the shape of the lens.

We shall analyze the spherical aberrations of IOLs related to the shape of these lenses, taking into account at all times the eye which is nonaccommodated or focussed on infinity.

The schematic model of a pseudophakic eye used (Fig. 30.4) is a centered system in which the cornea is represented by a single spherical diopter, the refraction index of the aqueous humor is the same as that of the vitreous humor (n) (schematic eye of Gullstrand-Emsley[24]), and the IOL is represented by a thin lens.

In order to study the spherical aberration of IOLs and the total spherical aberration of pseudophakic eyes, we have made use of Seidel's theory of aberrations, since this theory makes various premises, such as: the total aberrations of an optical system are the sum of the contributions of each surface, the aberrations of surfaces and of thin lenses can be expressed as simple equations, etc.

Although nowadays, thanks to the facilities of modern computers, a finite pattern of rays can be widely used, a third order theory (Seidel's theory, or the primary aberration theory) can be of use in the preliminary design of any optical system without having to resort to a large number of data, since these simple third order theory equations give approximate values of the aberrations inherent in an optical system.

The use of Seidel's theory to study the spherical aberration of IOLs can be justified on the grounds that the majority of people who use IOLs have very small pupils so the higher order aberrations are reduced to insignificant values.

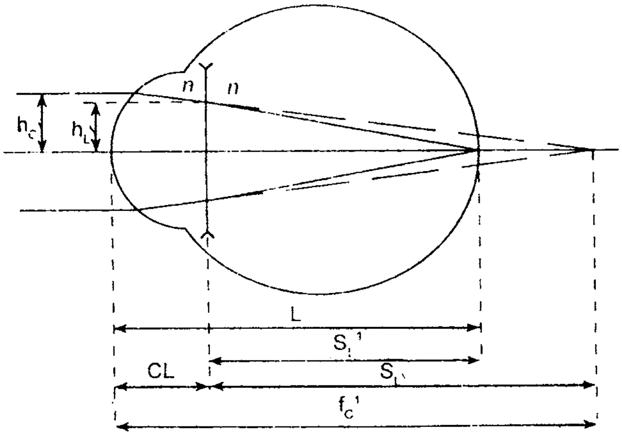

FIGURE 30.4. Schamatic pseudophakic eye—corrected with an intraocular lens

SEIDEL'S THEORY: SPHERICAL ABERRATION

For a spherical diopter with radius of curvature r separating two mediums with refraction indexes n_1 and n_2, Seidel's spherical aberration or primary spherical aberration (S_{IS}) is given by the equation[25] where h is the height at which the light incides on the surface, and s' is the distance to the Gaussian image.

$$S_{IS} = \frac{n_1(n_2 - n_1)h^4}{n_2}\left[\frac{1}{r} - \frac{1}{s'}\right]^2\left[\frac{n_2}{r}\ \frac{n_2 n}{}\right] \qquad (3)$$

Therefore, Seidel's spherical aberration of the cornea (S_{IC} can be calculated using the equation:

$$S_{IC} = \frac{h_c{}^4 P_c{}^3}{(n-1)^2 n^2} \qquad (4)$$

The symbols used in this equation are defined in the Appendix.

Bearing in mind that we disregard the thickness of the IOL, Seidel's spherical aberration in this type of lens (S_{IL}) can be determined using the following equation for a thin lens.[25]

$$S_{IL} = \frac{h_L{}^4 P_L{}^3}{4n^2}\left[\frac{n_L{}^2}{(n_L - n)^2} + \frac{(n_L + 2n)n^2}{n_L(n_L - n)^2}X^2 + \frac{(3n_L + 2n)}{n_L}Y^2 + \frac{4n(n_L + n)}{n_L(n_L - n)}XY\right] \qquad (5)$$

Were,

$$Y = \frac{s_L' + s_L}{s_L' - s_L} \qquad (6)$$

$$X = \frac{r_2 + r_1}{r_2 - r_1} \qquad (7)$$

The symbols used in this equation are defined in the Appendix.

The power of the intraocular implant (P_L) can be calculated making use of Gauss' equation for a thin lens:

$$P_L = -\frac{n}{s_L} + \frac{n}{s_L'}$$

Since we have considered that the eye is focussed on infinity, the object distance (s_L) from the intraocular lens is (Fig. 30.4):

$$s_L = f_c' - CL \qquad (8)$$

Our objective is for the eye to be emmetrope, therefore, the light beam will focus on the retina after having been refracted through the intraocular lens, so that (Fig. 30.4):

$$s_L' = L - CL \qquad (9)$$

Therefore, the power P_L of the implant can be calculated by means of the equation:

$$P_L = \frac{(f_c' - L)n}{(f_c' - CL)(L - CL)} \qquad (10)$$

If we take into consideration equations (8) and (9), equation (6) can be written as:

$$Y = \frac{L + f_c' - 2CL}{L - f_c'} \qquad (11)$$

The symbols used in this equation are defined in the Appendix.

From equations (5), (10) and (11) we can see that Seidel's spherical aberration of an IOL depends on the position of the lens in the eye (CL), the corneal power (P_c), axial length of the eye (L) (all these data (CL, P_c and L) depend on the individual eye), and the shape factor.

From Equation (5) we can see that, if the other variables (CL, P_c and L) are constant, S_{IL} is a function of the square of the shape factor and can therefore be simplified to:

$$S_{IL} = \frac{h_L^4 P_L^3}{4n^2} (AX^2+BX+C) \tag{12}$$

where the parameter P_L is defined by equation 10 and:

$$A = \frac{(n_L + 2n)n^2}{n_L(n_L - n)^2} \tag{13}$$

$$B = \frac{4n(n_L+n)}{n_L(n_L - n)} Y \tag{14}$$

$$C = \frac{n_L^2}{(n_L - n)^2} + \frac{3n_L+2n}{n_L} Y^2 \tag{15}$$

where the position factor Y is defined by equation (11)

Now we shall analyze the total Seidel's spherical aberration of the eye as a whole, which is the sum of Seidel's aberration of the cornea plus that of the IOL. Thus, if we add up the contributions of the cornea (S_{IC}) and of the IOL (S_{IL}) given by the equations (4) and (12), the total Seidel's spherical aberration for the eye as a whole is:

$$S_{IT} = h_c^4[D+E(AX^2+BX+C)] \tag{16}$$

where A,B and C are given by equations (13), (14) and (15), and:

$$D = \frac{n}{(n - 1)^2 f_c'^3} \tag{17}$$

$$E = \frac{P_L^3}{4n^2} \left(\frac{h_L}{h_c} \right)^4 \tag{18}$$

The relationship (h_L/h_c) depends on the individual parameters of the schematic eye and the position of the IOL in the eye (Fig. 30.4).

Analysis of Seidel's Spherical Aberration in an Intraocular Lens

Jalie[11] assumed that the spherical aberration of a pseudophakic eye should be the same as the spherical aberration of a phakic eye. In a phakic eye, most of the spherical aberration comes from the cornea and for this reason, it seems that the natural shape of the crystalline lens does not affect the value of the spherical aberration of the cornea. In other words, the crystalline lens itself is practically applanatic in the nonaccommodated state. The shape of an IOL should reproduce this situation.

If we consider equation (12), the value of X which is necessary to cancel out Seidel's spherical aberration in an intraocular lens (s_{IL}) is given by:

$$X = \frac{-B \pm \sqrt{B^2 - 4AC}}{2A} \tag{19}$$

The roots of this equation will be real numbers when:

$$\left(\frac{L + f_c' - 2CL}{L - f_c'} \right)^2 \geq \frac{n_L (n_L + 2n)}{n_L^2 - 2n_L n + n^2} \tag{20}$$

Therefore, Seidel's spherical aberration in an IOL (S_{IL}) will be cancelled out when the corneal power, axial length and position of the lens comply with equation (20), and the two shape factors that will cancel out S_{IL} are given by equation (19).

If Seidel's spherical aberration in an intraocular lens, S_{IL}, cannot be cancelled out because the corneal power, axial length and position of the lens do not comply with equation (20), it can atleast be minimized (S_{ILmin}). Since equation (12) is square in terms of shape factor, S_{IL} as a function of X is a parabola with its vertex at (X_{Lmin}, S_{ILmin}). For a given position factor, the shape factor (X_{Lmin}) which minimizes Seidel's spherical aberration in an IOL is obtained taking derivatives of S_{IL} with respect to the shape factor X and equating to zero. In this way, we obtain:

$$X_{Lmin} = -2Y \frac{n_L^2 - n^2}{(n_L + 2n)n} \tag{21}$$

and the value of this minimum is:

$$S_{ILmin} = \frac{h_L^4 P_L^3}{4n^2} \left[\frac{n_L^2}{(n_L - n)^2} - \frac{n_L}{n_L + 2n} Y^2 \right] \tag{22}$$

Analysis of the Total Seidel's Spherical Aberration in the Whole Eye

In the previous section, we analyzed Seidel's spherical aberration in IOLs. In this way, the spherical aberration of a pseudophakic eye reproduces the spherical aberration of a phakic eye. However, instead of trying to reproduce the conditions of a phakic eye, we could try to improve them. Therefore, in this section we shall deduce what conditions are necessary to cancel out and minimize the total spherical aberration of the whole eye.

It can be seen that equation (16) is square in terms of the shape factor, and therefore, the value of X necessary to cancel out all of Seidel's spherical aberration is given by:

$$X = \frac{-B \pm \sqrt{B^2 - 4A\left(C + \frac{D}{E}\right)}}{2A} \tag{23}$$

The roots of this equation are real numbers if:

$$\left(\frac{L + f_c' - 2CL}{L - f_c'}\right)^2 \geq \frac{n_L + 2n}{n_L} + \left(\frac{n_L^2}{(n_L - n)^2} + \frac{D}{E}\right) \tag{24}$$

Therefore, the total Seidel's spherical aberration of the whole eye (S_{IT}) will be eliminated when the corneal power, axial length and position of the lens comply with equation (24), and the two shape factors which will cancel out SIT are given by equation (23).

If the total Seidel's spherical aberration of the whole eye (S_{IT}) cannot be eliminated because the corneal power, axial length and position of the lens do not comply with equation (24), it can atleast be minimized ($S_{IT\min}$). Since equation (16) is square in terms of shape factor, SIT as a function of X is a parabola with its vertex at ($X_{T\min}$, $S_{IT\min}$). The value of the shape factor which minimizes the total Seidel's spherical aberration is obtained by taking derivatives of S_{IT} with respect to the shape factor X and equating to zero. Thus, we obtain:

$$X_{T\min} = -2Y \frac{n_L^2 - n^2}{(n_L + 2n)n} \tag{25}$$

Therefore, the value of the shape factor which minimizes the total Seidel's spherical aberration is the same as that which minimizes the aberration of the IOL only.

If we substitute equation (25) in equation (16), we obtain the minimum value of the total Seidel's spherical aberration of the whole eye ($S_{IT\min}$):

$$S_{IT_{\min}} = h_c^4 \left[D + E\left(\frac{n_L^2}{(n_L - n)^2} - \frac{n_L}{n_L + 2n} Y^2\right)\right] \tag{26}$$

Transverse Spherical Aberration (TA)

The eye is considered emmetropic for a wavelength of 555 nm (C,I,E maximum photopic luminous efficiency of mean observer). Using a computer program of rays tracing, we can calculate the retinal blur circle corresponding to this wavelength as function of the pupil diameter.[2,3]

Chromatic Aberration

The chromatic aberration on the retinal plane, or the transverse chromatic aberration (TCA), can be defined as the difference between the radii of the retinal blur circles corresponding to the limiting wavelengths, 430 and 680 *nm*[2,3]:

$$TCA = R_V - R_R$$

where R_v is the radius of the blur circle for lower wavelengths and R_R is the radius of the spot for higher wavelengths. The TCA will be positive if the green spot is greater than the red one and negative if the opposite occurs.

Modulation Transfer Function (MTF)

The polychromatic MTF can be obtained using the point-spread function (PSF) taking into account spherical aberration and defocus coefficients.

The polychromatic PSF and MTF are computed by integration of their monochromatic counterparts through the visible spectrum (430-680 nm) sampled at 1 nm intervals. The monochromatic MTFs are weighted by the CIE photopic luminous efficiency function of the eye.

The monochromatic PSF is calculated taking into account the Stiles-Crawford effect.

$$PSF_\lambda = \frac{B}{\lambda^2}\left|\iint_\Sigma exp\left[i\frac{2\pi}{\lambda} w(\rho, \lambda)\right]\sqrt{A}\, J_o(\alpha\rho)\,\rho\, d\rho\, d\theta\right|^2 \tag{27}$$

where

B is a normalization term, and Σ is the exit pupil area.
A is the Stiles-Crawford appodizing function.
0 $<\rho<1$ is the normalized radial coordinate in the exit pupil plane.
θ is the angular coordinate in the exit pupil plane.
α is given by the equation

$$\alpha = \frac{\pi l d}{Z} \tag{28}$$

where *l* is the radial coordinate of the observation point, *d* is the distance between the planes of the exit pupil and the Gaussian image, and z the distance between the planes of the exit pupil and the plane where the PSF is calculated.

The rays entering the eye are not equally effective. In general, their efficiency decreases as they enter more eccentrically. For this reason, the Stiles-Crawford appodizing function, A, is assumed Gaussian[18]:

$$A = \exp\left(-0.05\, R^2_p\, \rho^2 \ln 10\right) \qquad (29)$$

where R_P is the exit pupil radius (in millimeters). $w(\rho,\lambda)$ is the aberration function for a rotationally symmetric system:

$$w(\rho, \lambda) = w_{20}(\lambda)\, \rho^2 + w_{40}(\lambda)\, \rho^4 + w_{60}(\lambda)\, \rho^6 \qquad (30)$$

where w_{20} is the defocussing coefficient, w_{40} and w_{60} are the third and fifth spherical aberration coefficients respectively.

Calculation of the Optimum Benging Factor of IOLs

The optical quality of the pseudophakic eyes can be calculated by means of the coefficient A[4].

$$A = \frac{1}{\lambda} \sqrt{2\int_0^1 w^2(\rho)\, \rho\, d\rho} \qquad (31)$$

Where λ is the wavelength, W(r) is the aberration function of a rotationally symmetric system:

$$W(\rho) = W_{20}\rho^2 + W_{40}\rho^4 + W_{60}\,\rho^6 + W_{80}\,\rho^8 + W_{100}\,\rho^{10} \qquad (32)$$

where $0<p<1$ is the normalized radial coordinate in the exit pupil plane, W_{20} is the defocus coefficient, W_{40}, W_{60}, W_{80} and W_{100} are the third, fifth, seventh and ninth spherical aberration coefficients respectively.

The deformations [aberration function, W(r)] of an aberrated wavefront with respect to the reference sphere are related to the transverse spherical aberration in the observation plane[20] which in our study is placed at the Gaussian image point. Taking into account this relation, the coefficients W_{20}, W_{40}, W_{60}, W_{80} and W_{100} are calculated. W_{20} is negligible, due to the fact that the observation plane is the plane normal to the optical axis at the Gaussian image point (which is considered the retina), except for the IOLs with high spherical aberration because the spherical aberration of the pupil is important.

▼ RESULTS

We applied this theoretical study to 12 theoretical cases of myopic pseudophakic eyes with different combinations of axial length (between 27 and 33mm) and corneal power (between 42 and 48 D).

Table 30.1 shows the power of the IOL to be implanted so as to obtain emmetropia in these 12 cases. The IOL power range is between –9.80 D and +9.61 D.

TABLE 30–1. Calculation of the power of the intraocular lens to obtain emmetropia in 12 theoretical cases of pseudophakic eyes with different combinations of corneal power and axial length, using the schematic eye of Gullstrand-Emsley. All the and the power in diopters.

Pc\L	*27*	*30*	*33*
42	9.61	3.13	-2.02
44	7.05	0.57	4.48
46	4.46	0.02	7.17
48	1.83	4.64	9.80

Both the expression of Seidel's spherical aberration of an IOL (equation 12) and the expression of the total Seidel's spherical aberration (equation 16) depends on the height of incidence on the cornea (h_c). However, in this chapter we have not taken a specific height of incidence. Instead we have studied—S_{IL}/h_c^4 and S_{IT}/h^4_c (S_{IL} and S_{IT} expressed in units of wavelength for a wavelength of 555 nm, and *hc* expressed in millimeters), From equations (19), (21), (23) and (25), we can see that the shape of the lens necessary to cancel out or minimize Seidel's spherical aberration does not depend on the height of incidence.

Seidel's Spherical Aberration in an IOL (S_{IL})

Figure 30.5 shows how S_{IL} varies as a function of the shape factor when P_c=46 D and for all the axial lengths studied. For the other cases studied, the graphs show a similar parabolic shape.

In general, it can be seen that when the IOL power increases in absolute value, the parabola is more closed indicating that Seidel's spherical aberration is more sensitive to variations in the shape factor. Therefore in the case of high IOL powers, the shape factor of the IOL should be carefully considered since it has a considerable effect on the spherical aberration.

In addition to analyzing Seidel's spherical aberration in the IOL as a function of the shape factor in these 12 cases of high myopia, we also studied the combinations of axial length and corneal power for which Seidel's spherical aberration in a thin IOL can be eliminated (equation 20). Fig. 30.6 represents the limits within which the axial length must fall, in cases of different corneal power, in order to eliminate Seidel's spherical aberration in an IOL. We have determined

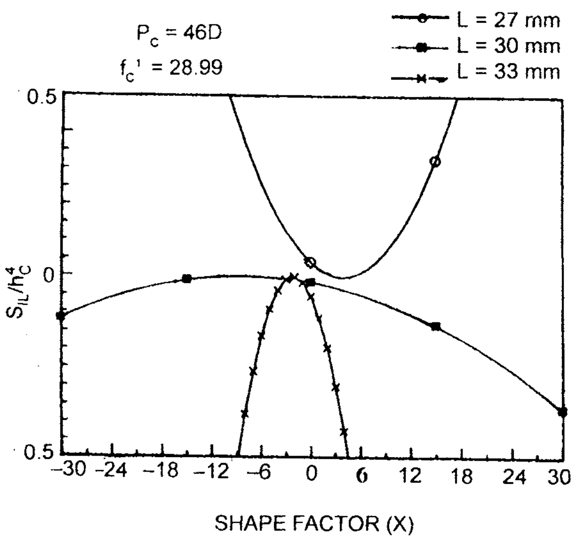

FIGURE 30-5. Variation of S_{IL}/h^4_c as a function of the shape factor, when P_c= 46 D, and for all the axial lengths studied (27, 30, and 33 mm). S_{IL} is expressed in wavelength units when γ = 555 nm and h_c in millimeters

that in 8 of the 12 cases studied, it is possible to eliminate S_{IL} by choosing the appropriate shape factors (equation 19). The two shape factors are meniscuses with the convexity towards the cornea.

In the other 4 cases (P_c = 42 D and L= 27 mm, P_c= 44 D and L= 27 mm, P_c = 46 D and L= 33 mm and P_c= 48 D and L= 33 mm), S_{IL} could only be minimized and not eliminated.

Total Seidel's Spherical Aberration of the Whole Eye (S_{IT})

Figure 30.7 shows how S_{IT} varies as a function of the shape factor when P_c = 48 D and for all the axial lengths studied. For the rest of the cases studied, the graphs present a parabolic shape similar to that of Fig. 29.7 and resemble that which would be obtained for S_{IL} as a function of the shape factor, since considering the contribution of the cornea modifies the position of the curves but does not affect their shape.

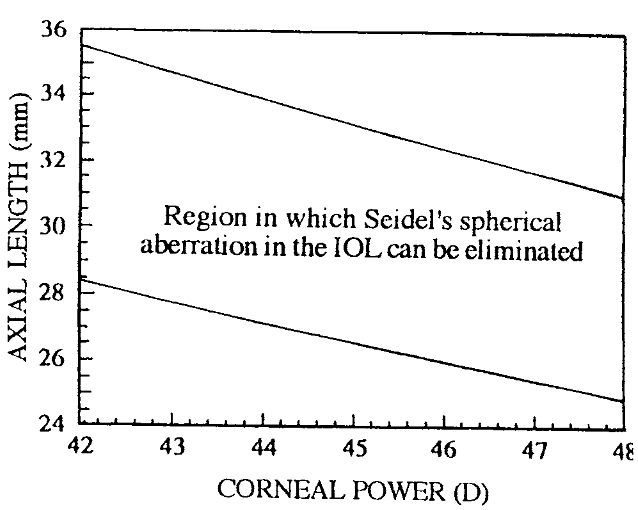

FIGURE 30-6. Limits within which the axial length must fall in cases of different corneal power in order to eliminate Seidel's spherical aberration in the IOL

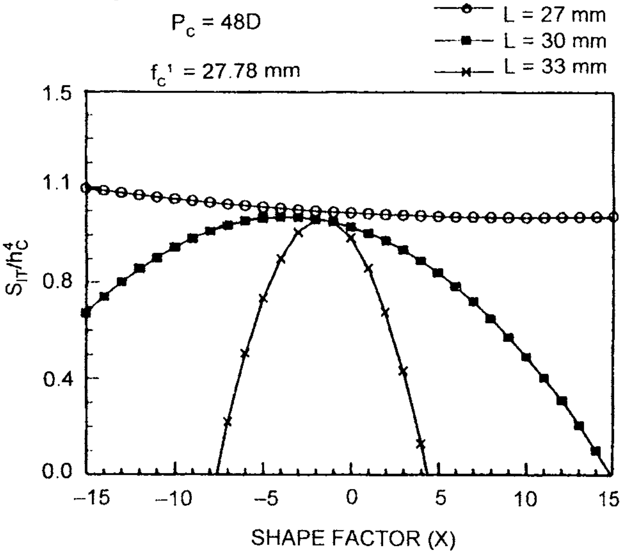

FIGURE 30-7. Variation of S_{IT}/h_c^4 as a function of the shape factor, when P_c= 48 D, and for all the axial lengths studied (27, 30, and 33 mm). S_{IT} is expressed in wavelength units when g = 555 nm and h_c in millimeters

We have already reached the conclusion that S_{IT} can be eliminated when equation (24) is complied with, i.e. when the aberration of the IOL and that of the cornea have the same value but are of opposite signs. Of the 12 cases studied, only in the 6 cases which required a negative power to obtain emmetropia can S_{IT} be eliminated by choosing the appropriate shape factors (equation 23). Of the two lenses which correspond to each case, one solution is a meniscus with a convex surface towards the retina, and the other is a meniscus convex towards the cornea. The meniscus

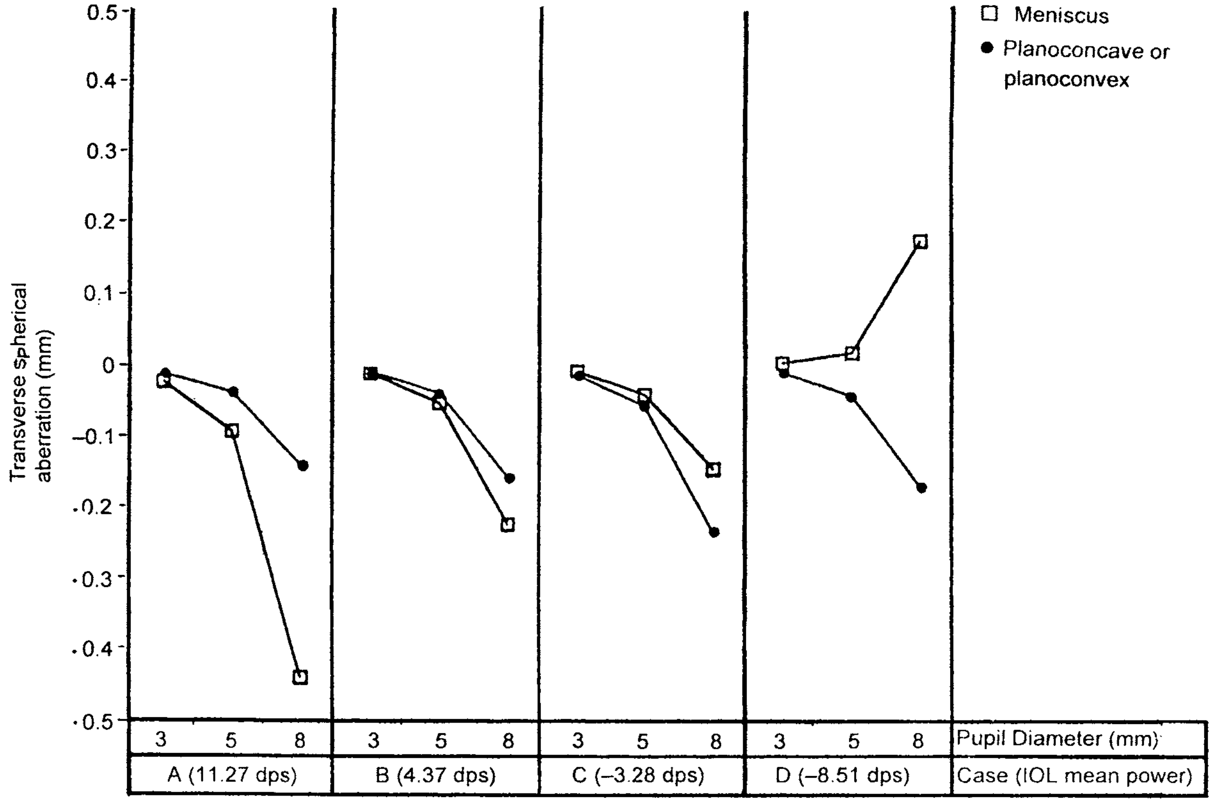

FIGURE 30-8. Transverse spherical aberration for each case of theoretical pseudophakic eyes with 3, 5 and 8 pupil diameters

which is convex towards the retina is called an inverted IOL lens,[26] and has several physiological advantages compared with the IOLs normally used—convex-plane, biconvex and plane-convex. For example, the risk of postoperative detachment of the retina is reduced, and the distance between the IOL and the iris is increased which means that the possibility of forming synechia is reduced. Consequently, these lenses are the ideal solution since they not only eliminate the spherical aberration, thereby, improving the image quality and also have physiological advantages.

For the 6 cases of corneal power and axial length that require a positive emmetropization power, it is not possible to eliminate S_{IT} completely, but it can be minimized. For each of these 6 cases, the two solutions which minimize S_{IT} are meniscuses which are convex towards the cornea. This means that from a physiological point of view these lenses are not ideal. In these 6 cases, we studied the S_{IT} which the most commonly used shapes present (convex-plane, biconvex, and plane-convex), and found that the flat-convex lens presents an aberration which is only slightly greater than the minimum value. This shape has always been considered to be the one that minimizes the spherical aberration. Possible meniscus lenses which are convex towards the retina were also studied. These lenses present a total Seidel's spherical aberration which is approximately twice that of the convex-plane lens aberration. However, the physiological advantages of these meniscus lenses should also be taken into account.

Transverse Spherical Aberration, Chromatic Aberration and MTF

The Seidel's spherical aberration, the transverse spherical aberration (TA), the transverse chromatic aberration (TCA), the modulation transfer function (MTF), and the coefficient A are very useful when applied to the design of IOLs. We use these parameters and functions to study the design of IOLs in myopic

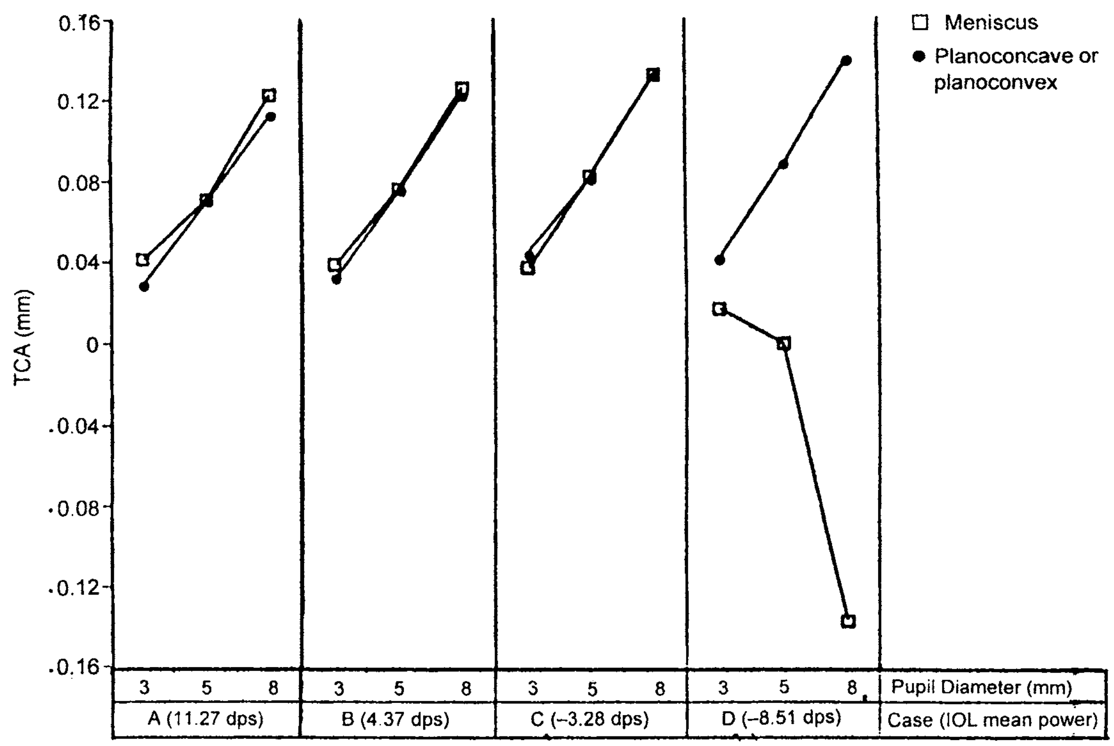

FIGURE 30-9. Chromatic difference of the blur circles (TCA) for each case of theoretical pseudophakic eyes with 3, 5 and 8 pupil diameters

pseudophakic eyes with different combinations of axial length (between 27 and 33 mm) and corneal power (between 42 and 48 D).

Calculations of Seidel's spherical aberration were done employing a schematic model of a pseudophakic eye that (Fig. 30.4) is a centered system in which the cornea is represented by a single spherical diopter, the refraction index of the aqueous humor is the same as that of the vitreous humor {(*n*) (schematic eye of Gullstrand-Emsley)},[24] and the IOL is represented by a thin lens.

The transverse spherical aberration, the chromatic aberration, the modulation transfer function and the coefficient A of the myopic pseudophakic eyes were studied using a modified version of the phakic theoretical eye used by Navarro *et al*,[27] replacing the crystalline lens by an IOL that corrects the highly myopic eye in the paraxial zone for a wavelength of 555 nm (CIE maximum photopic luminous efficiency of the mean obsever).

We have studied 4 theoretical cases of pseudophakic eyes that are shown in Table 3 (IOL power = +10.8 D (Case A), +4.2 D (Case B), -3.2 D (Case C) and -8.4 D (Case D).

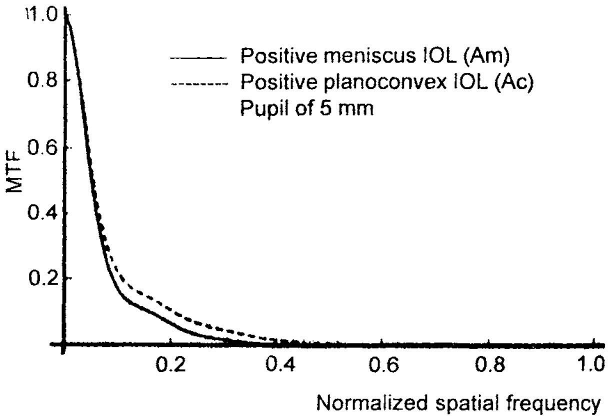

FIGURE 30-10. Polychromatic MTF for the pseudophakic eye A. Pupil diameter: 5 mm

Figure 30.8 shows the transverse spherical aberration for the pseudophakic eyes studied at a 555 nm wavelength for 3, 5 and 8 mm pupil diameters. In cases

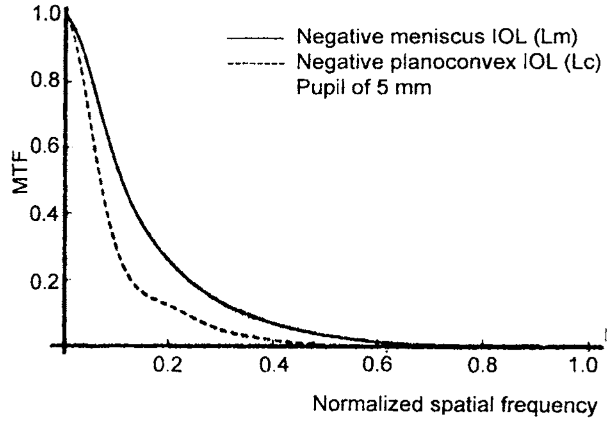

FIGURE 30-11. Polychromatic MTF for the pseudophakic eye D. Pupil diameter: 5 mm

of A, B and C, there is negative transverse spherical aberration (the image point moves nearer to the cornea as the radius of the pupil increases). In case D, the meniscus lens produces a positive transverse spherical aberration (the image point moves further from the cornea as the radius of the pupil increases), contrary to a planoconcave IOL. The TCA was calculated for the same cases than TA.

Taking into account spherical aberration, Figure 30.9 shows the TCA for extreme wavelengths 430 and 680 nm. In the cases of A, B and C, the TCA difference between the meniscus IOL and the planoconvex or concave IOL is very small. For case D, the behavior for a negative planoconcave IOL (DC) is similar to cases A, B and C, but for a meniscus-shaped IOL (Dm), the evolution of the TCA as a function of pupil diameter is just the opposite due to the fact that the spherical aberration that is produced is positive.

Figure 30.10 and 11 show the polychromatic MTF for a positive IOL (case A) and for negative IOL (case D) respectively, for a pupilar diameter of 5 mm.

▼ DISCUSSION

The Seidel's aberration theory has proved to be very useful when applied to the design of IOLs. Studies have been done using this theory to determine how the shape of the lens affects the quality of the image.[12-14,26,28] All these studies were carried out using theoretical emmetropic eye models. However, in this chapter, theoretical myopic eyes were studied and for this reason, the results obtained regarding the most appropriate shape factors are different.

Considering all the findings, we can say that if we take into account the type of eye we wish to correct with an IOL, together with its dimensions and corneal power, we can find a lens whose shape factor is such that the spherical aberration of the lens is minimized or even eliminated. Therefore, we can conclude that if the lens used has the appropriate geometrical shape, it is possible to correct the eye by means of this IOL which, moreover, presents no spherical aberration. An analysis of the shape factors which appear indicates that the type of lens to be used in the case of high myopia should be shaped like a meniscus. It was also found that in certain cases and taking into consideration the position of the meniscus, not only the desired refractive effects but also extremely important physiological advantages were obtained.

Although it may be true that the theoretical variation of the spherical aberration is not very great when the shape factor is modified, when we analyze clinical cases of patients implanted with IOLs shaped like a meniscus, excellent results regarding the postsurgical visual sharpness were obtained. This was greater than expected in between 80 percent and 90 percent of the patients.[29]

For pseudophakic eyes with low myopia (IOL high positive power, case A), the planoconvex IOL is better than the meniscus IOL due to the fact that the planoconvex IOL gives less spherical aberration and TCA, and better polychromatic MTF for all the pupilar diameters.

For pseudophakic eyes with a medium myopia (IOL low power, cases B and C), the quality image give by TA, TCA and polychromatic MTF for meniscus and planoconvex concave IOLs is very similar. In these cases, it was better to implant a meniscus IOL due to the several physiological advantages it offers.

For pseudophakic eyes with very high myopia (IOL high negative power, case D), optically, the best IOL is the meniscus taking into account TA, TCA and polychromatic MTF. Furthermore, physiologically, it reduces the danger of postoperative retinal detachment which increases as myopia increases. These results agree with the results obtained using total Seidel's spherical aberration.

Taking into account A coefficient, in the case of a pseudophakic eye that is corrected with a positive IOL power, the planoconvex IOL (X = + 1) gives the best optical quality. However, in the case of a pseudophakic eye, i.e. corrected with a negative IOL power, a meniscus with a specific bending factor gives the minimum A value and therefore the best image quality.

Considerating all studies (Seidel's spherical aberration, transverse spherical aberration (TA), transverse chromatic aberration (TCA), polychromatic modulation transfer function (MTF); and A coefficient) in pseudophakic eyes, for positive IOLs lenses the planoconvex IOL is the most adequate. This is in agreement with previous studies done by Smith and Lu[13] and Atchison.[14] However, for negative powers a meniscus IOL is the best, clinical study agrees with these results.[29]

Consequently, it is obvious that it is necessary to take the shape factor into account when calculating the power of IOLs, since it is then possible to choose the lens which, in addition to producing a minimum or no aberration, improves the quality of the final image.

APPENDIX

Sign Conventions

1. The object is situated at the left of the optical system so that initially the light travels from left to right.
2. The radius of curvature r of a surface is positive if the center of curvature is to the right of its vertex.
3. The distance *s* of the object from (the vertex of) the surface is negative if the object is to the left of the surface.
4. The distance *s'* of an image from (the vertex of) a surface is positive if the image is to the right of the surface.
5. The height *h* of an object or *h'* of an image from the optical axis is positive if it is above the axis.

Definition of Symbols

S_{IS}	Seidel spherical aberration of a spherical refracting surface
S_{IC}	Seidel spherical aberration of the cornea
S_{IL}	Seidel spherical aberration of an IOL
S_{ILmin}	Minimum Seidel spherical aberration of an IOL
S_{IT}	Total Seidel spherical aberration of the whole eye
S_{ITmin}	Minimum total Seidel aberration of the whole eye
h_c	Height above the optical axis at which the light incides on the cornea
p_c	Corneal power
f_c	Focal image distance from the cornea
n	Refraction index of aqueous humor and vitreous humor (taken here as 1.333333)
h_L	Height above the optical axis at which the light incides on the IOL
n_L	Refraction index of the IOL (taken here as 1.49)
P_L	IOL power
Y	Position factor of the IOL
X	Shape factor of the IOL
X_{Lmin}	Shape factor which minimizes Seidel's spherical aberration of an IOL
X_{Tmin}	Shape factor which minimizes the total Seidel spherical aberration of the whole eye
$s_L s_{L'}$	Gaussian distances of object and image from the IOL
r_1, r_2	Radii of curvature of the first and second surfaces of the IOL
CL	Position of the lens, distance from the cornea to the IOL (taken here as 3.6 mm)
L	Axial length of the eye.

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