

Intraocular lens to correct corneal coma

Juan Tabernero

Laboratorio de Optica, Departamento de Física, Universidad de Murcia, Campus de Espinardo (Edificio CiOyN),
30071 Murcia, Spain

Patricia Piers

Advanced Medical Optics, 9728 NX Groningen, The Netherlands

Pablo Artal

Laboratorio de Optica, Departamento de Física, Universidad de Murcia, Campus de Espinardo (Edificio CiOyN),
30071 Murcia, Spain

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We present a new methodology to obtain, to the best of our knowledge, the first intraocular lens (IOL) designed to balance the coma induced by the cornea due to the global ocular tilt. This lens is designed to mimic the situation naturally occurring in the normal healthy eye. The new proposed IOL provides an improved optical quality for all lens powers. © 2007 Optical Society of America
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Recent studies of simultaneous measurements of corneal and ocular aberrations^{1,2} in normal eyes showed that there is a natural compensation of the spherical aberration (SA) between the cornea and lens for young subjects. Normal aging tends to disrupt this compensation mechanism because the SA of the lens gradually changes from negative to positive.³ This fact contributed to the development of new aspheric intraocular lenses (IOLs) designed to correct the average value of corneal SA.^{4,5} Other corneal aberration terms, such as coma, are also internally balanced in the normal eye.^{6,7} This compensation effect for coma can be explained by the typical incidence angles in the eye's optics. The fovea is usually located on the temporal side of the optical axis (in object space).⁸ The location of the fovea results in angular differences between the visual axis, or the line of sight, and the best approximated optical axis of the eye of about 5° (being most commonly in the range from 3° to 7°). Corneal coma increases as this angle increases. However, coma for the complete eye does not show the same tendency, remaining similar for subjects with very different angular values. Ray-tracing simulations showed that when the incident field angle increases, the coma generated at the cornea and the lens had systematically opposite signs, therefore providing a partial balance for this aberration. In this Letter, we present the design process of a new IOL that systematically reproduces the natural behavior of the human lens by providing a compensation for corneal coma.

It is important to understand the physical parameters that govern the image formation of an optical system with coma. The Seidel primary aberration of coma for a lens in air (thin lens theory) is directly proportional to the angle of incidence of the principal ray (in other words, an increase in lens tilt with respect to the principal ray will generate increased coma) multiplied by a linear combination of the shape and position factors.⁹ Therefore, for each posi-

tion factor, it is always possible to calculate a shape factor for the lens that cancels the coma for all range of tilts with respect to the principal ray angle. However, the optical system of the eye is more complicated than this simple formulation. The eye has a nonconventional distribution of refractive indexes (air-cornea-aqueous-lens-vitreous) and we need a new procedure to evaluate this system. It is possible to use ray-tracing techniques to design and optimize IOLs in realistic eye models. However, it may also be important for the optimization procedure to have a logical idea of what the physically best IOL shape is for the eye, at least at the initial stage of the design process. To work with nonconventional asymmetric refractive index distributions in lens systems, Hazra and Delisle¹⁰ presented the Seidel primary aberrations of a thin lens immersed in different object and image medium in terms of redefined shape and position factors. In particular, primary coma for a thin lens of optical power K , refractive index n , object space index n_1 , and image space index n_2 can be expressed as a function of shape and position factors with the following expression:

$$S_{\text{coma}} = -\frac{1}{4}n_1h^3K^2\bar{u}[p_1X^2 + p_2Y^2 + p_3XY + p_4X + p_5Y + p_6], \quad (1)$$

where h is the height of the marginal ray at the lens, \bar{u} is the principal ray angle, and the p factors are exclusively functions of the refractive indexes tabulated in Ref. 10. The shape factor X and the position factor Y are described below, where c_1 is the curvature of the anterior lens surface, c_2 is the curvature of the posterior surface, and u and u' are the marginal ray angles at the object and image spaces, respectively:

$$X = \frac{(n - n_1)c_1 + (n - n_2)c_2}{(n - n_1)c_1 - (n - n_2)c_2}, \quad Y = \frac{n_2u' + n_1u}{n_2u' - n_1u}. \quad (2)$$

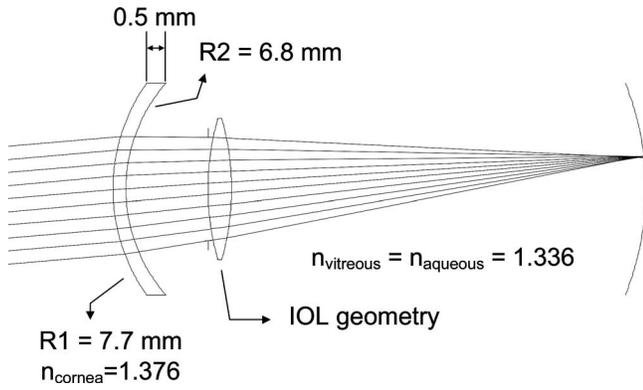


Fig. 1. Schematic of a pseudophakic eye model with Gullstrand parameters for the cornea.

For this asymmetric refractive index distribution, the relationship between coma and the shape and position factors is quadratic. This would mean that in such a system, for each position factor, it is possible to find two different shapes that would cancel coma.

We are interested in the specific optical system of the eye after a cataract surgery when the crystalline lens is replaced by an IOL. Figure 1 shows a schematic of the system with corneal parameters from Gullstrand's unaccommodated eye model. We use the above-mentioned formulas to express the coma of each ocular component of this system as a function of shape factor. If we consider our object to be situated at infinity, then the position factor for the cornea is 1. Therefore, the equation for corneal coma can be simplified as follows:

$$S_c(\text{cornea}) = -\frac{1}{4}h^3K_c^2\bar{u}[p_{1c}X_c^2 + (p_{3c} + p_{4c})X_c + (p_{2c} + p_{5c} + p_{6c})]. \quad (3)$$

For the coma generated by the IOL it is important to realize that the refractive indices for vitreous and aqueous have essentially the same value (~ 1.336). In this particular case¹⁰ (with symmetry between object and image space refractive indices), primary coma for the IOL is expressed as

$$S_c(\text{IOL}) = -\frac{1}{3}h^3K_{\text{IOL}}^2\bar{u}[p_{4\text{IOL}}X_{\text{IOL}} + p_{5\text{IOL}}Y_{\text{IOL}}]. \quad (4)$$

Our interest is to determine the shape factor of the IOL that cancels the total coma for the cornea IOL system. If we neglect the separation between the components (strictly we should apply stop-shift equations to the cornea, resulting in some extra coma generated by the corneal SA¹¹), the optimum shape factor for the IOL can be expressed as

$$X_{\text{IOL}}^{\text{Opt.}} = -\frac{1}{p_{4\text{IOL}}}\left[\frac{3}{4}\frac{K_c^2}{K_{\text{IOL}}^2}\{p_{1c}X_c^2 + (p_{3c} + p_{4c})X_c + (p_{2c} + p_{5c} + p_{6c})\} + p_{5\text{IOL}}Y_{\text{IOL}}\right]. \quad (5)$$

To calculate this optimum value we must introduce the p factors (tabulated in Ref. 10) and assume val-

ues for the average corneal power and its shape factor. We used the parameters from the Gullstrand eye model: 43 D and a shape factor of 1.27, using radii of curvature of 7.7 mm for the anterior surface, 6.8 mm for the posterior surface, and indexes 1.376 for the cornea and 1.336 for the aqueous. The position factor for the IOL (Y_{IOL}) is calculated with simple paraxial formulas once the power of the lens to be designed is fixed. The IOL shape factor determined by applying Eq. (5) will theoretically compensate coma for all values of ocular tilt angles. The IOL radii of curvature obtained with this procedure are used as the initial estimate in an optimization method. For this purpose, we used Zemax optical design software (ZEMAX Development Corporation San Diego). In this case an aspheric cornea with an average value measured from a large population was used.⁵ A merit function was defined to minimize SA and coma for different field angle positions (0° , 5° , and 10°). By using the asphericity coefficients (fourth and sixth powers) and lens radii of curvature as variables, and with the constraint of lens power, a least squares optimization process was applied. The profiles obtained for this new IOL are shown in Fig. 2. The optimized lenses are meniscus lenses bent toward the retina for the lower powers, evolving to biconvex shapes as the power increases.

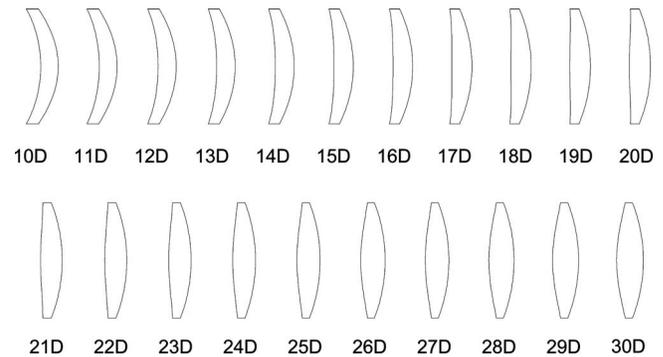


Fig. 2. New IOL profiles obtained with the procedure described in the text specially designed to balance corneal coma and corneal SA.

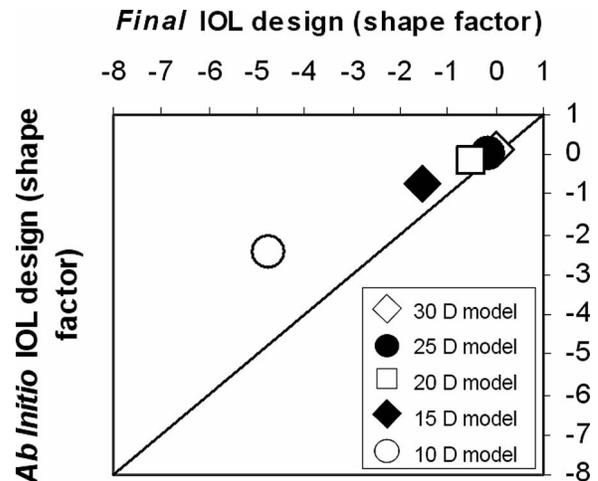


Fig. 3. *Ab initio* shape factors as a function of the final shape factors after optimization.

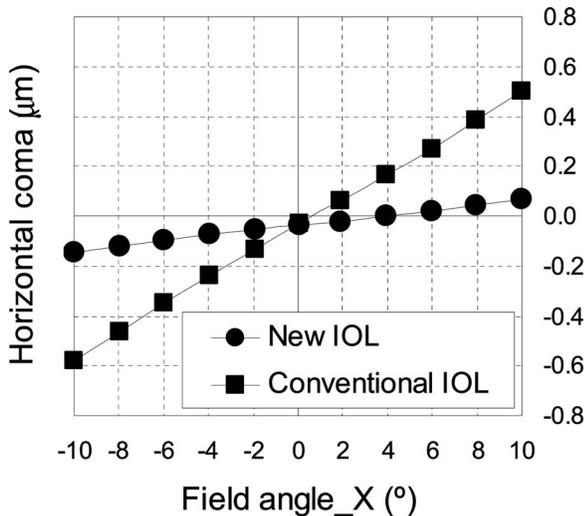


Fig. 4. Horizontal coma (Zernike coefficient Z_8 , 5 mm pupil diameter) as a function of the horizontal field angle in an aberrated pseudophakic eye model (the corneal surface is measured from topography). Filled squares represent the case when a conventional IOL is implanted and the filled circles represent the situation when our new IOL design is implanted.

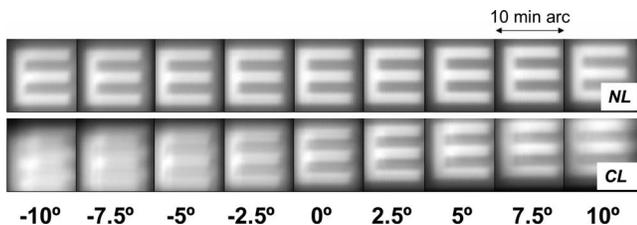


Fig. 5. Convolution of the eye's PSF with a Snellen optotype (50% contrast) in the eye model from Fig. 4. The same two cases are presented: with a conventional lens (CL) implanted and with the new lens (NL) design presented in this Letter.

It is interesting to evaluate how the end point design differs from the initial solution obtained by analytical calculations. This is presented in Fig. 3, showing that the final shapes are closely related to the initial design values for the higher-power models. In the case of the lower-power lenses, an extra bending value was added during the optimization procedure to allow the proper coma and SA compensation simultaneously. Therefore, our initial solution was in fact an optimum solution for the higher powers and a partial solution for the lower powers where the stop-shift equation applied to the cornea generates a more weighted coma term. This extra term is theoretically proportional to $\sim 1/K_{IOL}^2$, which explains its relative importance for the lower powers.

It is also important to explore the performance of these IOLs under realistic conditions. Here we used an ideal aspheric cornea that only has coma as a function of the incidence field angle. Real corneas do not have zero coma at null incidence angle. Also, if the corneal SA differs from the average values used for this design, it will generate an extra term for coma at the pupil plane due to the stop-shift effect

that remains uncorrected. Therefore, we can separate out corneal coma in two terms: an "intrinsic" term due to the reasons expressed above that can only be corrected with a customized manufacturing procedure, and an angularly generated coma, due to the global tilt of the optics of the eye with respect to the line of sight. This IOL will always correct the generation of this part of the coma present in the eye. For this reason, it is also interesting to mention that the optical performance of this IOL will be relatively insensitive to surgically, as well as physiological, induced tilt. Other surgical consequences, such as IOL decentration,¹² will affect its optical performance in a way very similar to conventional aspheric IOLs.¹³

To further show the real performance of this IOL we measured the shape of the corneal surface of a cataract patient and performed ray-tracing calculations using a procedure described as "cataract virtual surgery"¹³ with the newly designed lenses. Figure 4 shows coma as a function of field angle for a 15 D IOL with this novel design implanted compared to the coma generated when a 15 D conventional (biconvex) IOL design is implanted. Figure 5 shows the convolution of the eye's point-spread function¹⁴ (PSF) with a Snellen letter for both IOLs.

In summary, we present a new IOL designed to correct for coma induced by the cornea. We performed a series of realistic simulations showing that this IOL provides a superior retinal optical quality compared with conventional IOLs.

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