Corneal Optical Aberrations and Retinal Image Quality in Patients in Whom Monofocal Intraocular Lenses Were Implanted

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Objectives: To compare retinal image quality and optical corneal aberrations in patients in whom monofocal polymethyl methacrylate intraocular lenses (IOLs) were implanted with those in healthy subjects of a similar older age (60-70 years old) and to use the results to suggest improved optical designs of IOLs to maximize retinal image quality.

Methods: A double-pass apparatus was used to measure retinal image quality for 3-, 4-, and 6-mm pupil diameters. Corneal aberrations for a 4-mm pupil were calculated by a ray-tracing technique from the elevations provided by corneal topography. Two groups of 20 subjects of a similar older age were studied: in one group, polymethyl methacrylate monofocal IOLs were implanted; and in a second group, healthy subjects were used as a reference.

Results: The average retinal image quality was similar in older healthy patients and in patients in whom IOLs were implanted, with both groups having a significantly worse image quality than healthy younger subjects (aged 20-30 years). Both groups were more tolerant to defocus than younger subjects.

Conclusions: The average retinal image quality of patients in whom IOLs were implanted was worse than that of healthy younger subjects despite the good optical quality of isolated IOLs. This apparent paradox can be understood by the nature of the aberration coupling in the eyes that undergo implantation. The ideal substitute for the natural lens is not an IOL with the best-isolated optical performance, but rather one designed to compensate for the aberrations of the cornea—a design somehow inspired by the crystalline lens of younger subjects.

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THE IMPLANTATION of intraocular lenses (IOLs) is common practice in cataract surgery and is a solution to cataracts and aphakia. In general, it is a rather successful procedure; however, there are still some important questions requiring additional study. For instance, a major concern is the retinal image quality and visual performance of patients in whom IOLs have been implanted relative to those of healthy subjects of a similar age. In addition, it is important to explore improved IOLs designed to provide additional capabilities, such as some range of pseudoaccommodation without a considerable loss of performance, or new aberration profiles in the IOLs to improve retinal image quality after surgery.

Many of the answers to the previous questions are related to the type of optical aberrations present in the IOLs and, more important, to how these combine with the eye's aberrations to produce the final retinal image. Today, IOLs are manufactured to meet standard specifications[1,2] of high optical quality when tested on an optical bench.[3,4] However, the final retinal image quality of patients in whom IOLs were implanted was not better than that of healthy subjects,[5,6] despite the fact that typical monofocal IOLs have better optical quality than the healthy crystalline lens.[7-9] This apparent disagreement between measurements in vivo and in vitro can be partially explained by considering the possible tilts and/or decentrations of the implanted IOLs, which would reduce the final optical performance of the eye. However, typical values for these effects are too small[10] to fully explain the observed optical deterioration. A better explanation arises from an understanding of the aberration coupling of optical systems. An aberration profile that is appropriate for an isolated IOL, or even for a lens considered in a theoretical eye or an International Standards Organization model eye, may be inadequate to compensate for the optics of the corneal surface in real eyes. Deteriorated optical quality of the

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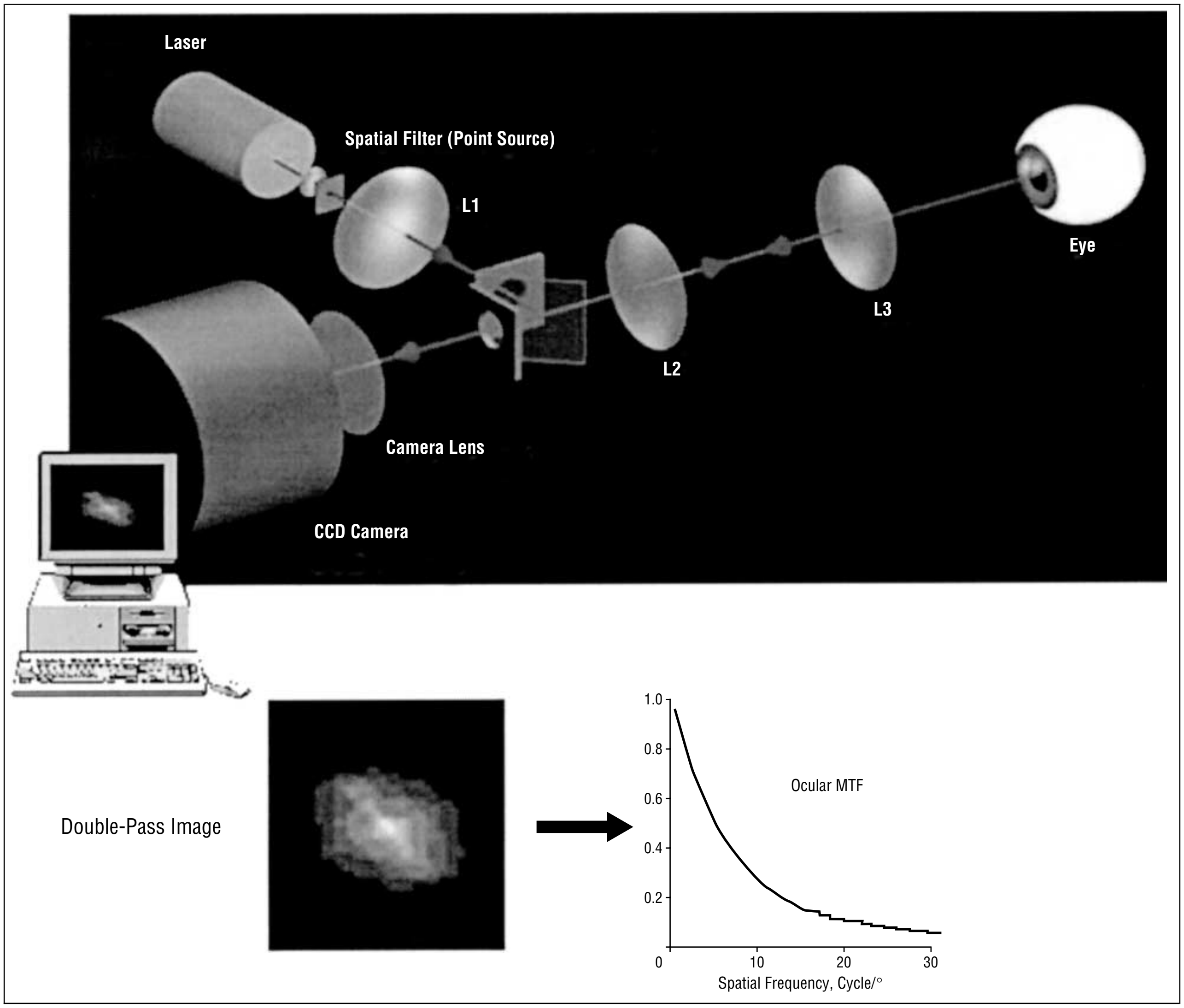

Figure 1. The double-pass apparatus and procedure. Double-pass images of a point source are recorded by a charge-coupled device (CCD) camera after double pass of the light through the ocular media. From the retinal image, the modulation transfer function (MTF) of the eye is computed.

cornea after surgery would also limit the performance of the eye in which an IOL was implanted, although the enormous improvements in surgical techniques cause this possibility to be of minor relevance.[11]

In this context, this study examines the retinal image quality and corneal aberrations of 2 groups of 20 subjects of a similar older age: in one group (aged 56-80 years), polymethyl methacrylate monofocal IOLs were implanted; and in a second group (aged 60-70 years), healthy subjects were used as a reference. This will allow us to further understand the optical performance of eyes in which IOLs have been implanted.

SUBJECTS AND METHODS

The optical performance of the living eye can be measured by different, and in most cases, complementary procedures. By direct recording of the double-pass retinal image,[12-14] an overall estimate of the eye optics is obtained, usually expressed through the point-spread function or the modulation transfer function (MTF). By using aberrometric techniques,[15-18] the optical aberrations of the whole eye are obtained and the retinal image or the MTF is calculated. Furthermore, by using computer ray-tracing techniques, the aberrations produced by the anterior surface of the cornea alone can be determined from the corneal shape.[19] Finally, by comparing the corneal aberrations with the overall retinal image quality, it is possible to establish the relative contribution to aberrations of the different ocular elements.[8]

RECORDING DOUBLE-PASS RETINAL IMAGES: APPARATUS AND PROCEDURE

A double-pass apparatus adapted to record retinal images in a clinical environment was used for this study. **Figure 1** is a schematic representation of the apparatus and the procedure used to measure the MTF. The basic principles, operation, and computational analysis of this method have been reported extensively elsewhere.[12,13,20,21] In brief, the image of a green (543-nm) helium-neon laser–generated point source is formed on the retina. The light reflected from the retina formed the double-pass image that was recorded by a slow scan–cooled charge-coupled device camera. The double-pass image was sent to a personal computer for processing. Two apertures of equal size conjugated with the eye pupil plane acted as the artificial entrance and exit pupils, when the natural pupil of the eye was dilated. A second camera was used to control the pupil centration with respect to the measuring beam (not shown in the Figure). The typical light exposure in the apparatus was more than 3 orders of magnitude below safety standards.[22] The subject's head was placed on a chin rest mounted on 2-dimensional positioners, allowing the centering of the natural pupil with respect to the artificial pupil.

The eye's pupil was dilated and the accommodation paralyzed by instilling approximately 40 μL of 1% cyclopentolate hydrochloride. In some subjects, an additional 20 μL of 2.5% phenylephrine hydrochloride was instilled to dilate the pupil up to 6 mm in diameter. The refractive error in the subject was corrected by moving the relative positions of a Badal system (L2 and L3), and a cylindrical trial lens corrected astigmatism if required.

Double-pass images were recorded under the best refraction for 3 pupil diameters: 3, 4, and 6 mm. For 4-mm pupils, additional images were recorded for defocus of ±0.5 diopters (D). For each condition of pupil size and focus, 3 double-pass retinal images and 1 background image were recorded. The duration of each exposure was 4 seconds. The final double-pass image was the result of averaging the 3 retinal images and subtracting the background image, and the ocular MTF was calculated as the square root of the modulus of the Fourier transformation of the double-pass image. From the 2-dimensional MTFs, 1-dimensional MTFs were computed by averaging across all directions. The ocular MTF was used as a description of retinal image quality. This function describes the reduction in contrast from the object to the image produced by the optics of the eye for each spatial frequency and can be related to the contrast sensitivity function. To characterize the overall optical performance of the eye, we use a single variable, the Strehl ratio, which is defined as the quotient of the area under the actual aberrant MTF curve and the area under the diffraction-limited MTF curve, corresponding to a perfect system.

ABERRATIONS AND OPTICAL QUALITY OF THE CORNEA

The corneal optical aberrations (for a 4-mm-diameter pupil) produced by the anterior surface of the cornea from the elevation data provided by a corneal topography system (Master-Vue System; Humphrey Instruments, San Leandro, Calif) have been estimated.[19] **Figure 2**A shows a diagram of the procedure. From the elevation at each point in the pupil, we calculated the corneal wave-front aberration, W, as the difference in optical path length between the principal ray that passes through the center of the pupil and a marginal ray:

$$W = nz + (n'd' - n's'), \tag{1}$$

where n and n' are refractive indexes and z, d', and s' are distances, as represented in Figure 2.

The corneal wave-front aberration was represented (up to the fourth order) as a weighted sum of the first 15 Zernike polynomials, Z_n^m (m and n are natural numbers representing the order of the Zernike polynomials):

$$W(r,\theta) = \sum_{n=0,m}^{n=4} c_n^m Z_n^m(r,\theta), \tag{2}$$

where r represents the radial coordinate over the pupil (Figure 2).

Each Zernike coefficient, c_n^m, represents an individual aberration. The lower orders correspond to the known Seidel aberrations. For example, $c_2^{\pm 2}$ represents astigmatism; $c_3^{\pm 1}$, coma; and c_4^0, spherical aberration. We calculated the astigmatism as follows:

$$\text{Astigmatism} = \left(\frac{1}{r_0^2}\right)\left(4\sqrt{6} \times \sqrt{(c_2^{-2})^2 + (c_2^{+2})^2}\right), \tag{3}$$

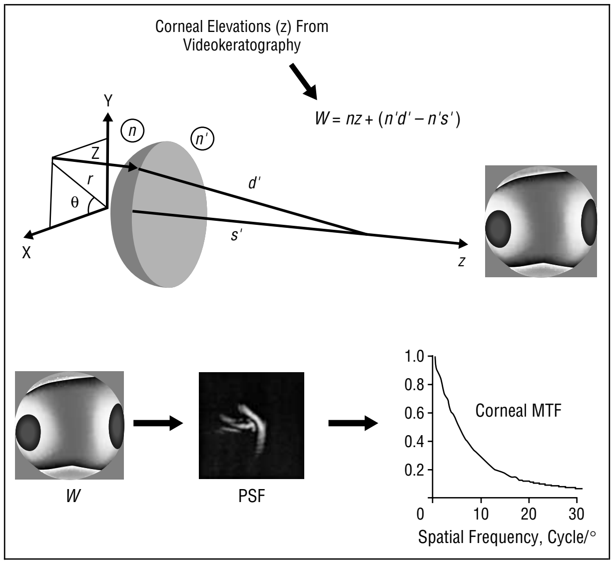

Figure 2. A, The ray-tracing procedure used to estimate the corneal aberrations (W), which are computed as differences in optical path length between marginal and principal rays. X, Y, and Z represent coordinate axes; r (radius) and θ (angle), radial coordinates of an arbitrary point at the exit pupil of the eye; n and n', refractive indexes; and z, d', and s', distances. B, From W, the point-spread function (PSF) and the modulation transfer function (MTF) for the cornea are estimated.

where r_0 is the pupil radius in millimeters, and the Seidel spherical aberration and the Seidel coma are as follows:

$$\text{Spherical Aberration} = -6\sqrt{5}c_4^0 \tag{4}$$

and

$$\text{Coma} = 3\sqrt{8} \times \sqrt{(c_3^{-1})^2 + (c_3^{+1})^2}$$

The spherical aberration obtained in this way is positive if marginal rays focus in front of the paraxial focus. The remaining higher-order aberrations measured are lumped into a single variable:

$$\sqrt{\sum_i (c_i)^2} \tag{5}$$

microns, with i excluding astigmatism, coma, and spherical aberration.

From the corneal wave-front aberration, the MTF and the Strehl ratio corresponding to the anterior surface of the cornea were also calculated (Figure 2B is a schematic representation of the procedure). We tested the accuracy of the complete procedure using reference surfaces for a pupil of up to 6 mm in diameter. The error in the estimation of the aberrations is lower than 0.05 μm for a 4-mm pupil, demonstrating that this method is sufficiently accurate for this study. Additional details of the procedure and its accuracy are described by Guirao and Artal.[19]

SUBJECTS

Forty subjects distributed into 2 groups participated in the study. The first group consisted of 20 patients (10 women and 10 men) in whom monofocal rigid polymethyl methacrylate IOLs (BUV-95, Storz, St Louis, Mo) of 13-mm diameter were implanted, using a conventional wide-incision technique. The surgery, which used extracapsular cataract extraction, was completed during 1997 in all patients. A 6-mm incision was made in the superior conjunctiva at the base of the limbus. An anterior capsulotomy was performed before removal of the

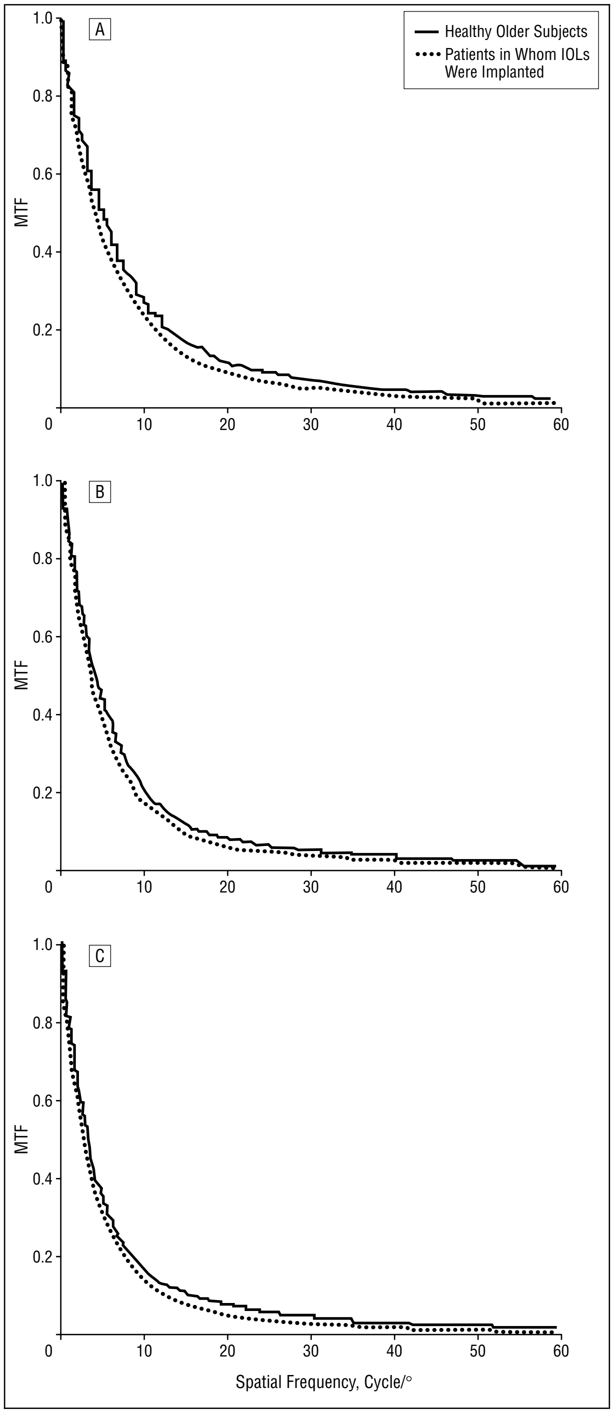

Figure 3. Ocular modulation transfer functions (MTFs) averaged across all subjects in each group, healthy older subjects (aged 60-70 years) and patients in whom intraocular lenses (IOLs) were implanted (aged 56-80 years), as a function of the spatial frequency. A, Pupils with 3-mm diameters. B, Pupils with 4-mm diameters. C, Pupils with 6-mm diameters.

cataractous lens, implantation of the posterior chamber IOL, and extraction of the viscoelastic gel injected for aiding the surgery. Finally, the wound was closed using a nylon 10-0 suture. Patient ages ranged from 56 to 80 years (mean±SD, 67±3 years). The second group contained 20 healthy older subjects (9 women and 11 men), with ages ranging from 60 to 70 years (mean±SD, 63±3 years). This group of healthy subjects was used as a reference for comparison with the group in which IOLs were implanted.

Subjects and patients were selected after passing an ophthalmologic examination with the following exclusion criteria: a refractive spherical or cylindrical error of more than 2 D, keratometric astigmatism of more than 1.5 D, a corrected visual acuity lower than 20/25, any previous surgery on the eye to be tested in healthy subjects, amblyopia, any known ocular or retinal pathological features, and IOL decentered more than 1 mm in patients in whom an IOL was implanted. The study followed the tenets of the Declaration of Helsinki, and signed informed consent was obtained from every subject after the nature and all possible consequences of the study had been explained. Data are given as mean±SD unless otherwise indicated.

RESULTS

RETINAL IMAGE QUALITY

Figure 3 shows the average MTFs for the group of patients with implanted IOLs and for the reference group of healthy older subjects, for each pupil diameter at best focus. The MTFs are similar in both groups for the 3 pupil diameters. The slight differences between groups are not significant (90% confidence level), although the average MTF for the group with implanted IOLs is systematically slightly worse for each of the 3 pupil diameters. The MTF for healthy younger subjects (aged 20-30 years) is significantly better than for older subjects for every pupil diameter.[13,14] As an example, **Figure 4** shows the MTFs for healthy older subjects and subjects in whom IOLs were implanted, together with the curve for healthy younger subjects,[13] for a pupil diameter of 4 mm. The Strehl ratio for every eye as a function of age is plotted in **Figure 5** for the 4-mm pupil. The average Strehl ratios are as follows: 3-mm pupils, 0.19±0.07 (reference, 0.22±0.06); 4-mm pupils, 0.12±0.03 (reference, 0.14±0.03); and 6-mm pupils, 0.07±0.02 (reference, 0.08±0.02). **Figure 6** shows the comparison between the average MTFs at best focus and at 2 small defocus values (±0.5 D), for the 4-mm pupil. The results for the positive and negative defocus were similar, indicating that the position of best focus was correctly determined. The relative decay of the MTF with defocus is similar for the patients in whom IOLs were implanted and the older subject reference group. This indicates that the tolerance to defocus is similar in patients with IOLs and in healthy older subjects (and larger than in healthy younger eyes[13]).

CORNEAL ABERRATIONS

Figure 7 shows the values of different corneal aberrations for the patients with IOLs and the healthy older subjects, represented as a function of subject age. Figure 7A shows the corneal astigmatism, which is similar for both groups. On average, the astigmatism is slightly larger in the patients in whom IOLs were implanted (−0.9±0.5 D) than in the reference group (−0.7±0.5 D), although the difference is not significant. Values of the corneal spherical aberration are similar in the 2 groups, as shown in Figure 7B, and the mean±SD is the same for both groups (0.7±0.2 μm). The astigmatism and spherical aberration results suggest that the base shape of the cornea (main curvature and asphericity) is similar in healthy subjects and in patients in whom IOLs were implanted. How-

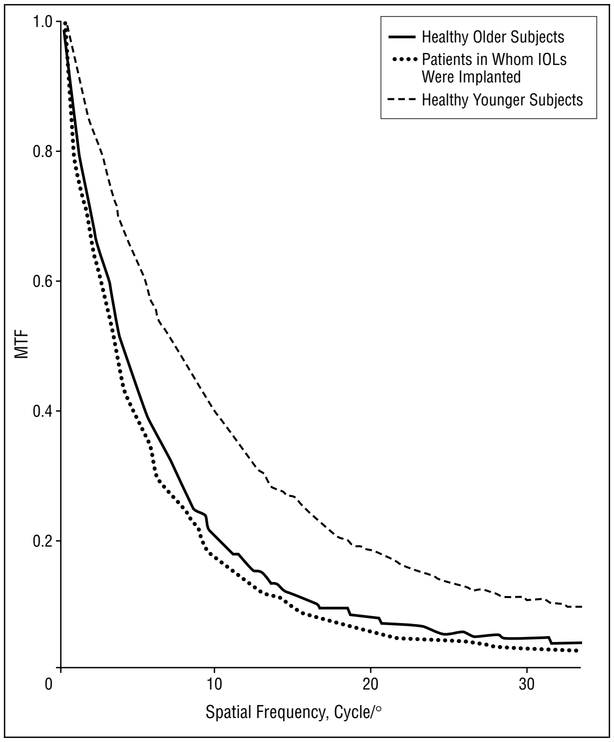

Figure 4. Ocular modulation transfer functions (MTFs) averaged across all subjects for a 4-mm pupil for healthy older subjects (aged 60-70 years), patients in whom intraocular lenses (IOLs) were implanted (aged 56-80 years), and healthy younger subjects (aged 20-30 years). The curve for the younger subjects is from Guirao et al.[13]

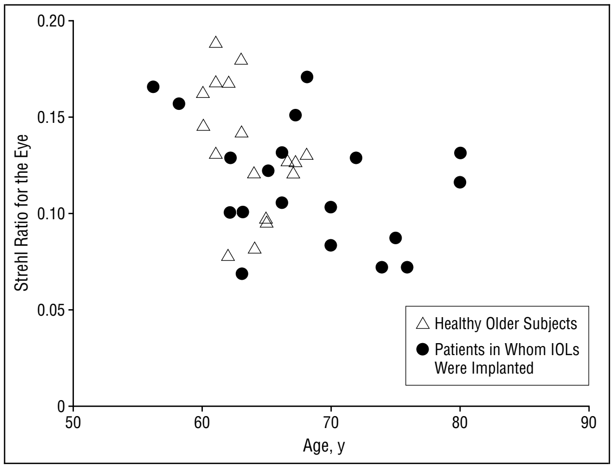

Figure 5. Optical quality of the eye via the Strehl ratio, calculated from the ocular modulation transfer function of each healthy older subject (aged 60-70 years) and each patient in whom an intraocular lens (IOL) was implanted (aged 56-80 years), as a function of age (4-mm pupil diameter).

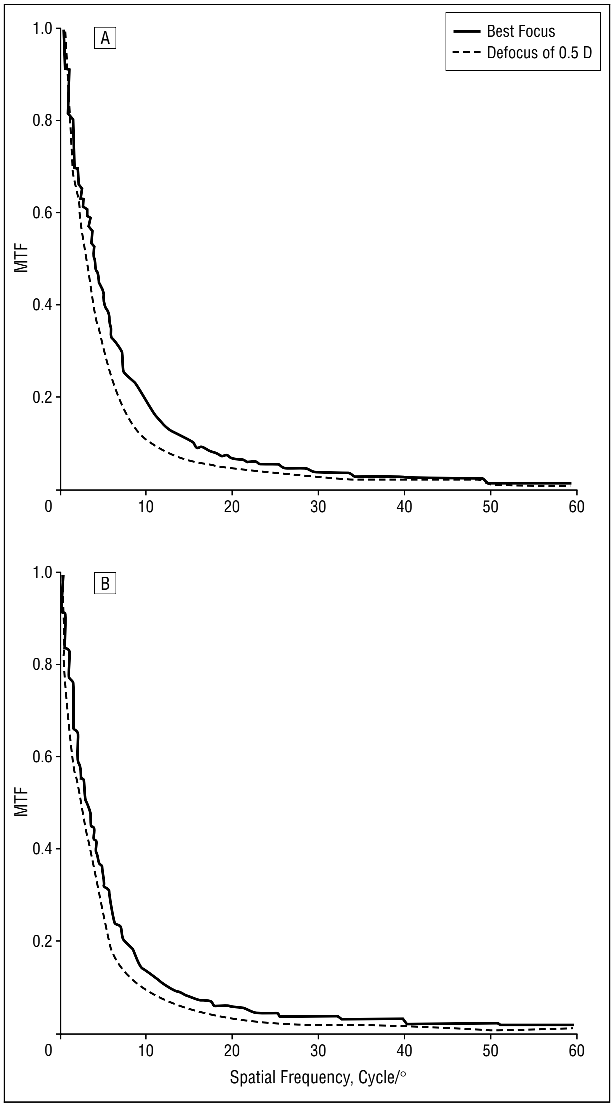

Figure 6. Average ocular modulation transfer functions (MTFs) for the 4-mm pupil at best focus and at a defocus of 0.5 diopters (D). A, Patients in whom an intraocular lens was implanted. B, Healthy older subjects (aged 60-70 years).

ever, other corneal aberrations are higher in patients with IOLs. Figure 7C shows the values of coma. There is a tendency for coma to increase slightly with age, as previously reported.[23] In addition, some patients in whom IOLs were implanted have a higher value for this aberration. The value of coma in the group in which an IOL was implanted (0.91 ± 0.58 µm) is significantly higher than in the reference group of healthy older subjects (0.57 ± 0.27 µm). A similar situation is seen for the rest of the higher-order aberrations (Figure 7D); the value in the patients in whom IOLs were implanted (0.08 ± 0.07 µm) is higher than in the healthy older subjects (0.05 ± 0.02 µm). Some patients in whom IOLs were implanted have more corneal aberrations. This is probably because of the large incisions (6 mm) required for the implantation of the rigid IOLs used.

The MTFs associated with only the anterior surface of the cornea were calculated from the previously mentioned corneal aberrations. The comparison of the average corneal MTFs in both groups is shown in **Figure 8** for a pupil with a 4-mm diameter. The optical performance of the cornea is slightly worse on average in patients with IOLs. The relative reduction of the MTF from the reference group to the group in which an IOL was implanted is similar for the cornea (Figure 8) and for the complete eye (Figure 3). **Figure 9** plots the Strehl ratio obtained from the corneal MTFs for each subject and patient. Values for the corneal Strehl ratio are as follows: 0.21 ± 0.09 for the patients in whom IOLs were implanted and 0.26 ± 0.10 for the reference group.

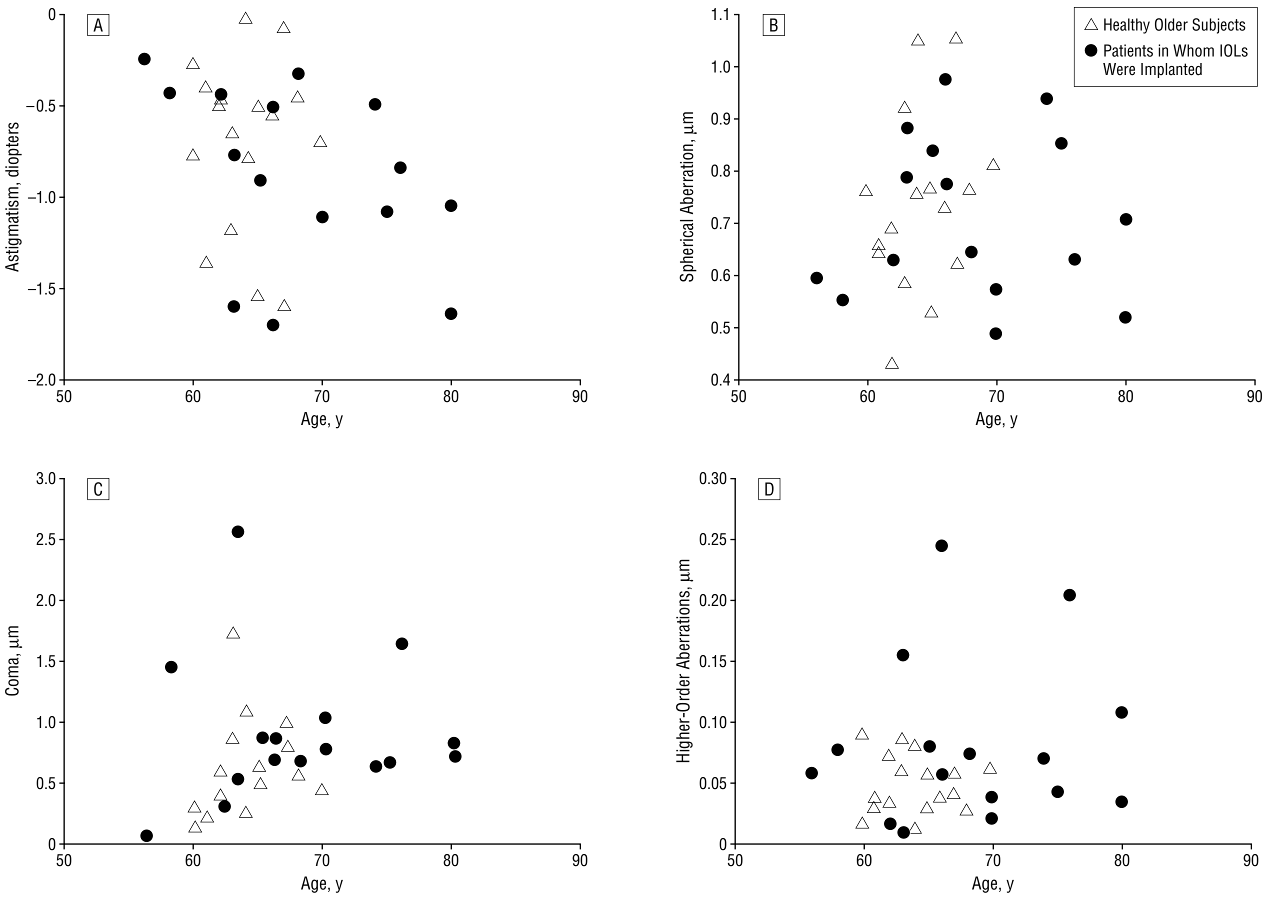

Figure 7. Corneal aberrations for each healthy older subject (aged 60-70 years) and each patient in whom an intraocular lens (IOL) was implanted (aged 56-80 years), for the 4-mm pupil, as a function of age. A, Astigmatism. B, Spherical aberration from equation 4. C, Coma from equation 4. D, Rest of the higher-order aberrations up to the fourth order, from equation 5. The equations are given in the "Aberrations and Optical Quality of the Cornea" subsection of the "Subjects and Methods" section.

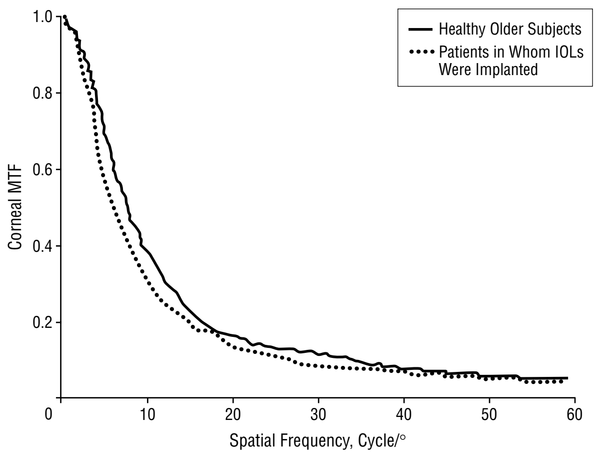

Figure 8. Average corneal modulation transfer functions (MTFs) for the 4-mm pupil for the healthy older subjects (aged 60-70 years) and the patients in whom intraocular lenses (IOLs) were implanted (aged 56-80 years).

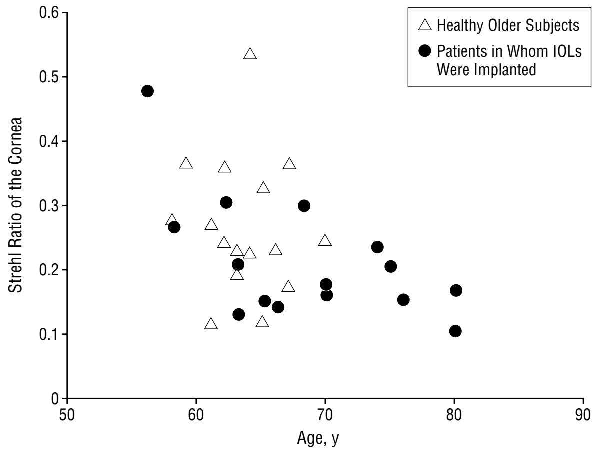

Figure 9. Optical quality of the cornea via the Strehl ratio calculated from the corneal modulation transfer function of each healthy older subject (aged 60-70 years) and each patient in whom an intraocular lens (IOL) was implanted (aged 56-80), as a function of age.

COMPARISON OF CORNEAL WITH OCULAR PERFORMANCE

Figure 10 shows the Strehl ratio for the complete eye vs the cornea in patients in whom IOLs were implanted. There is a correlation trend ($r=0.43$, $P=.04$), statistically significant, implying that the eyes with poorer image quality are the eyes with poorer optical corneal quality, as expected for eyes with IOL implants. The dispersion indicates individual differences in IOL implantation (tilts

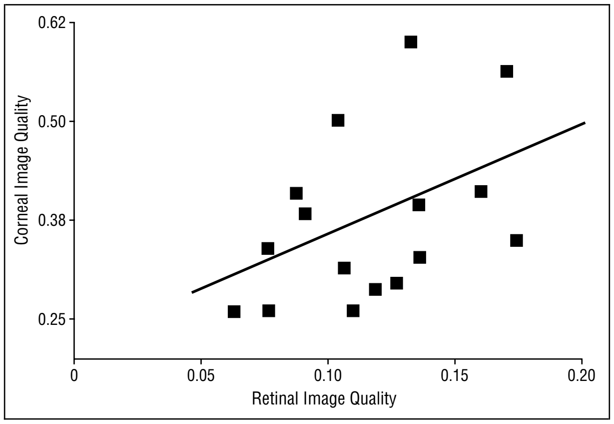

Figure 10. Correlation between the optical quality (Strehl ratio) of the complete eye and that of the cornea for patients in whom intraocular lenses were implanted (linear regression, $r=0.43$, $P=.04$).

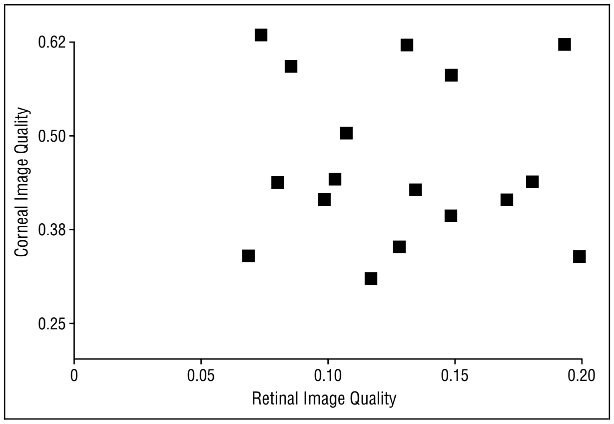

Figure 11. Correlation between the optical quality (Strehl ratio) of the complete eye and that of the cornea for healthy younger subjects (aged 20-30 years) (to be compared with Figure 10).

and decentration). The same type of IOL perfectly implanted in every eye would yield a perfect correlation ($r=1.0$) (Figure 10). **Figure 11** shows the same comparison between ocular and corneal optics in the group of healthy older subjects. In this case, there is no correlation, which indicates that the natural crystalline lens plays a different role in every eye.

COMMENT

The average retinal image quality of patients in whom IOLs were implanted was similar or slightly worse than that of healthy subjects of a similar age, and clearly worse than that of healthy younger subjects. These results indicate that, despite the good optical quality of IOLs, the retinal image quality of eyes with IOL implants is generally worse than that of eyes with natural lenses. However, as an advantage, the tolerance to defocus is higher in older subjects with IOL implants and in healthy older subjects than in healthy younger subjects. This is a beneficial effect appearing in eyes with more aberrations. At best focus, the retinal image quality is worse than that for a system with less aberrations, but this retinal image quality remains similar for moderate amounts of defocus. As a consequence, eyes in which IOLs have been implanted and healthy older eyes are more tolerant to small refractive errors than healthy younger eyes.

Corneal aberrations were similar or slightly larger in the patients in whom IOLs were implanted than in the reference group of healthy older subjects. The IOLs were rigid, requiring surgical procedures with large incisions (6 mm), which is likely the cause of the increased aberrations shown by a few patients (Figure 7). Small-incision foldable IOLs would be expected to yield no differences in presurgery and postsurgery corneal aberrations. Corneal aberrations in the 2 groups studied herein were larger than those in healthy younger subjects.[23] However, the change in corneal aberration found with age was relatively small[23]; other researchers[24] found nearly no changes. What is more important is that the small increase in corneal aberrations alone, due to either incisions or aging, cannot account for the limited retinal image quality in the patients in whom IOLs have been implanted.

These results show an apparent paradox: while IOLs yield an extremely good image quality when measured on an optical bench, the final retinal image performance in eyes with implanted IOLs is only similar to that of healthy older eyes and is clearly inferior to that of younger eyes. Because an increase in corneal aberrations cannot fully explain this observation, there are 2 plausible explanations. First, the ocular performance after IOL implantation may be limited due to inaccurate placement of the IOL. Tilts and/or decentrations of the IOL will produce aberrations that may be comparable to the aberrations of natural crystalline lenses. The dispersion found in Figure 10 shows that these aberrations of the IOL are present after implantation, because a constant IOL for all of the patients would have produced a perfect correlation between the corneal and the ocular optical quality. Nevertheless, this reason alone cannot explain why patients in whom IOLs were implanted did not show better image quality than healthy older subjects. According to Guirao et al,[13] the values for the ocular Strehl ratio of a group of 20 healthy younger subjects between the ages of 20 and 30 years (4-mm pupil) ranged between 0.19 and 0.33 (mean±SD, 0.26±0.04). For patients in whom IOLs have been implanted, the Strehl ratio (Figure 5) ranges from 0.07 to 0.17 (mean±SD, 0.12±0.03). Therefore, all of the patients had a lower image quality than even the worst of the healthy younger subjects. Despite the potential misplacement of the implanted IOLs, in a sample of 20 patients, one would expect to have at least a few with no or little decentration and then have optical performances as high as those in healthy younger subjects.

An additional reason can fully explain our results and the apparent paradox. The ideal substitute for the natural lens is not an IOL with the best-isolated optical performance, but rather one designed to compensate for the aberrations of the cornea (**Figure 12** shows this explanation). Thus, an improved design for an IOL would have an aberration profile that compensates for the corneal aberrations, to maximize the quality of the retinal image. However, an aberration-free IOL (diffrac-

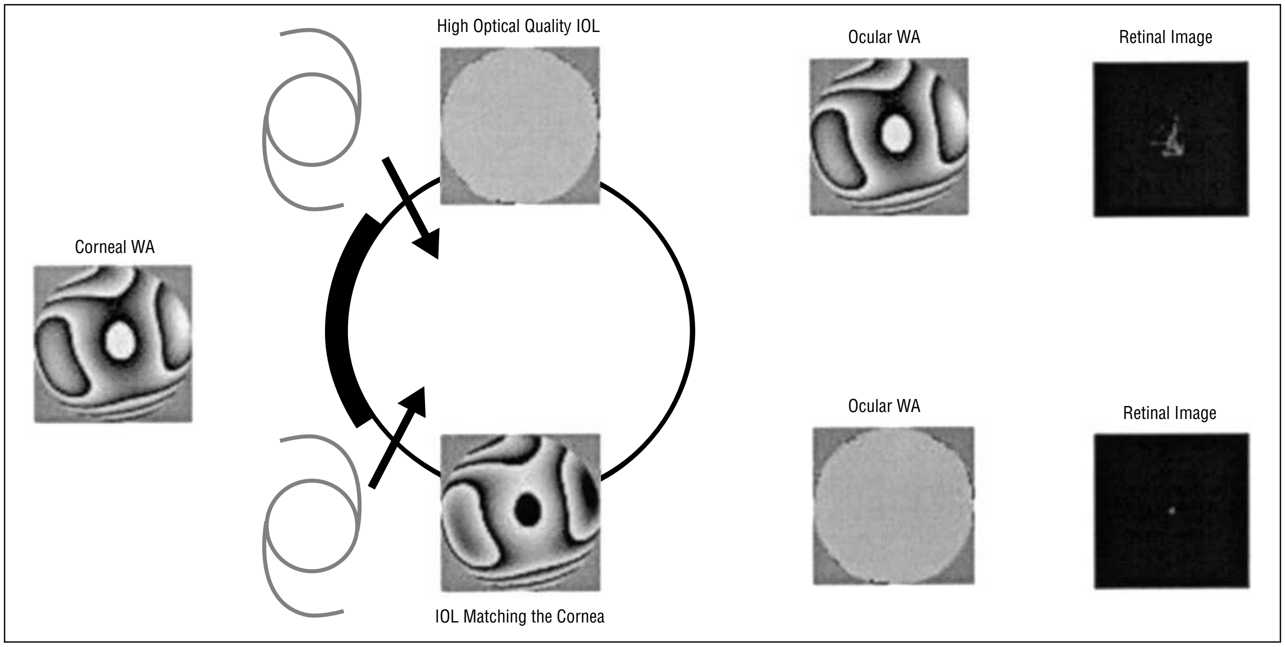

Figure 12. Representation of the coupling between the cornea and the intraocular lens (IOL). An IOL without aberrations will produce an eye with the aberrations of the cornea and relatively poor retinal images. However, an IOL with aberrations approximately contrary to those of the cornea will produce an eye nearly free of aberrations. WA indicates wave aberration.

tion limited) or an IOL with an aberration profile with the same sign as the corneal aberrations will produce larger total ocular aberrations. The ideal solution to this problem would be a customized IOL for any individual cornea.

A concern associated with IOLs with customized aberration profiles is that if the position of the IOL cannot be precisely controlled in the surgery, then the final aberrations could be similar or even larger than those of conventional IOLs.[25] A useful approach would be the use of a customized IOL with aberrations adapted to compensate only for spherical aberration. The correct balance of the corneal spherical aberration of the patient will still be achieved even in cases in which the IOLs are slightly decentered or tilted.[26] However, the improvements in surgical techniques will probably allow precision in IOL positioning,[11] enough at least for partial aberration compensation, and will make worthwhile the correction of more complex patterns, including several aberrations. This kind of customized design would mimic the behavior of the lens in younger subjects, in whom the corneal aberrations are partially compensated by the natural lens.[8] This is not generally the case in older eyes, in which the changes in the aberrations of the lens with age reduce the compensation of aberration present in younger eyes, resulting in a reduced quality of the retinal image.[27] Thus, older subjects undergoing cataract surgery could benefit from customized IOL designs to reduce the ocular aberrations.[28]

In summary, we measured the retinal image and the corneal aberrations in healthy older subjects and in patients after the implantation of monofocal polymethyl methacrylate IOLs. This method is useful for testing the clinical success of IOL implantation and for exploring the possibility of producing more efficient IOL designs. These results clearly suggest that an IOL with good optical quality (aberration free) is not the best design choice. A better IOL design would be the one that corrects for the corneal aberrations, producing lower total ocular aberrations and, hence, a higher-quality retinal image and an improved visual performance.

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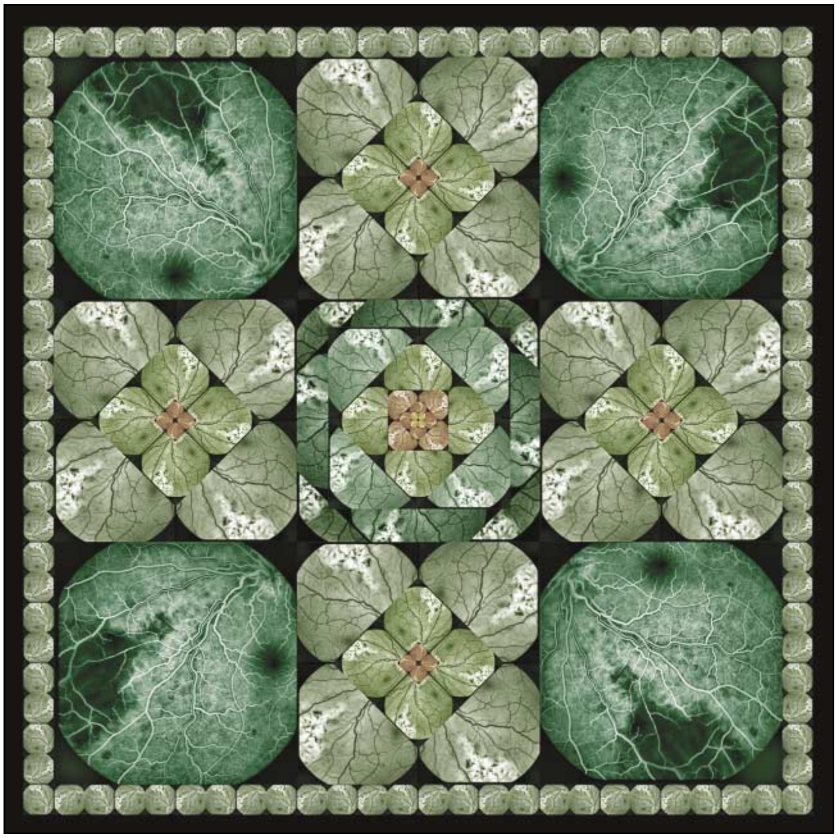

Fundus Flower. Created by Patrick J. Saine, MEd, CRA, Dartmouth-Hitchcock Medical Center, Lebanon, NH.