IMAGE QUALITY IN PSEUDOPHAKIC EYES WITH TWO DIFFERENT TYPES OF INTRAOCULAR LENSES RANGING IN THE DEGREE OF HIGH MYOPIA

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ABSTRACT

The image quality of pseudophakic eyes with intraocular lenses in high myopia was studied by applying geometric and wave optics. Two types of intraocular lenses (IOL) were compared—one that was meniscus shaped and the other either planoconcave or planoconvex [bending factor $(X) = +1$]. A geometric study of image quality was used to analyze the transverse spherical aberration (TA) and the chromatic aberration (chromatic difference of the blur circles, CDBC). The loss of image quality and visual acuity increases as the TA and CDBC increase. The polychromatic modulation transfer function (MTF) was obtained using the point-spread function (PSF), taking into account spherical aberration and defocus coefficients. Finally, for chromatic and spherical aberrations and polychromatic MTF, the type of IOL that would best improve image quality for a given patient can be established. © 1997 Society of Photo-Optical Instrumentation Engineers. [S1083-3668(97)00304-3]

Keywords ophthalmic systems; implants; high myopia; image quality; spherical and chromatic aberrations; modulation transfer function (MTF).

1 INTRODUCTION

If an implanted intraocular lens with the appropriate power is placed correctly with respect to the visual axis, and the eye model is formed by centered refracting surfaces with rotational symmetry, the most significant aberration to be considered in pseudophakic eyes is spherical aberration.[1] There are two possible choices for intraocular lens (IOL) design: minimizing the spherical aberration of the whole eye,[2] or obtaining the same spherical aberration as in a phakic eye.[1]

With regard the second choice, Jalie[1] found that the IOL shape that 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 17.98 D. However, Wang and Pomerantzeff[2] found that the shape factor that 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 $+19.61$ D.

On the other hand, Smith and Lu[3] found that for corneas with asphericities less negative than about -0.512, the spherical aberration of the eye as a whole was minimized with a planoconvex IOL, with the curved surface facing the cornea (plano-convex, $X = +1$). Atchison's research[4] 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,[4] which also analyzed six ametropic eyes with refractive errors of approximately $+10$, $+5$, and $+2$ D (hypermetropia) and -2, -5, and -10 D (myopia). Nevertheless, in all cases the intraocular lens 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 intraocular lens power is needed to achieve emmetropia.[5]

Some experimental studies[6,7] have been published on the optical quality (modulation transfer function, MTF) of eyes implanted with intraocular lenses by using a double-pass method. In these studies, the optical performance of different types of bifocal IOLs were compared with that of conventional monofocal IOLs. However, the optical performance of different types of monofocal IOLs is not compared.

Another recent study used modulation transfer function measurements to provide a standard test of minimum optical quality of positive intraocular lenses[8] using a water cell with plane entrance and

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exit windows. The results show that a meniscus-shaped lens gives an MTF that is significantly worse than the biconvex and planoconvex lenses.

Recently, studies[5] have been done on how to minimize or even eliminate spherical aberration in pseudophakic eyes with intraocular lenses in high myopia using two types of lenses: meniscus-shaped and planoconvex or planoconcave. In this study, the pseudophakic schematic eye model used is a centered system in which the cornea is represented by a single surface with spherical curvature; the aqueous humor and the vitreous humor have the same refractive index (Gullstrand–Emsley schematic eye); and the intraocular lens is considered to have zero thickness. Other studies show that in an emmetropic eye, diffraction and chromatic aberration are the factors that most affect image quality and therefore visual acuity.[9–13]

L. N. Thibos[11] designed a reduced model that predicts experimental values for chromatic aberration with a good degree of accuracy. However, this model is made up of only one refractive surface and therefore cannot be used to directly analyze the influence of any variation introduced in the eye by an 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.[14] For these reasons, it is of utmost importance to analyze diffraction and chromatic aberration together with spherical aberration in a theoretical pseudophakic eye model that more closely mimics a real eye.

We have used a modified version of the whole theoretical eye used by Navarro et al.[15] (Table 1). This model fits the experimental measurements of the longitudinal spherical aberration (LSA), chromatic difference of refractive error (CDRx),[16] chromatic difference in image position (CDP),[10,16] and polychromatic MTF of the eye quite well.[17] Therefore this model predicts on-axis aberrations with high precision.[15] Moreover, in this eye model, all of the refractive surfaces and ocular media are shown, thereby making it possible to study the influence of any of the ocular parameters (indexes, curves, distances, etc.) on image quality.

2 METHODS

Calculations were done using the theoretical eye described in the introduction (Table 1). For the study of pseudophakic eyes with intraocular lenses in high myopia, the theoretical eyes was modified in the following way (Figure 1):

- The eye lens was replaced by a centered IOL that corrects the high-myopic eye in the

paraxial zone for a wavelength of 555 nm (C.I.E. maximum photopic luminous efficiency of mean observer).
- The radius of the anterior surface of the cornea and the axial length varied in each case (Table 2) so that the IOL power was high positive, low positive, low negative, and high negative. The radius of the second surface remained at 6.5 mm.

The meniscus-shaped lenses are placed with their convex surface toward the retina, given the physiological advantages of this placement. For example, the danger of postoperative retinal detachment is reduced because the vitreous humor is kept further back than after implantation of a lens with the convex surface toward the cornea.[5]

For the positive IOLs, the center thickness is calculated so that the IOL diameter is 8 mm and the edge thickness is 0 [Figure 1(a)]. It is assumed that the negative IOLs have 0 center thickness because it will not affect the results. Taking into account the fact that the IOL diameter is 8 mm, an edge thickness that depends on the curvature radii is calculated [Figure 1(b)].

The IOL is placed behind the natural pupil. Thus, in planoconvex IOLs, the anterior vertex is placed where the natural pupil is located [Figure 1(a)]. In IOLs with concave anterior surfaces (planoconcave and meniscus IOLs), the anterior vertex is placed so that the edges coincide with the location of the natural pupil [Figure 1(b)].

We consider four extreme theoretical cases of pseudophakic eyes that were highly myopic before surgery (Table 2): case A shows low myopia (-6.50 D); cases B and C, middle myopia (-12.25 D and -18.25 D); and case D, high myopia (-23.00 D). In each case a different type of intraocular lens was used: a meniscus-shaped one (Am, Bm, Cm, and Dm cases) and planoconcave or planoconvex ones (Ac, Bc, Cc, and Dc cases). The radii of curvature for each meniscus lens are calculated so that the transverse spherical aberration is close to the emmetropic theoretical eye, but the radius of the posterior surface must be smaller or equal to 16.5 mm in absolute value (larger values are very close to a plane surface).

Table 2 shows the corneal power (Pc), the radius of the anterior surface of the cornea (r1c), the axial length of the eye to be corrected (L), the radii of curvature for the IOL (r1 and r2), the IOL thickness (eiol), and the IOL principal power (Piol). The intraocular lenses are made of polymethylmethyacrylate (PMMA).

A distant object on-axis (it is assumed that the optic axis, the achromatic axis, coincides with the visual axis[10]) is used in the calculations. The eye is considered emmetropic for a wavelength of 555 nm (C.I.E. maximum photopic luminous efficiency of mean observer). Using geometrical optics, we have

Table 1 Complete list of theoretical eye parameters with references.

Parameters	Theoretical eye	References
Radius of curvature (mm)		
Anterior surface of cornea	7.8	
Posterior surface of cornea	6.5	Ref. 20 (Le Grand, 1945)
Anterior surface lens	10.2	
Posterior surface lens	-6	
Asphericity (Q)*		
Cornea anterior	-0.26	
Cornea posterior	0	
Lens anterior	-3.1316	Ref. 7 (Navarro et al., 1985)
Lens posterior	-1	
Thickness (mm)		
Cornea	0.55	
Aqueous	3.05	Ref. 20 (Le Grand, 1945)
Lens	4	
Chromatic aberration**		
a,b,c,d of Cornea	1.37394, -0.00815504, 0.00110849, 0.000128928	
a,b,c,d of Aqueous	1.33556, -0.00874562, 0.00109209, 0.000133039	Hertzberger formula** coefficients using refractive indices from Table 2. Ref. 7 (Navarro et al., 1985)
a,b,c,d of Crystalline	1.41488, -0.00697508, 0.00181921, 0.000161433	
a,b,c,d of Vitreous	1.332882, -0.00686524, 0.00143418, 0.000096445	
Axial length (mm)	24.20	

* $y^2 + (1+Q)x^2 - 2Rx = 0.$

** $n(\lambda) = a + b\lambda^2 + (c/(\lambda^2 - 0.035)) + (d/(\lambda^2 - 0.035)^2)$ λ in μm.

calculated the transverse spherical aberration (TA) for this wavelength, for 3-, 5-, and 8-mm pupil diameters, for each case (Figure 2).

The chromatic aberration on the retinal plane, or the chromatic difference of the blur circles (CDBC), is defined as the difference between the radii of the retinal blur circles corresponding to the limiting wavelengths, 430 and 680 nm.

$$CDBC = R_V - R_R \qquad (1)$$

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 CDBC will be positive if the green spot is greater than the red one and negative if the opposite occurs (Figure 3).

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

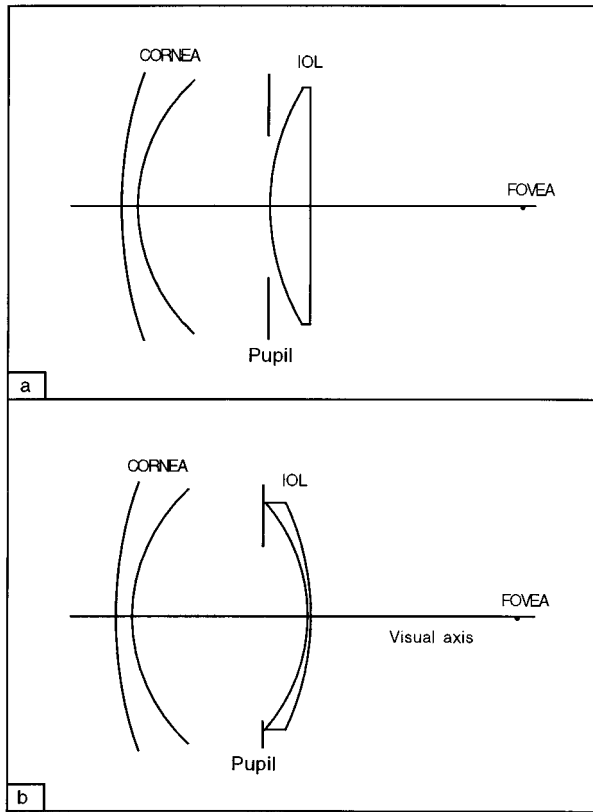The monochromatic PSF is calculated by taking into account the Stiles–Crawford effect.

Fig. 1 Pseudophakic theoretical eye with (a) planoconvex IOL and (b) with divergent meniscus IOL.

$$PSF_\lambda = B \frac{1}{\lambda^2} \left| \int\int_\Sigma e^{i2\pi/\lambda\omega(\rho,\lambda)} A^{1/2} J_0(\alpha\rho)\rho d\rho d\theta \right|^2,$$

(2)

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, and θ is the angular coordinate in the exit pupil plane.

$$\alpha = \frac{\pi 1 w}{z}$$

(3)

where 1 is the radial coordinate of the observation point, w is the distance between the planes of the exit pupil and the Gaussian image, and z is 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 to be Gaussian.[9]

$$A = \exp(-0.05 R_P^2 \rho^2 \ln 10),$$

(4)

where R_P is the exit pupil radius (in millimeters).[15] $w(r,l)$ is the aberration function for a rotationally symmetric system[18]:

$$\omega(\rho,\lambda) = \omega_{20}(\lambda)\rho^2 + \omega_{40}(\lambda)\rho^4 + \omega_{60}(\lambda)\rho^6$$

(5)

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

The wave aberration function $w(r,l)$ can be related to the transverse spherical aberration (TA) by using[19]:

$$\frac{\partial\omega(x,\lambda)}{\partial x} = -\frac{TA(x,\lambda)}{r_\omega}$$

(6.1)

$$\frac{\partial\omega(y,\lambda)}{\partial y} = -\frac{TA(y,\lambda)}{r_\omega},$$

(6.2)

where (x,y) are Cartesian coordinates in the exit pupil and r_ω is the radius of curvature of the reference sphere.

For a system with rotational symmetry, without loss of generality, we can take $x = 0$ and use Eq. (6.2).

In this case:

Table 2 Theoretical cases of pseudophakic eyes ranging from high positive IOL power (A) to high negative IOL power (D).

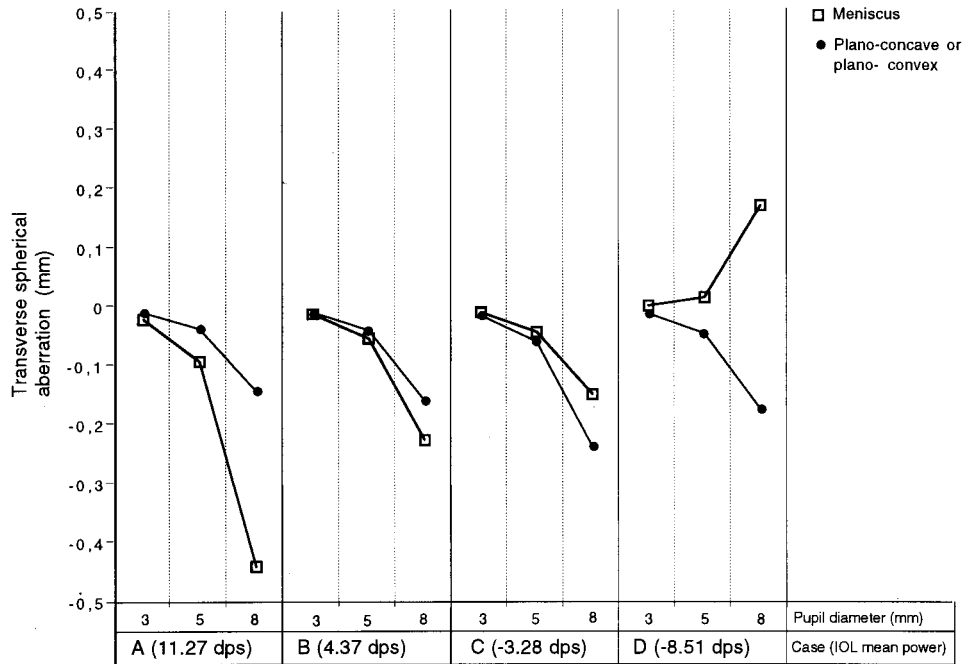| Pc (dt)	r1c (mm)	L (mm)	r1 (mm)	r2 (mm)	eiol (mm)	Piol (dt)	Case
42	8.02	27	−42.60	−10.2	0.63	+11.69	Am
			+14.33	∞	0.57	+10.85	Ac
		30	−31.1	−16.5	0.23	+4.48	Bm
			+36.37	∞	0.22	+4.26	Bc
48	8.02	30	−12.13	−16.5	0	−3.32	Cm
			−47.79	∞	0	−3.24	Cc
		33	−8.56	−16.5	0	−8.61	Dm
			−18.4	∞	0	−8.41	Dc

Fig. 2 Transverse spherical aberration for each case of theoretical pseudophakic eyes with 3-, 5-, and 8-mm pupil diameters.

$$\rho^2 = y^2 (2/D)^2 \qquad (7)$$

and introducing:

$$C_{20}(\lambda) = 2\,\omega_{20}(\lambda)(2/D)^2 \qquad (8)$$

$$C_{40}(\lambda) = 4\,\omega_{40}(\lambda)(2/D)^4 \qquad (9)$$

$$C_{60}(\lambda) = 6\,\omega_{60}(\lambda)(2/D)^6, \qquad (10)$$

where D is the maximum diameter of the exit pupil, we can write Eq. (5) as:

$$C_{20}(\lambda)y + C_{40}(\lambda)y^3 + C_{60}(\lambda)y^4 = -\frac{TA(y,\lambda)}{r_\omega}. \qquad (11)$$

The coefficients C_{20}, C_{40}, and C_{60} are fitted by a computer program. C_{20} depends on wavelength but coefficients C_{40} and C_{60} depend on wavelength only to a small degree. Using Eqs. (8), (9), and (10), $\omega_{20}(\lambda)$, ω_{40}, and ω_{60} are obtained.

The range of wavelengths considered was 430 to 680 nm because this is the spectral region for which the human eye is most sensitive. The study was done for 3-, 5-, and 8-mm pupil diameters.

3 RESULTS

Figure 2 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 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.

Taking into account spherical aberration, Figure 3 shows the CDBC for the extreme wavelengths 430 and 680 nm. In the cases of A, B, and C, the CDBC differences 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 CDBC as a function of pupil diameter is just the opposite because the spherical aberration that is produced is positive.

Figures 4 and 5 show the polychromatic MTF for a positive IOL and for negative IOLs respectively, for a pupilar diameter of 5 mm.

Figures 6 and 7 show the spatial frequency with 3-, 5-, and 8-mm pupil diameters for an MTF value of 0.23. This is the value obtained for an emmetropic theoretical eye with a 3-mm pupil diameter for a 30 c/deg spatial frequency (separate power equal to 1 arcmin). In each case the type of IOL that produces a higher frequency for a given pupil diameter allows the eye to discriminate more lines per millimeter for a contrast equivalent to an MTF of 0.23.

For positive and negative IOLs with low power (cases B and C), the transverse spherical aberration (Figure 2) and the CDBC (Figure 3) of the meniscus IOL and the planoconvex or concave IOL are very similar. Therefore the polychromatic MTFs of the meniscus IOL and the planoconvex or concave IOL are very similar also (Figures 6 and 7).
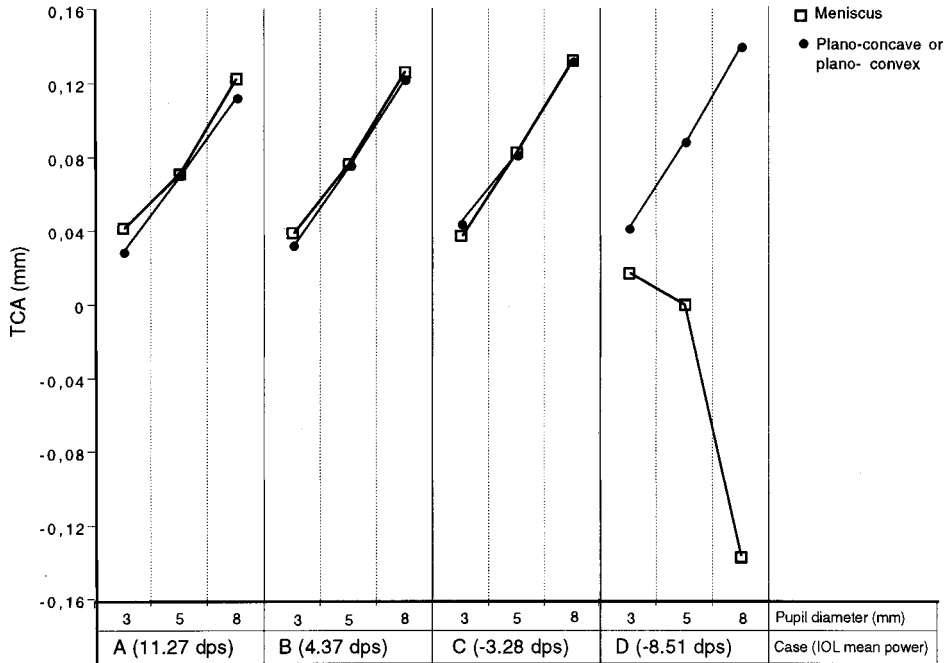
Fig. 3 Chromatic difference of the blur circles (CDBC) for each case of theoretical pseudophakic eyes with 3-, 5-, and 8-mm pupil diameters.

On the other hand, for IOLs with high power (cases A and D), the difference between the meniscus IOL and the planoconvex or concave IOL in the spherical aberration and the chromatic aberration is greater than for cases B and C (Figures 2 and 3). In the cases of positive high IOL power (case A, lowest myopia), the polychromatic MTF is improved with a planoconvex compared with a meniscus IOL due to spherical aberration (Figures 4 and 6). In the case of negative high power (case D, highest myopia), with meniscus the positive spherical aberration decreases the CDBC to a negative sign. There-

fore the polychromatic MTF for a meniscus IOL is much better than for a planoconcave IOL (Figures 5 and 7).

4 CONCLUSIONS

In the case of a pseudophakic eye with low myopia (IOL high positive power, case A) the planoconvex IOL produces a better image quality than does the meniscus IOL. The transverse spherical aberration (Figure 2) and the CDBC (Figure 3) are lower with a planoconvex IOL. Therefore, for this type of IOL,
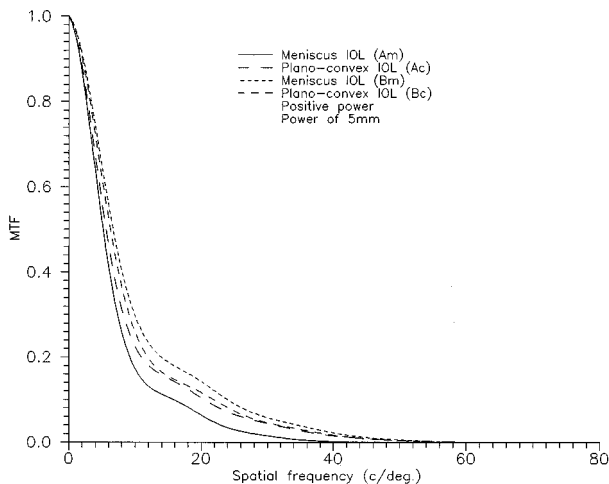

Fig. 4 Polychromatic MTF for pseudophakic eyes with positive IOL power (cases A and B). Pupil diameter, 5 mm.
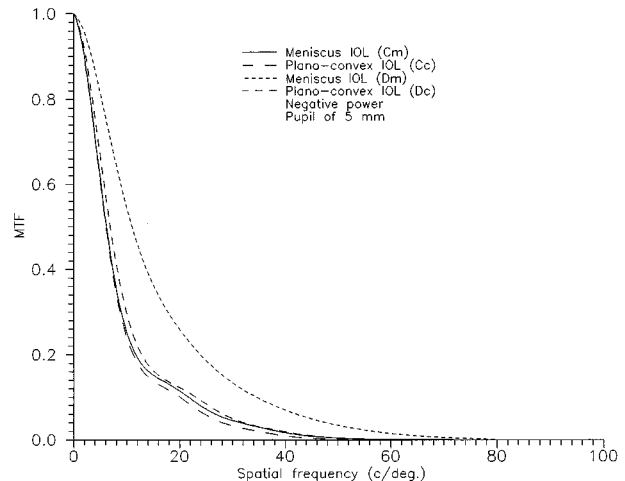

Fig. 5 Polychromatic MTF for the pseudophakic eyes with negative IOL power (cases C and D). Pupil diameter, 5 mm.
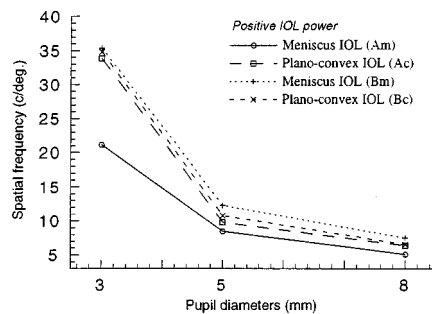
Fig. 6 Spatial frequency for 3-, 5-, and 8-mm pupil diameters for an MTF of 0.23 (MTF for emmetropic theoretical eye with 3-mm pupil diameter and with 30 c/deg spatial frequency) for cases A and B.

the MTF (Figure 4) is better and the resolution frequency of the ocular optical system for a given contrast is higher (Figure 6).

In the cases of a pseudophakic eyes with middle myopia (IOL low power, cases B and C), the quality image for meniscus and planoconvex or concave IOLs is very similar. From the point of view of geometrical optics, the CDBC (Figure 3) is similar. However, for positive powers, the meniscus IOL produces a slightly greater spherical aberration than a planoconvex IOL (Figure 2, case B). For negative powers, the spherical aberration is slightly greater with a planoconcave IOL (Figure 2, case C). From the point of view of wave optics, the meniscus IOL gives a better MTF (Figures 4 and 5) and a higher resolution frequency of the ocular optical system for a given contrast (Figures 6 and 7).

In the case of high myopia (IOL high negative power, case D), the meniscus IOL produces better image quality than the planoconcave IOL. For meniscus IOLs, the spherical aberration is positive (Figure 2), decreasing the CDBC for low and middle pupil diameters (3 and 5 mm, Figure 3). Therefore the meniscus IOL gives a better MTF (Figure 5) and a higher resolution frequency of the
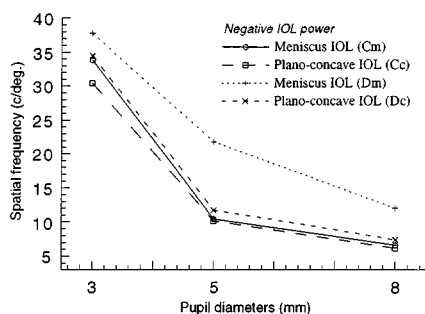
ocular optical system for a given contrast (Figure 7). These results agree with studies done by González et al.[5]

For IOL high and low (from the point of view of geometrical optics) positive powers, the planoconvex IOL ($X = +1$) gives the best optical quality. These results agree with previous studies done by Smith and Lu[3] and Atchison.[4]

Acknowledgments

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Fig. 7 Spatial frequency for 3-, 5-, and 8-mm pupil diameters for an MTF of 0.23 (MTF for emmetropic theoretical eye with 3-mm pupil diameter and with 30 c/deg spatial frequency) for cases C and D.