

Analysis of the Optical Quality of Intraocular Lenses

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PURPOSE. To evaluate the optical quality of different intraocular lenses (IOLs).

METHODS. An optical test bench and suitable software were used to assist in analysis of the optical Fourier transform (OFT) of a test image and to determine the quality of the lens in terms of spatial frequency response. The OFT was automatically converted, by means of an optical-electronic calibration procedure, into a modulation transfer function (MTF) for each lens. The passband value calculated by computer analysis of the MTF is an objective index of the lens quality. Three randomly acquired samples of 24 different models of foldable IOLs were compared. Statistical analysis was performed with two-way and one-way ANOVA for repeated measurements and with the Ryan-Einot-Gabriel-Welsch multiple F test.

RESULTS. The method was demonstrated to be precise and accurate. A large range of passband values was found. Statistically significant differences between the mean passband values for different lenses were found. The lowest passband value (125.60 line pairs [lp]/mm) was measured for the IOL (Lenstec LH3000; Lenstec, Inc., St. Petersburg, FL) and the highest (191.48 lp/mm) for the Acrysof SA30AL (Alcon, Fort Worth, TX).

CONCLUSIONS. Different IOLs can transmit different spectra of spatial frequencies. The best frequency response was provided by acrylic IOLs, particularly those with an asymmetrically biconvex profile. This could be due to a reduction of optical degradation provided by this type of profile. A lens with a higher frequency response should determine a better quality of vision once implanted and the frequency response should therefore be considered when choosing the intraocular lens model. (*Invest Ophthalmol Vis Sci.* 2004;45:2682-2690) DOI: 10.1167/iovs.03-1024

Currently, the most frequently performed cataract surgery procedure is phacoemulsification with intraocular foldable lens (IOL) implantation. The materials, design, and technology used to produce IOLs have undergone a continuous evolution in the past decades. Although surgical techniques and the materials and design of IOLs have been extensively discussed, the optical quality of the IOL has not always been taken into account.

Many ophthalmologists speculate that it is possible to improve visual acuity using customized corneal ablation¹ or adap-

tive optics.² The currently used IOL should therefore be optically superior to the natural crystalline lens once implanted in the eye after cataract surgery.

The IOL, together with the total ocular optics, must produce a certain level of image quality at the retina. The IOL, therefore, cannot be the limiting element of vision.

Once an IOL is released by the manufacturer, it is generally assumed to be free of optical defects. Since 1984, the minimum qualification standard for resolving power indicated by the American National Standards Institute (ANSI) has been 100 line pairs per millimeter (lp/mm) for an IOL tested in air using a 3-mm aperture.^{3,4} Several authors, however, have reported that this requirement may be inadequate for assuring that IOLs are not the limiting factor of vision.⁵⁻⁷

Many methods have been used to assess the various aspects of the imaging quality of lenses. The Fourier analysis of the spatial visual stimuli has become common in the past 35 years and the measurement of the modulation transfer function (MTF) of the lens has also been used.⁸⁻¹⁰ This is a measure of the resolving power of the lens and of the definition of the image produced by the lens. MTF measurements have better repeatability and reproducibility than that of the previous industry practice of resolution testing in air with parallel light and the U. S. Air Force three-bar target.⁹

An optical Fourier transform (OFT) of an image is produced on the back focal plane when an ideally convergent lens is transilluminated by a collimated beam of coherent light placed on the front focal plane.¹¹ The OFT is affected by a scale factor that depends on the focal distance (f) of the lens and on the wavelength (λ) of the source. The OFT is the spectrum of the image; in other words, the representation of the image in terms of spatial frequencies transmitted by the lens. When a nonideal lens and an ideal test image that contains an equal amount of all spatial frequencies are used, the OFT is characteristic of that lens. But, to compensate for f and λ , a precalibration is necessary.¹¹ This can be performed by obtaining a transformation of an image that has a known spatial frequency—for example, a grid. The OFT can be converted into the MTF for each IOL.

The purpose of our study was to evaluate the optical quality of different IOLs using an optical test bench and software to analyze the images obtained and measuring the MTF for the lens tested.

METHODS

An optical test bench previously used to analyze images in other investigations was modified for this study.^{12,13}

The optical test bench is made up of several components (Figs. 1, 2). A 632.8-nm helium-neon laser light source is expanded by a telescope system into a coherent, collimated beam of light with a diameter of approximately 50 mm. The expanded laser beam shines on the test image, which contains the broadest possible band of spatial frequencies. Furthermore, it was essential that these frequencies be evenly distributed on the same axis, and a thin slit was therefore chosen as the test image. This type of image comes close to the infinitely fine ideal line, simulating an impulse in one dimension (i.e., the optical translation of a signal used in electronics as an entry to test amplifiers and

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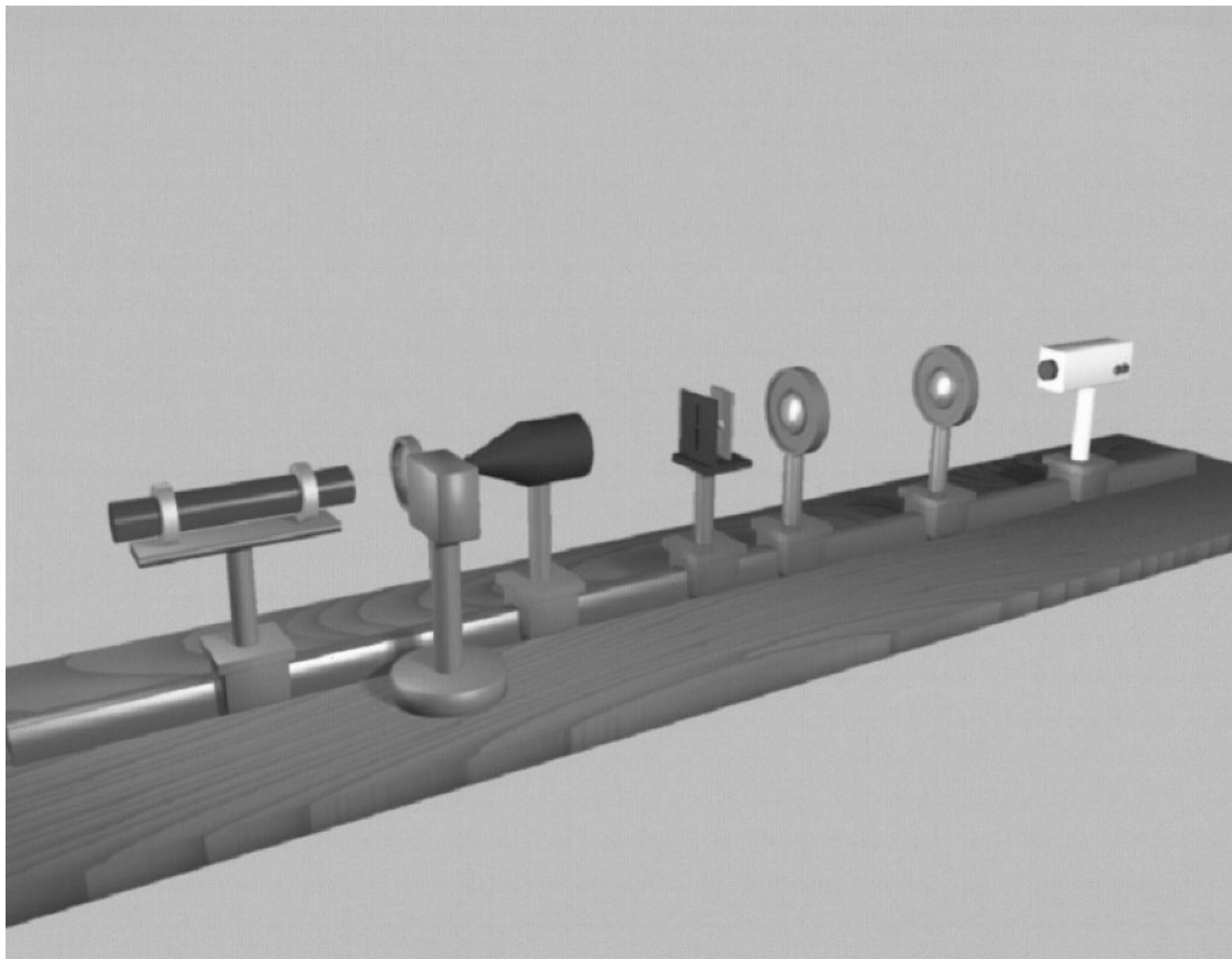


FIGURE 1. Optical test bench. The several components of the optical bench are illustrated.

electronic systems, for example). This ideal-point light source is characterized by a spectrum of spatial frequencies that is very broad, ideally infinite, continuous, and on one axis.

The image is seen by the intraocular lens, suitably attached to a diaphragm support. Because it is a convergent lens, the IOL produces an OFT of the entering image on the back focal plane. The OFT obtained represents the spatial frequency spectrum transmitted by the IOL. The analysis of the extension of this spectrum provides a measure of the optical quality of the lens.

A relay lens formed by two precision optical collimators with a focal length of 38.1 cm completes the optical test bench and forms the system used to focus the OFT on a CCD video camera. Because the IOL has a focal distance of approximately 1.5 cm, it would have been difficult and imprecise to place the CCD at this position. For this reason the front focal plane of the first collimating lens matches the back focal plane of the IOL and antitransforms the transform, reproducing the image. The second collimating lens once again transforms the image and reproduces the transform on the CCD, which is the entry point of a digital image-processing system.

The OFT produced by the IOL and acquired as described is affected by a scale factor. To obtain the real MTF, independent of the lens power and of the whole optical system, we performed a calibration procedure. This procedure required the acquisition of the OFT of two calibrating images produced by each IOL. As calibrating images we

chose two grids of 80 and 100 lines/mm. The OFT of these grids contains repetitions at regular intervals on the transform plane, permitting the calibration of the frequency axis. For example, with an 80-lines/mm grid, repetitive spots centered at frequencies of 0, 80, and 160 lines/mm, and so on, were obtained.

The software used first sought the OFT of the 80-line grid, followed by that of the 100-line grid, and then calculated the number of pixels between one repetition and another to determine the number of pixels corresponding to 1 line/mm. The optical test bench was then ready to analyze the OFT of the image produced by the IOL (Fig. 3).

Three randomly acquired samples of 24 models of IOL were tested by three different examiners: Acrysof MA60BM, Acrysof MA30BA, Acrysof SA60AT, and Acrysof SA30AL (Alcon, Fort Worth, TX); Clariflex, Sensar AR40, Sensar AR40e, SI40NB, and SI55NB (Advanced Medical Optics [AMO], Santa Barbara, CA); Hydroview (Bausch & Lomb, Tampa, FL); ACR6D, HP58, and 600SE (Corneal, Paris, France); Stabibag XL and Stabibag (Ioltech, La Rochelle, France); Lenstec LH 3000 (Lenstec, Inc.); Acrylic 2000 (Medennium, Irvine, CA); Morcher Bigfoot (Morcher GmbH, Stuttgart, Germany); MXM AC3 and S-60125 (Laboratories MXM, Vallauris Cedex, France); and Tecnis Z9000 and 911A CeeOn (Pharmacia Upjohn, Uppsala, Sweden); PMS E48-500 (PMS GmbH, Tuttlingen, Germany); and Staar Visacryl (Starr Surgical, Monrovia, CA). All IOLs evaluated had the same dioptric power (20 D).

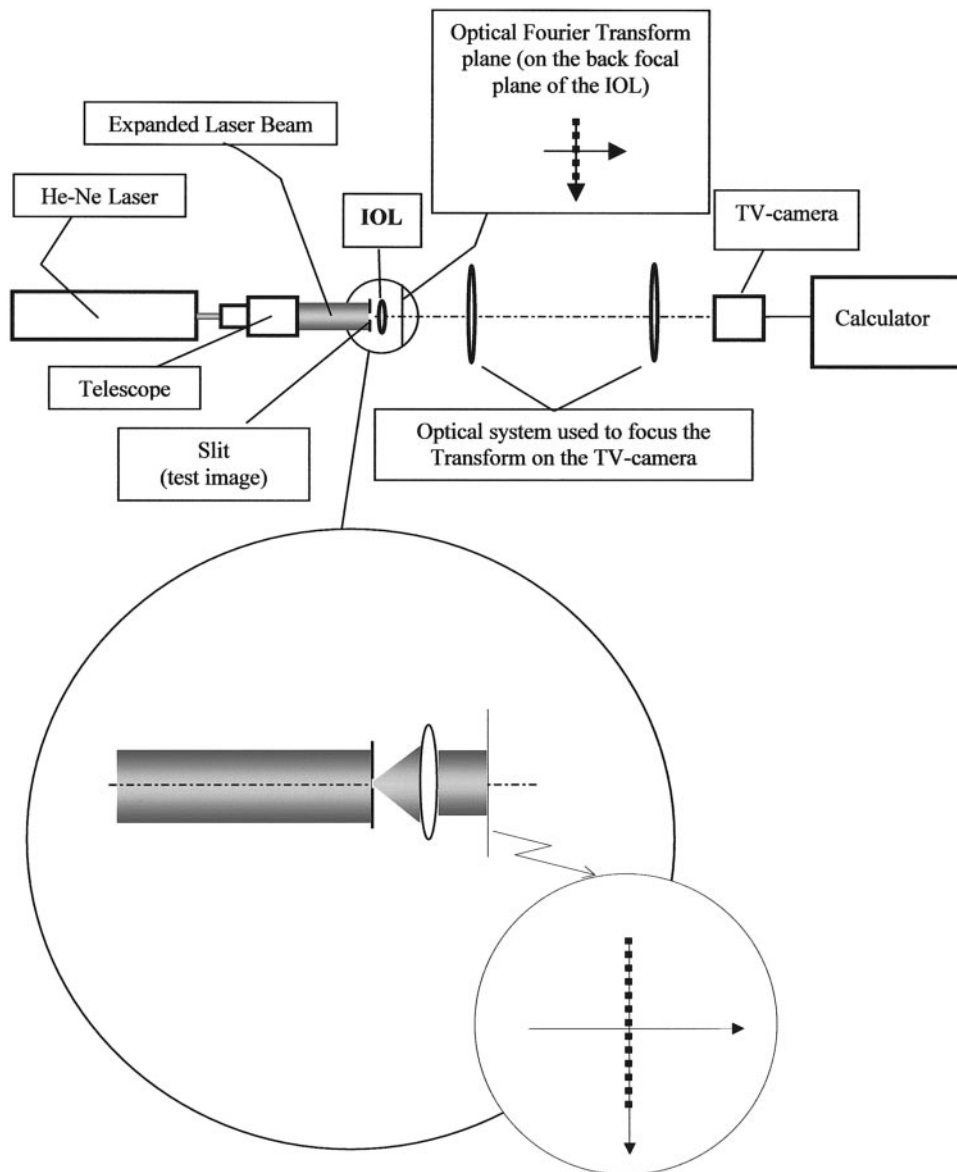


FIGURE 2. Flowchart of the optical test bench. The expanded laser beam is projected on the slit test image and focused on the back focal plane of the IOL analyzed. Two optical collimators reproduce the OFT on the video camera. The acquired image is then processed by the software.

Calculations were performed on the images obtained from the IOLs evaluated to derive the graph of the frequency response, also expressed as the MTF of the intraocular lens. The whole procedure was performed on computer (software developed in a MatLab environment; The MathWorks, Natick, MA).

The graph of the frequency response obtained from the slit response was oscillatory and required interpolating the peaks. The passband (that is, the spatial frequency for which the width of the frequency response is reduced to 70%) was determined from each graph of the frequency response. This is a parameter conventionally used in electronics to measure the maximum frequency at which a system transmits or amplifies a signal. This variable was used to compare the results provided by the different lenses (Fig. 4).

We performed six analyses of the frequency response for each intraocular lens. Each measurement was performed randomly and necessitated recalibration for each measurement.

Statistical Analysis

Six repeated measurements of passband for three different samples of each IOL model were performed. The mean and standard deviation for

each sample lens were calculated. To measure the statistical significance of the differences between the three sample lenses and within the repeated measurements, we used two-way analysis of variance (ANOVA) for repeated measurements. The overall mean of the 18 individual measurements and standard deviation were calculated for each IOL model. We then applied one-way analysis of variance to test for statistically significant differences between the 24 IOL model types. Successively, the Ryan-Einot-Gabriel Welsch multiple F test was applied on the ranked values to compare each value with the value that followed.

All statistical analysis were performed on computer (SPSS ver. 10.0 for Windows; SPSS Sciences, Chicago, IL).

RESULTS

The OFT obtained with the Tecnis Z9000 IOL (Pharmacia) could not be elaborated by the software, because the morphology of the OFT obtained was specific for this type of lens and was not comparable with that of the other lenses. In Figure 5 it is possible to observe the difference between

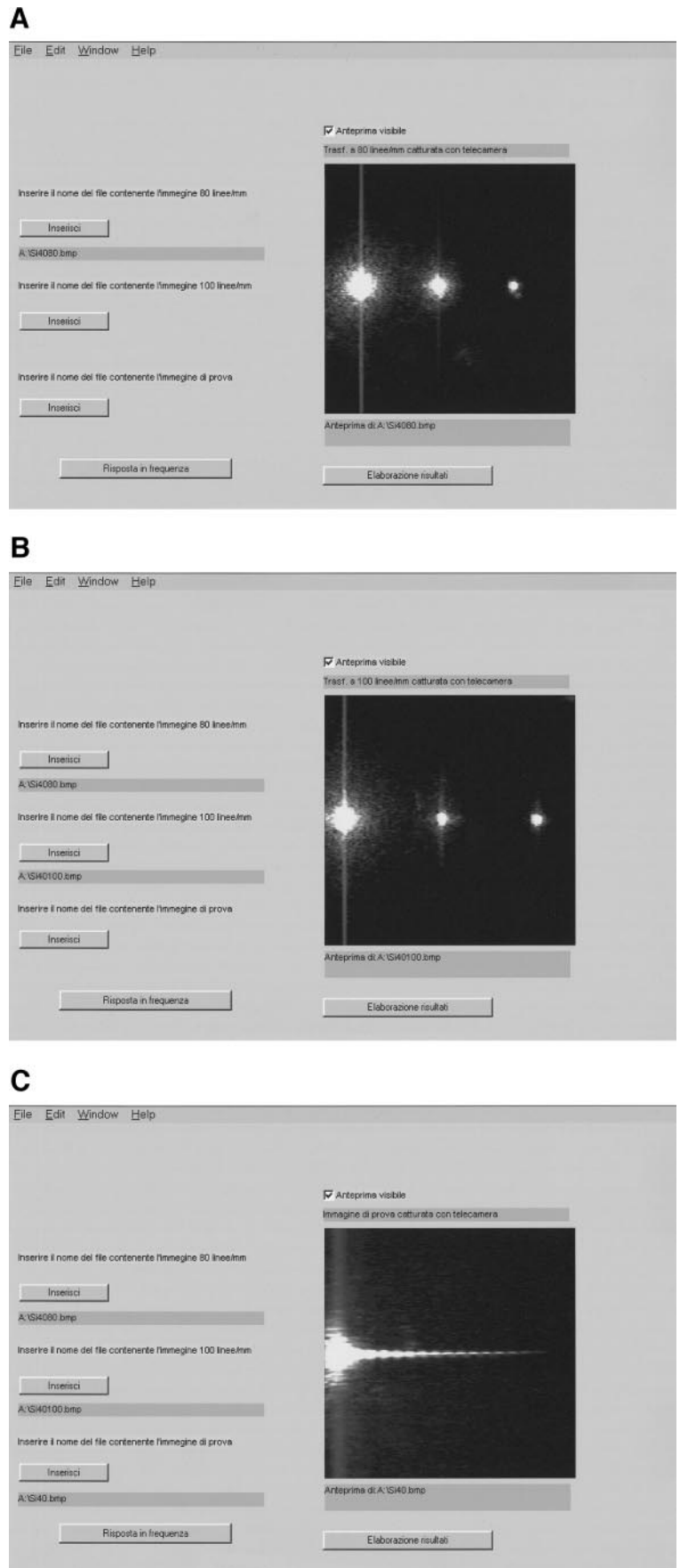


FIGURE 3. Software description: The OFT of the IOL to be analyzed is converted into the MTF. A calibration procedure, requiring two calibrating images with different fixed spatial frequencies is needed. The Fourier transform of these images contains repetitions at regular intervals on the transform plane. The program requires the transform of 80 lines/mm to be introduced (A), followed by that of the 100-lines/mm (B). Finally the transform of the slit image is required (C).

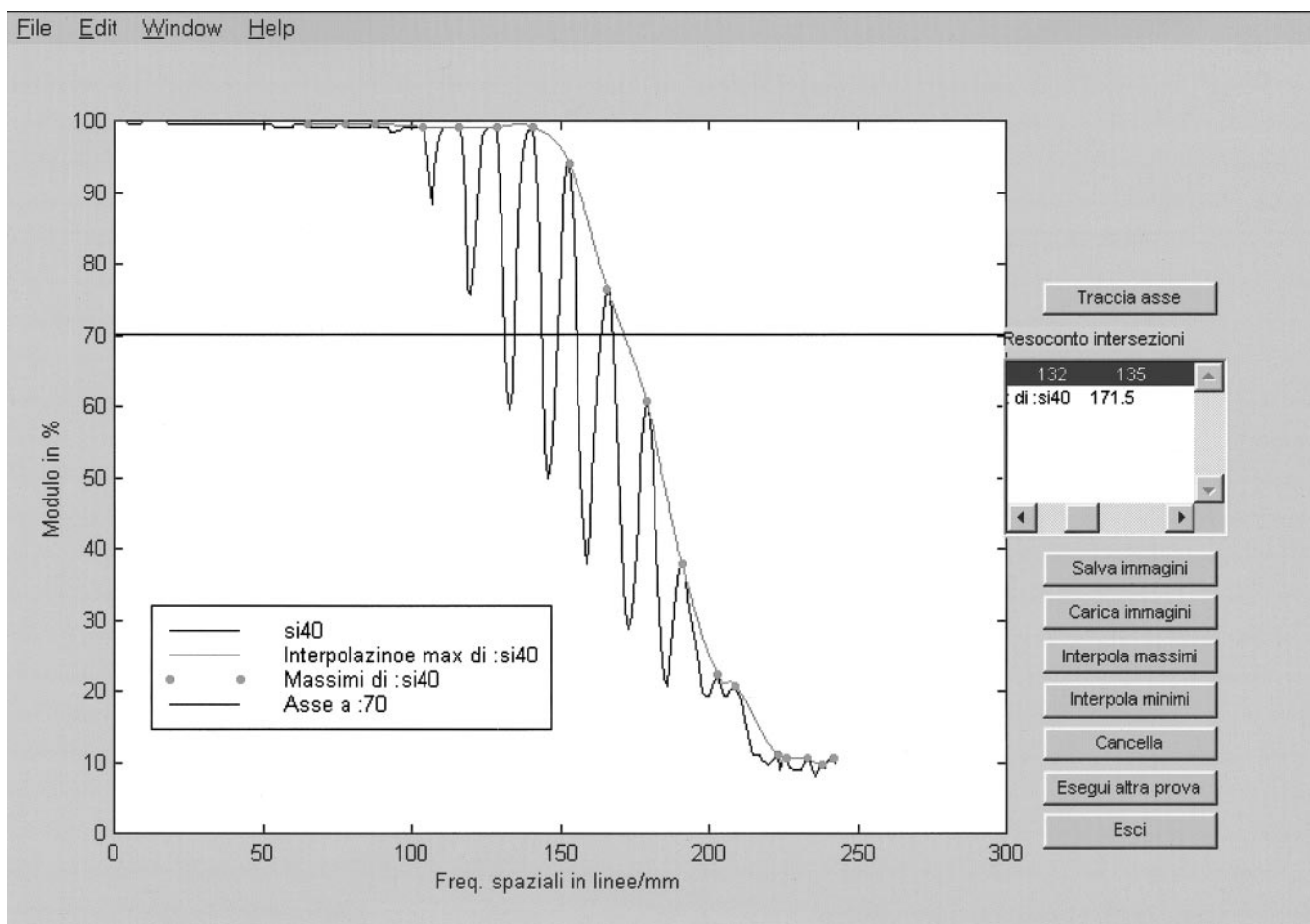


FIGURE 4. Frequency response of the IOL. *x-axis*: Spatial frequencies in lines/mm; *y-axis*: modulus in %. The software interpolates peaks (*brown dots* indicated as *Massimi di :si40* in the box) of the slit response (*black oscillatory curve* indicated as *si40* in the box) to obtain the curve of the frequency response (*brown curve* indicated as *Interpolazione max di :si40* in the box). The spatial frequency for which the width of the frequency response is reduced to the 70% is considered as the passing band (*horizontal black line* indicated as *Asse a :70* in the box). This variable has been considered in order to compare the optical quality of different intraocular lenses.

the OFT of the 911A CeeOn IOL and the Tecnis Z9000 IOL (Pharmacia). These two lenses differ only in the shape of the anterior surface. Because the Tecnis Z9000 IOL was designed with a lens surface to compensate for the positive spherical aberration of the cornea, it is heavily affected by spherical aberration. This aberration causes a distortion, in particular a widening, of the OFT of the test images. The OFT of the reticules and of the slit should be distributed on the horizontal axis, but, because of the widening of the lines (Fig. 5), the axis can be not be identified automatically. For this reason it was not possible to compare data obtained from this type of lens. The OFT visualized with this lens was therefore not considered.

A graph of the frequency response, also expressed as the MTF of the intraocular lens, was obtained for each lens.

The frequency response curve was obtained from the graph of the slit response by interpolating the peaks of the oscillatory response. The passband (i.e., the spatial frequency for which the width of the frequency response is reduced to 70%) was considered, to compare the results provided by the different lenses (Fig. 4).

The six repeated measurements of the passband for the three different samples for each IOL model were substantially the same in the means and standard deviations for all the 23 IOL models (Table 1, 1st, 2nd, and 3rd, lens). Therefore, the two-way ANOVA for repeated measurements re-

sulted not significant for each IOL model, in accordance with the null hypothesis of absence of variability between samples. Variability within measurements for different types of IOLs can consequently be accepted with certainty. These results guarantee this method to be highly precise.

The overall mean and standard deviation of the 18 individual measurements for each IOL model are reported in Table 1 (last column) and showed in Figure 6. These results presented a large range of passband means. The lowest passband (125.63 lp/mm) was measured for the Lenstec LH 3000 IOL and the highest (191.54 lp/mm) for the Acrysof SA30AL (Alcon). The one-way ANOVA applied to test the hypothesis that mean values of 23 IOL models are equal produced statistically significant ($P < 0.01$) results. The Ryan-Einot-Gabriel Welsch multiple F range test, applied to the ranked values in Table 1 (last column), showed statistically significant ($P < 0.05$) results for all IOL model, except the 600SE (Corneal), the Big Foot (Morcher), PMS, SI40 (AMO), Stabibag XL (Ioltech), and Acrysof MA60BM (Alcon), each of which had mean passband values that were not significantly different compared with the values that followed.

The frequency response of the IOLs examined varied according to the material and the profile of the lens. The highest spatial frequencies were transmitted by the acrylic IOLs, with

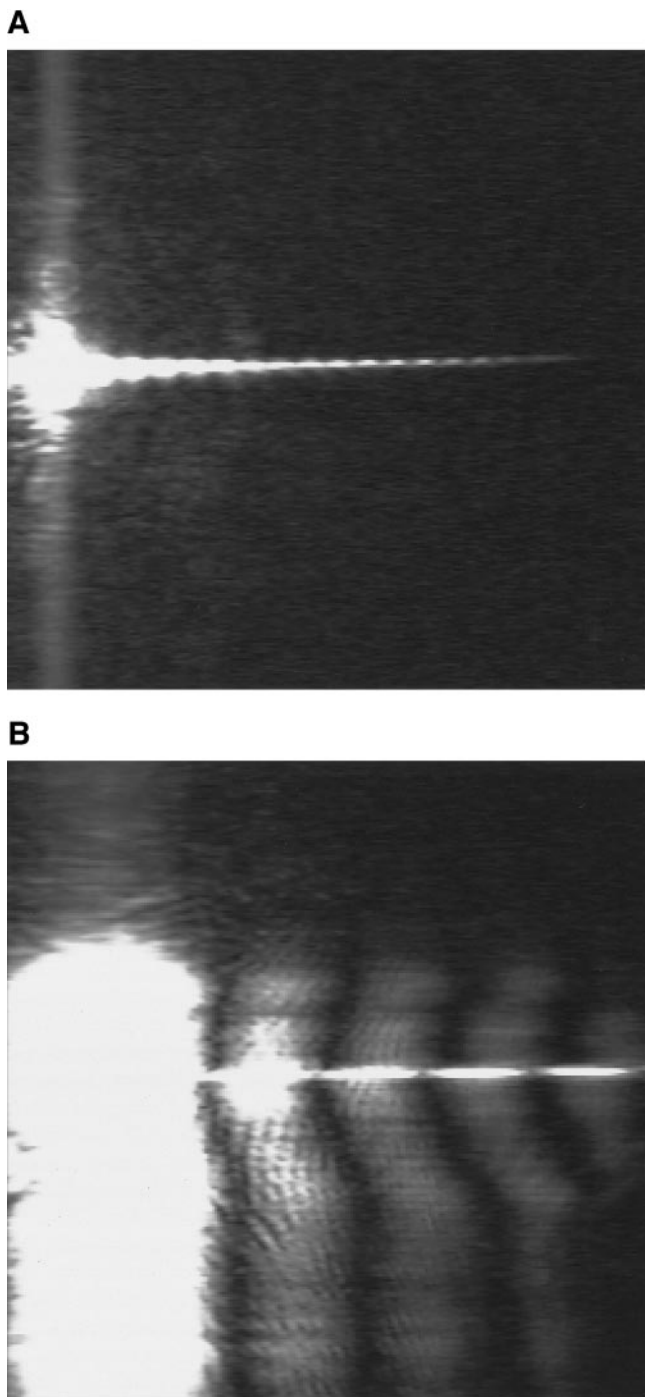


FIGURE 5. The OFT of the 911A CeeOn and the Tecnis Z9000 (Pharmacia) IOLs. The OFT of the Pharmacia 911A CeeOn IOL (A) and the Tecnis Z9000 IOL (B) are shown. These two lenses differ only in the shape of the anterior surface. The Tecnis Z9000 IOL was designed to compensate for the positive spherical aberration of the cornea. This surface causes a distortion—in particular, a widening of the OFT.

a high refractive index associated with an unequal biconvex profile.

DISCUSSION

The image presented to the retina by the optical system is usually degraded by the optical imperfections of the eye and by

diffraction at the pupil.¹⁴ Among the human visual system's limits in visual performance are aberrations, diffraction, light scatter, finite photoreceptor size and spacing, and elaboration in the neural pathways of the signal from the retina to the brain.^{15–18} The consequence of aberrations and diffraction in the eye is the reduction of the contrast in the image formed at the retina, and the degree of degradation is dependent on the spatial frequency of the pattern considered.¹⁹

Using various new techniques, ophthalmologists today try to reach the potential highest visual acuity for patients. The aim is to improve visual acuity beyond what we consider to be normal, with an improvement of clinical outcomes in terms of visual acuity and contrast sensitivity. The term “supernormal” vision has been introduced to describe this possibility.¹ Quantification of optical aberrations to design the ideal refractive corrections has now come into use. These optimal corrections are intended to improve the optical quality of the images at the retinal plane. Results reported after wavefront-guided excimer laser surgery suggest that higher-order aberrations can be decreased.²⁰

Not only during refractive surgery, but also by means of other optical corrections, such as the introduction of an intraocular foldable IOL in the eye after cataract surgery, vision quality can be improved. It has been reported that contrast sensitivity in pseudophakic eyes is higher than in aphakic eyes with spectacle correction, but is lower when compared with normal phakic eyes.²¹ The cornea has been found to have a positive spherical aberration that increases with age.^{22,23} The young crystalline lens has a negative spherical aberration that increases with age, becoming positive around the age of 40 years.²⁴ The optical effect of the positive spherical aberration of the cornea could be reduced or eliminated by implanting an IOL with a negative spherical aberration. Aspheric IOLs have then been introduced.^{25,26} An improvement in quality of vision and in particular in contrast sensitivity has been documented after implantation of Tecnis Z9000 IOLs (Pharmacia).²⁷ To correct the unique astigmatic and spherical requirements for each individual cataract patient, individually crafting IOL has now been supposed.²⁸ When introducing the concept of custom IOL design, the optical quality of an IOL must not be underestimated, with the aim of increasing the contrast and spatial detail of the retinal image once the IOL is implanted within the eye's optics.

The retina and the spatial distribution of the photoreceptors in the foveola are at the end the decisive limiting factors to visual performance. Foveal cone spacing is assumed to be the cutoff spatial frequency determinant for the eye. Considering the foveal cone diameter to be approximately 2.5 μm , a cutoff frequency of approximately 120 cyc/deg has been postulated.¹⁵

Since 1984, the minimum qualifying resolving power of the ANSI standard is 100 lp/mm for an IOL tested in air using a 3-mm aperture. A spatial frequency of 100 mm^{-1} at the retina corresponds to a visual acuity of approximately 20/20. In angular terms, it is close to 30 cyc/deg.⁹ Considering the resolution of the retina to be limited by the spacing of light receptors, the human visual system can resolve to approximately 20/5 or 120 cyc/deg.¹⁵ This resolution is well above the conventional clinical measures, as it does not compensate for the optics of the eye and postreceptoral neural processing.

In our study we considered the OFT obtained for each lens evaluated, which represents the spatial frequency spectrum transmitted by the IOL optic. The analysis of the extension of this spectrum provides a measure of the optical quality of the lens. The graph of the frequency response has been obtained and expressed as the modulation transfer function of the in-

TABLE 1. Passband Values of IOLs Tested

IOL Model	1st Lens	2nd Lens	3rd Lens	Overall Mean (SD)*
Lenstec LH 3000	125.60 (0.41)	125.63 (0.47)	125.67 (0.41)	125.63 (0.40) ^(Q)
B&L Hydroview	131.55 (0.33)	131.62 (0.37)	131.62 (0.42)	131.59 (0.35) ^(P)
Medennium Acrylic 2000	150.52 (0.24)	150.53 (0.35)	150.53 (0.30)	150.53 (0.28) ^(O)
Staar Visacryl	154.22 (0.41)	154.25 (0.41)	154.23 (0.42)	154.23 (0.39) ^(N)
Pharmacia 911A	158.75 (0.52)	158.75 (0.44)	158.72 (0.56)	158.74 (0.48) ^(M)
Corneal ACR6D SE	161.92 (0.46)	161.87 (0.46)	161.85 (0.40)	161.88 (0.42) ^(L)
Corneal HP58	163.03 (0.62)	163.00 (0.71)	163.02 (0.62)	163.02 (0.61) ^(K)
Corneal 600SE	164.52 (0.43)	164.45 (0.40)	164.43 (0.40)	164.47 (0.39) ^{(J)†}
MXM AC3	164.52 (0.33)	164.50 (0.41)	154.52 (0.44)	164.51 (0.37) ^(D)
Morcher Big Foot	165.28 (0.40)	165.22 (0.40)	165.22 (0.40)	165.24 (0.38) ^{(I)†}
MXM S-60125	165.33 (0.40)	165.38 (0.40)	165.38 (0.38)	165.37 (0.38) ^(D)
AMO Clariflex	170.68 (0.36)	170.73 (0.23)	170.63 (0.34)	170.68 (0.30) ^(H)
PMS	171.42 (0.35)	171.47 (0.34)	171.45 (0.43)	171.44 (0.35) ^{(G)†}
AMO SI40	171.80 (0.30)	171.82 (0.34)	171.78 (0.38)	171.80 (0.32) ^{(G)†}
Ioltech Stabibag XL	171.80 (0.49)	171.85 (0.54)	171.82 (0.46)	171.82 (0.47) ^{(G)†}
AMO SI55	172.12 (0.44)	172.07 (0.49)	172.02 (0.51)	172.07 (0.45) ^(G)
Ioltech Stabibag	173.03 (0.33)	173.02 (0.32)	173.03 (0.30)	173.02 (0.29) ^(F)
AMO Sensar AR40	174.48 (0.42)	174.48 (0.43)	174.47 (0.45)	174.48 (0.41) ^(E)
AMO Sensar AR40c	175.97 (0.16)	175.98 (0.17)	175.75 (0.18)	175.90 (0.19) ^(D)
Acrysof MA60BM	185.62 (0.36)	185.60 (0.32)	185.50 (0.32)	185.60 (0.31) ^{(C)†}
Acrysof MA30BA	186.05 (0.33)	186.05 (0.34)	186.07 (0.34)	186.06 (0.32) ^(C)
Acrysof SA60AT	190.32 (0.38)	190.38 (0.36)	190.32 (0.29)	190.34 (0.32) ^(B)
Acrysof SA30AL	191.48 (0.35)	191.58 (0.41)	191.55 (0.38)	191.54 (0.36) ^(A)

Multiple comparison of differences among the means values of different IOL models. Data are the mean and standard deviation of six measurements for each lens.

* Mean and standard deviation of 18 measurements for each lens. The values ranges from 125.6 lines/mm for Lenstech LH 3000 to 191.48 lines/mm for Alcon Acrysof SA30AL. The one-way ANOVA ($P < 0.01$) and the Ryan-Einot-Gabriel Welsch multiple F test ($P < 0.05$) results were statistically significant.

† Means with the same letters are not significantly different. Means with different letters are statistically significant ($P < 0.05$). Data are not available for the Pharmacia Tecnis Z9000.

traocular lens. The spectrum of spatial frequencies is an intrinsic feature of each image, but of course if an image is an enlargement or a reduced version of another, the spectrum contracts or expands in accordance. Because in the visual process the image is reduced, the spectrum therefore expands. The system we described does not examine the frequency spectrum of a specific image, but the theoretically maximum spectrum that can be produced by an IOL, and therefore it provides a good method to compare the optical quality of different IOLs.

The MTF analysis of an IOL could be examined, for instance, using a 55-nm green wavelength, which corresponds to cone peak efficiency and is the band of visible light spectrum at which many lenses should be optimized.

Our measurements were performed using a standard optical bench for optical procession of the image, supplied with a 632.8-nm He-Ne red laser. Because the OFT is affected by a scale factor depending on the focal distance (f) of the lens and by the wavelength (λ) of the source, using light sources of different wavelengths may give slightly different MTFs. To compensate for f and λ , a precalibration procedure using grids with a known spatial frequency has been used.¹¹

The method used for this purposes follows the general principles of system theory to evaluate transfer functions and applies them to optics and optometry.¹¹ The specific technique used has been obtained in a general purpose laboratory for optical processing of images.¹³

The method was precise, as the six repeated measurements of the passband for the three different samples for each IOL model were almost equivalent, in mean values and standard deviations, for all 23 IOL models (Table 1). Therefore, the results of the two-way ANOVA for repeated measurements were not significant for each IOL model, in accordance with the null hypothesis of absence of variability between samples.

Variability within measurements for different types of IOL can consequently be accepted with certainty. These results guarantee this method to be highly precise.

The frequency response of the different IOLs examined varied according to several factors, including the material and the optic profile of the lens. The best frequency response was provided by acrylic IOLs, particularly those with an asymmetrically biconvex profile. This could be due to a reduction in optical aberrations provided by this type of profile. It would have been of interest to compare the Tecnis Z9000 IOL (Pharmacia) with a modified anterior surface designed to compensate for the positive spherical aberration of the cornea. It was not possible to compare data obtained testing this type of lens, because the OFT obtained had a specific morphology that the software for this system could not process (Fig. 5).

Given that 20/20 visual acuity corresponds to approximately 100 lp/mm and that the frequencies transmitted by the IOL studied were higher, no tested IOL was found to be a limiting factor for average tested visual acuity.

When trying to achieve the maximum potentiality for the ocular optical system, a higher level of optical quality is essential. An IOL of better optical quality could allow a greater spatial frequency spectrum to be transmitted to the retina. The use of IOLs capable of transmitting a broad spectrum of spatial frequencies would allow them to reach higher values of visual acuity—the ocular optical conditions being equal. Moreover, the implantation of an IOL with a superior optical quality could improve the quality of vision in general and in particular in terms of contrast sensitivity. For all these reasons, to hold in due consideration the optical quality of the IOLs that implanted every day all over the world during cataract surgery would be beneficial.

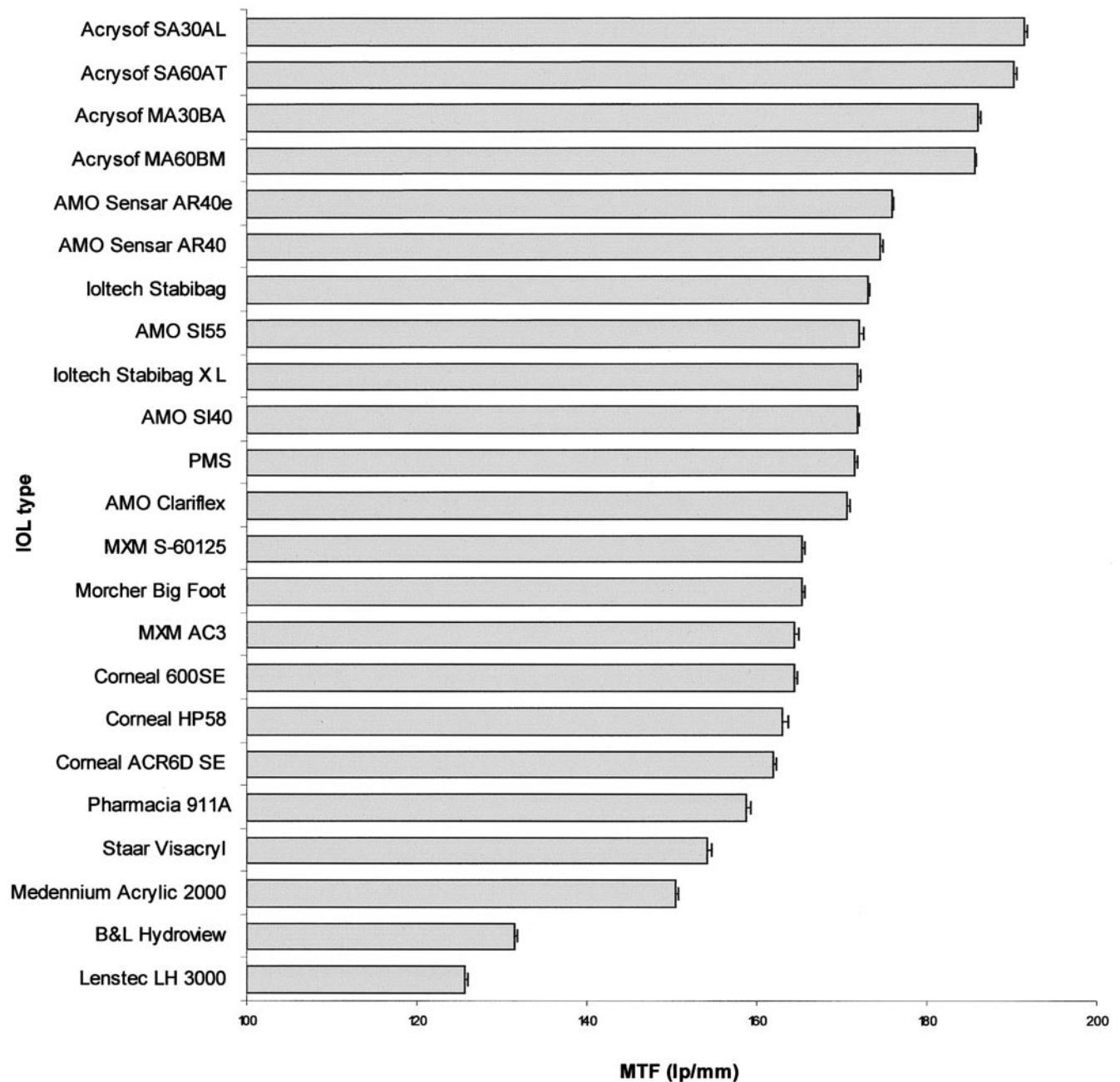


FIGURE 6. Graphic representation of the mean and standard deviation of the passband value of each IOL.

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