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Through focus image quality of eyes implanted with monofocal and multifocal intraocular lenses

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Abstract. A double-pass method is applied to determine the retinal image quality of eyes implanted with intraocular lenses (IOLs). The effect of focus on image quality was measured in two groups of patients that had been implanted with either monofocal or multifocal IOLs. The results show that the overall retinal image quality is reduced in eyes with multifocal lenses with respect to that implanted with monofocal IOLs. Although the depth of focus is larger in multifocal IOLs (4 to 5 D) than in the monofocal IOLs (2 to 3 D), some patients implanted with monofocal IOLs have higher image quality than those implanted with multifocal IOLs in a range of about 4 D around the best focus. In eyes implanted with monofocal IOLs, astigmatism plays a major role to reduce the retinal contrast, but also increases the depth of focus. These "*in vivo*" measurements show that there is considerable variability in image quality among individuals with the same type of monofocal IOLs. The main factors causing this variability seem to be age and astigmatism produced by surgery.

Subject terms: ophthalmology; retinal image quality; intraocular lenses; modulation transfer.

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1 Introduction

Intraocular lenses (IOLs) are commonly implanted in cataract surgery. Initially IOLs were mainly monofocal, but at present there are many multifocal IOLs available, which are being implanted. Multifocal IOLs have the potential advantage of reducing the dependence on spectacle correction for near vision after cataract surgery. Because the multifocal IOLs superimpose the near and far images on the retina, however, the overall ocular image quality might be reduced in comparison with that of monofocal lenses.

Several kinds of studies on the optical performance of different types of IOLs have been performed: optical bench testing, ray tracing, and clinical studies on the visual performance (mainly acuity and contrast sensitivity) in patients implanted[1-5] with IOLs. All those studies are useful to test the optical design in new IOL types or to evaluate the clinical success of IOL implantation. Although there are some attempts to relate IOL optical bench measurements and patients' visual performance,[6] the image quality of IOLs measured in optical bench outside the eye is difficult to extrapolate to the situation in the implanted eye. In addition, clinical (psychophysical) tests can be affected by nonoptical problems in the patients' visual systems. All these facts are good reasons for the need for direct optical measurement of retinal image quality in eyes implanted with IOLs. This should be the most appropriate kind of method to obtain a final complete evaluation of the optical performance of implanted lenses. The double-pass method is an adequate procedure to test both the IOL design and the implantation process, comparing the relative final performance of different types of lenses.

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In an earlier paper,[7] we applied the double-pass method to determine the ocular modulation transfer function (MTF) of eyes implanted with distinct types of IOLs. This allowed the comparison of the optical performance of eyes implanted with monofocal and three types of bifocal IOLs. The results showed that eyes implanted with bifocals have a reduction in the modulation transfer of around a factor of 2, but with similar optical resolution as the monofocal IOLs. That is the reason why in some clinical studies, where only visual acuity is compared, the performance of both monofocal and bifocal IOLs has been found to be approximately the same.

In this paper, we extend the double-pass method to investigate the actual differences of image quality as a function of focus in eyes implanted with two different types of IOLs: monofocal and bifocal. The depth of focus in IOLs, referred to in some of the clinical literature as pseudoaccommodation, is the range of focus in which a visual performance parameter (usually acuity) is above a given value. New designs of multifocal IOLs permit to extend the depth of focus by different means. The objective determination of through focus image quality after the IOL is implanted in the eye would permit a complete evaluation of the lenses.

2 Double-Pass Method to Determine the Retinal Image Quality

The double-pass method has been widely used to determine the retinal image quality in the human eye, mainly in normal subjects. Although this technique has usually been restricted to basic research in physiological optics, its clinical applications in ophthalmology and optometry are promising. The double-pass technique is based on imaging an object onto the retina. Then a fraction of the light is reflected back and the external retinal image (aerial image) is used to estimate the aberrations of the eye, point and line spread functions, and the ocular MTF. Flamant[8] recorded photographically the first double-pass line spread function and later other authors used photomultipliers to scan the aerial image of lines.[9,10] Arnulf et al.[11] extended the procedure to record a point by using an image intensifier system. More recently, an improved version of the double-pass system, used to record the aerial image of a point source with video cameras, was developed.[12,13] These improvements in the design of the double-pass experimental system enabled applying it in some clinical studies. We assessed the relative eye's image quality as a function of age[14] and we measured the ocular MTF in subjects implanted with different types of intraocular lenses[7] in the first steps of this research.

2.1 *Apparatus*

The double-pass system to measure the eye's image quality has been described in detail elsewhere.[12,13] Therefore, only the main characteristics are described here. Figure 1 shows a diagram of the experimental system. The beam coming from a He-Ne laser (632 nm), with a nominal power of 10 mW, passes through a high-density filter (DF) mounted on a rotary solenoid to be moved in and out of the beam. The attenuation of this filter is chosen to allow the subject to use the point object (O) as a comfortable fixation target. The neutral filter DF is momentarily removed during the data collection exposures (100 ms). The beam is spatially filtered by a 40× microscope objective (M), and a 10-μm pinhole (P), which acts as the point object (O). The emerging beam is collimated by the lens L_1 ($f' = 200$ mm); and a portion of the light is reflected toward the eye by a pellicle beamsplitter (BS), the transmitted light is removed from the beam path using a light trap (BD). Before entering the eye, the beam passes through an afocal system, consisting of two lenses with the same focal length L_2 and L_3 ($f' = 120$ mm). An artificial pupil of 4 mm diameter is imaged on the subject's pupil plane by lenses L_2 and L_3. This pair of lenses provides a method to continuously modify the subject's state of focus by moving lens L_2 and the stop (AP) separated by one focal length (focusing block, FB). This is particularly important in this study where the collection of each series of images is carried out for a determined state of focus. The eye forms the image of the point O on the retina O′ and part of the light is reflected back, passing again through the optical media of the eye, lenses L_2 and L_3, and the beamsplitter BS. The zoom lens L_Z ($f'_z = 60$ to 300 mm) forms the aerial image O″ on a

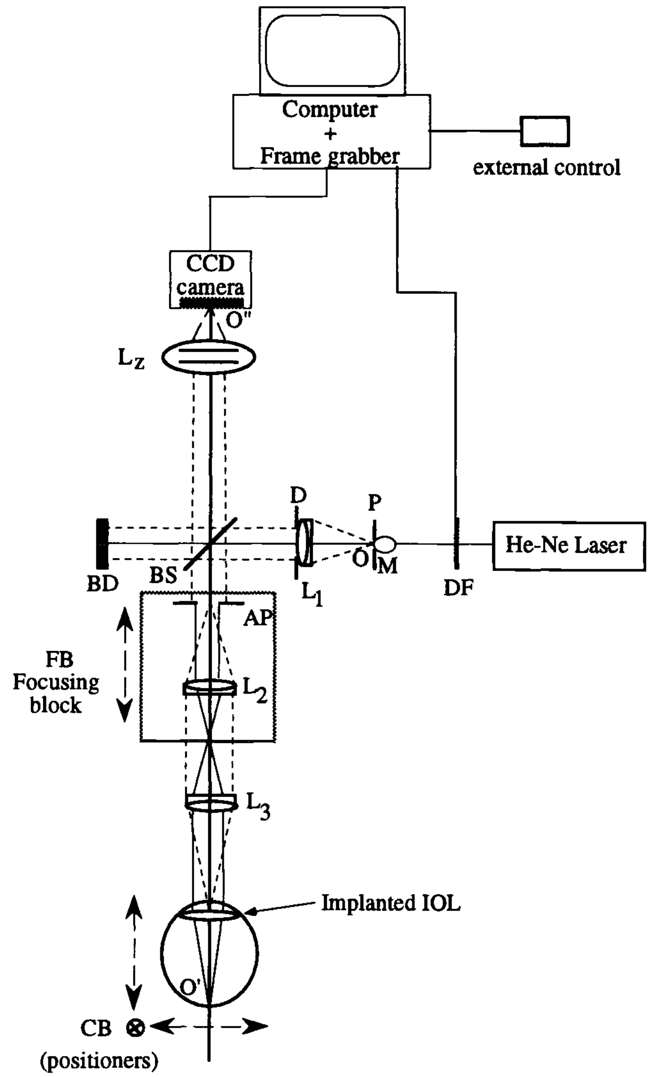

Fig. 1 Experimental double-pass system to record the retinal images of a point test. The He-Ne laser is used as the light source; DF, is a neutral density filter; *M*, microscope objective; *P*, pinhole; L1, collimator; BS, beamsplitter; BD, light trapping; AP, 4-mm artificial pupil; L_2 and L_3, lenses; and L_Z zoom lens. The system is explained in detail in the text.

CCD camera (Pulnix TM-745). A frame grabber (Matrox MVP-AT) permits digitizing the images in a PC computer.

The laser irradiance in the pupil plane during the 100-ms exposures is of the order of 0.3 mW/cm^2. For a 4-mm pupil diameter the laser power entering the eye is less than 0.04 mW. These exposure values are well below the maximum limit allowed by safety standards.[15]

2.2 *Procedure*

The short-exposure aerial retinal images of a point source in the fovea that are recorded are subsequently averaged in the computer to remove speckle (coherent noise) and thus simulate incoherent imaging conditions in the second pass. In this study, we averaged 16 frames, by taking two series of eight exposures each. The number of averaged exposures is chosen depending on the requirements of the experiments. In clinical studies, it is more appropriate to reduce the duration (recording less images) of the experiment, but at the cost of having the final images still noisy. All the images are 256×256 pixels, with the short exposure images having 8 bits/pixel and the final averaged image having 16 bits/pixel. A background image, obtained by placing a black diffuser in the pupil plane instead of the eye, is subtracted from the aerial images. The remaining background is removed by subtracting the average intensity value in the four corners of the image. The ocular MTF is then computed by the square root of the Fourier transform of the aerial image.

All measurements were performed with a 4-mm artificial pupil projected on the natural subject's pupil, which is kept equal to or larger than the artificial pupil by modifying the mean level of the illumination. The subject's head was stabilized by a chin-rest, which is mounted on a positioner (CB), used to align the center of the artificial pupil in the patient's natural pupil. The experimenter centered the subject's pupil with respect to the beam along the complete recollection of images in the experiment. By moving the focusing block (FB), the distance of the target was modified. Focus is changed in 0.5- or 1-D steps over a range of -6D to 6D.

2.3 *Types of IOLs and Selection of Subjects*

Two different types of IOLs, one monofocal and one multifocal, were studied. A monofocal lens (FORMFLEX II, IOLAB), with a monobloc design, 7-mm diameter, and 19 D. A multifocal lens (815 LE, Alcon) combines the effect of refraction and diffraction (with the posterior surface like a Fresnel zone). This IOL has 6 mm of useful diameter, 20 D, and the near focus 3.5 D of add power.

Measurements have been obtained in two groups of four patients each, implanted with either monofocal or multifocal IOLs. They ranged from 50 to 71 years old. Some of the patients implanted with monofocal IOLs had residual astigmatism (up to 1 D). All the patients were chosen after a long postoperatory period and based in clinical success. They passed a complete ophthalmological exam with good records of clean capsules, iris shape, pupilary reflex, visual acuity, and contrast sensitivity.

For comparison purposes, the two lenses used in this study were also tested in an optical bench in air to record the single-pass point spread functions of IOLs alone at different focuses (from -6 D to 3 D). From these measurements, MTFs and image quality parameters were computed.

3 Results

A selection of aerial (double-pass) retinal images at different states of focus obtained in three implanted eyes is shown. These results are presented as gray-level images [series (a) of the figures] and their horizontal sections [series (b) of the figures]. All the images are normalized in intensity to the same value. Figure 2 presents the aerial retinal images with focus varying from -3 D to 3 D for subject JFD (50 years old), implanted with a monofocal IOL with an excellent clinical success. This patient had no astigmatism. Figure 3 corresponds to subject ADB (71 years old) also implanted with a monofocal IOLs, but having residual astigmatism of 0.5 D. The aerial retinal images are from -2 D to 4 D of defocus, with the least confusion circle image at 1 D. Figure 4 corresponds to subject MRG (53 years old) implanted with a multifocal IOLs, with the aerial retinal images from -4 D to 2 D. These series of images easily show only qualitatively how image quality changes with focus in different subjects implanted with two types of IOLs.

To obtain quantitative measurements they need to be corrected from double pass through the eye. To do this, ocular MTFs are computed from the averaged aerial retinal images as explained. Samples of 1-D MTF results are presented in Fig. 5. The three graphs are plotted on the same scale of spatial frequency to allow a comparison among these results. These 1-D MTFs were computed by averaging the 2-D MTFs across all orientations (radial profiles). Figure 5(a) shows some previous results of averaged MTFs that are useful for comparison to those obtained in this study: the diffraction-limited system MTF (4-mm pupil diameter), the mean MTFs for normal young and older eyes,[15] and the mean MTFs for eyes implanted with monofocal and three types of multifocal IOLs (Ref. 5). Figure 5(b) shows the MTFs, in the best state of focus, for three eyes implanted with monofocal IOLs. The best MTF corresponds to subject JFD, who was practically astigmatism free, whereas the other MTFs are for subjects with approximately 0.5 and 1 D of astigmatism, respectively. Note the large influence of astigmatism in reducing the MTF. Figure 5(c) shows MTFs for a subject implanted with a multifocal IOL at three different positions of focus: 0, -2, and -4 D. The differences among these MTFs are smaller, but the modulation at all spatial frequencies is lower than that of the average MTF for the monofocal IOLs.

To compare different retinal images or MTFs in an easier way, it is useful to have a single parameter that evaluates the overall image quality. This is a difficult task, however, especially for highly aberrated systems, as is the case for out of focus and astigmatic images. The Strehl ratio[16] is a commonly used parameter that can be computed from the MTF. However, it is not well correlated with image quality when large aberrations are present. Therefore we have computed two other parameters to describe the overall image quality: the mean modulation in the retinal image for 2.6 c/deg and the volume under the 2-D aerial retinal image normalized to the volume under the aerial image corresponding to the diffraction-limited system. Before computing the volume under the aerial retinal images, these are normalized in intensity to the same value. We chose the value of the modulation at 2.6 c/deg in this range of spatial frequencies because we found a large variability among the MTFs for different conditions.

In Fig. 6, the modulation at 2.6 c/deg of all the subjects and some average results for reference are presented. The

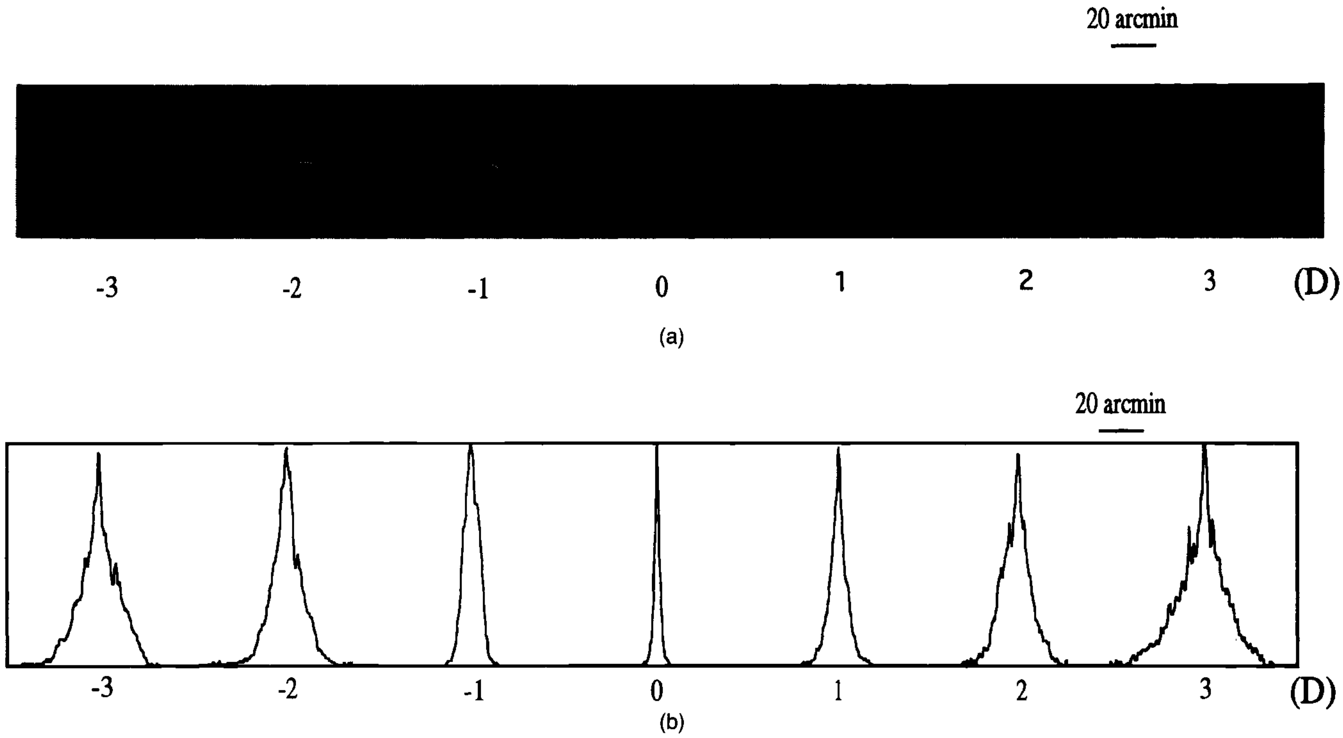

Fig. 2 (a) Aerial retinal images of a point test from −3 to 3 D of focus corresponding to an eye implanted with a monofocal IOL and practically astigmatic free (patient JFD). (b) Horizontal sections (normalized to the same arbitrary value) of the aerial images of (a).

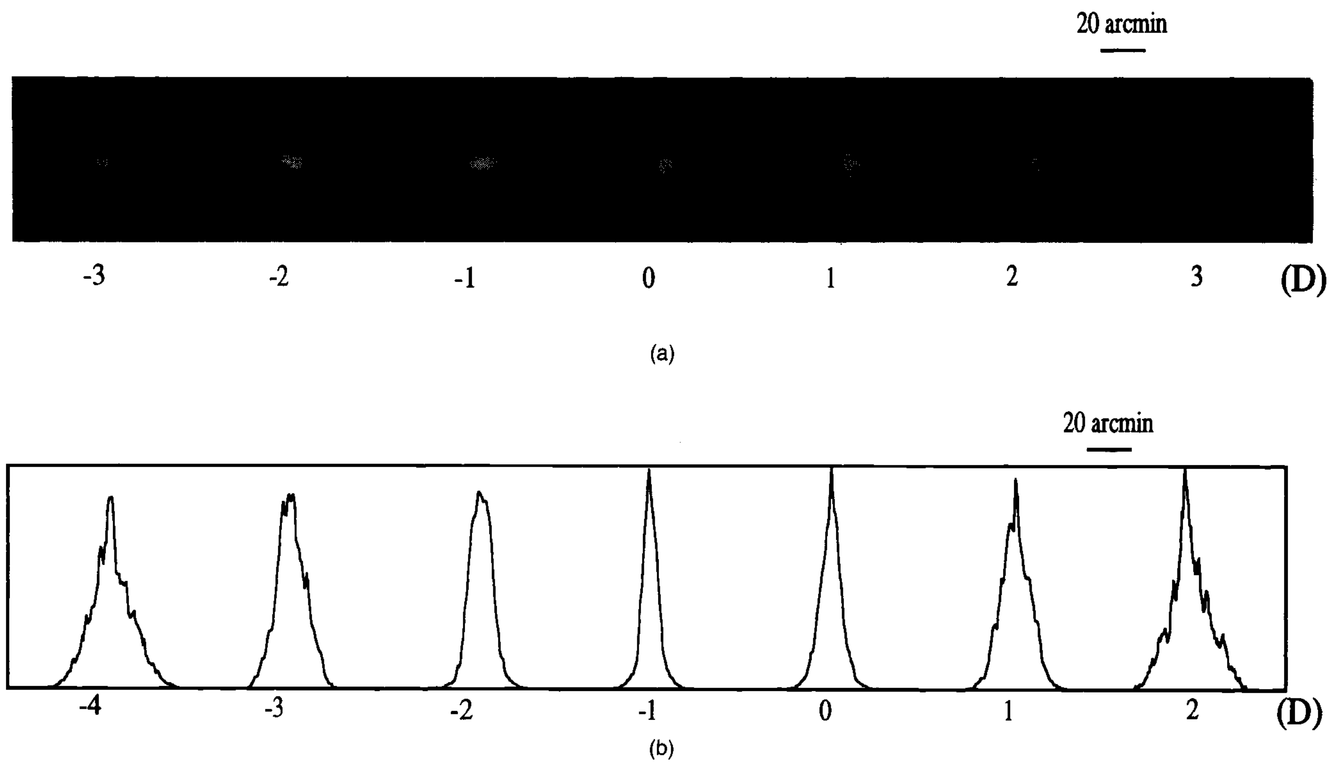

Fig. 3 (a) Aerial retinal images of a point test from −3 to 3 D of focus corresponding to an eye implanted with a monofocal IOL with 0.5 D of astigmatism (patient ADB). (b) Horizontal sections (normalized to the same arbitrary value) of the aerial images of (a).

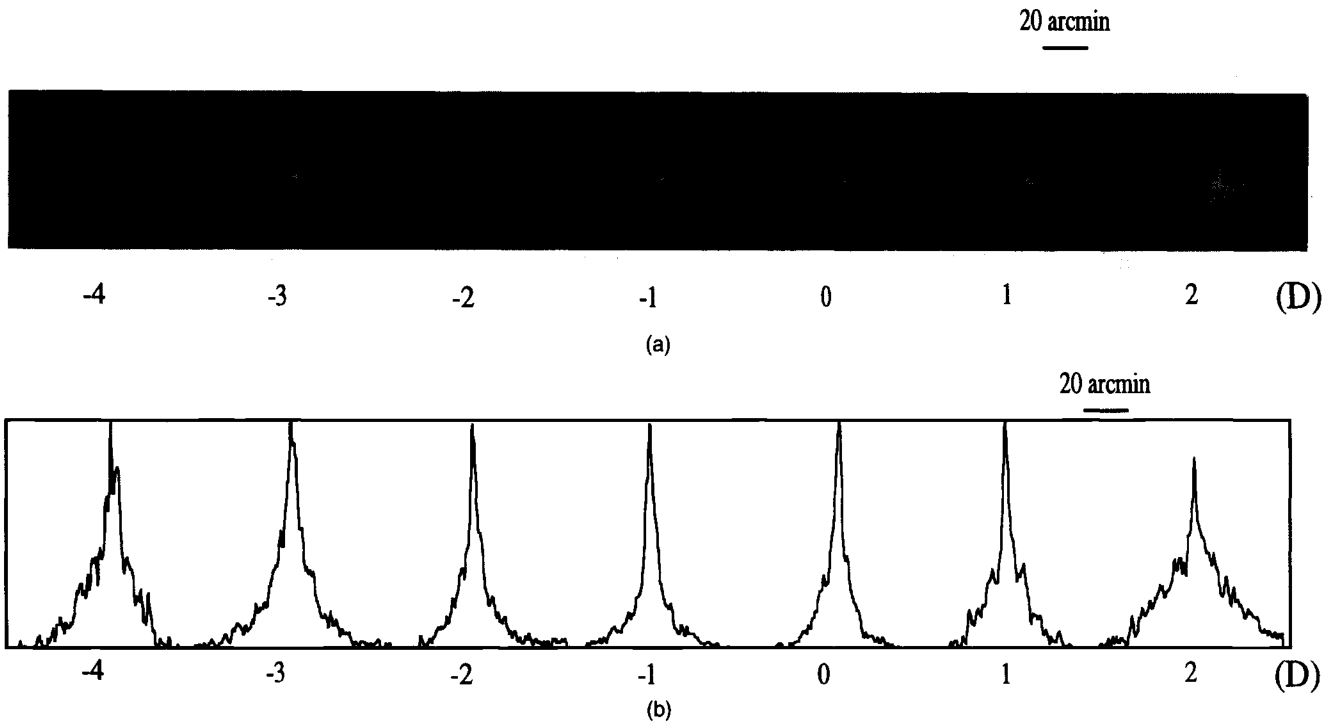

Fig. 4 (a) Aerial retinal images of a point test from −4 to 2 D of focus corresponding to an eye implanted with a multifocal IOL (patient MRG). (b) Horizontal sections (normalized to the same arbitrary value) of the aerial images of (a).

dashed line represents the modulation for a perfect (diffraction-limited) system, and the two stripes show the typical range of modulation for younger and older subjects.[15] The values of the modulation in the subjects of this study are for the best focus (best far focus in the multifocal IOLs) and they are represented by small squares. The two types of IOLs are surrounded by two ellipses. One interesting observation is that the overall image quality for the monofocal IOLs is dependent on astigmatism. The subject free of astigmatism presents a retinal image quality similar to normal young eyes. Eyes implanted with multifocal IOLs show lower values of the modulation with a smaller dispersion in the results.

The variation of image quality with focus as represented by these two parameters is also shown. Figure 7(a) shows the modulation as a function of focus for three eyes implanted with monofocal IOLs and Fig. 7(b) shows the modulation for two eyes implanted with multifocal IOLs and one eye with a monofocal IOLs as a reference. Figures 8(a) and 8(b) show how the other image quality parameter (volume under the aerial image) depends on focus for the same patients and conditions as in Fig 7.

When some residual astigmatism remains in the eyes implanted with monofocal lenses, the depth of focus (pseudoaccommodation) increases at the cost of the overall image quality. We can define the depth of focus as the range in which an overall image quality parameter is above half of value corresponding to the best focus. Under this assumption, the depth of focus in eyes implanted with monofocal eyes is around 2 D in astigmatism-free patients and around 3 D in patients with approximately 1 D of residual astigmatism. This is a well-known fact and it has been a typical clinical procedure to leave a small amount of astigmatism to increase the depth of focus. Using the same method to estimate depth of focus in eyes implanted with multifocal lenses, we found a value around 4 D, approximately double than in monofocal IOLs, but at the cost of a lower image quality. However, in absolute terms the range of focus where some eyes implanted with monofocal IOLs have an image quality larger than that of eyes with multifocal IOLs is approximately the same as the depth of focus in multifocal IOLs. [see Figs. 7(b) and 8(b).]

Figure 9 shows the results obtained in an optical bench (*in vitro*) in the same types of IOLs. The most interesting feature is that whereas in the case of eyes implanted with multifocal IOLs the values of the optical performance parameters remain practically constant in the pseudoaccommodation range, the lenses alone show two clearly defined peaks for near and far focus.

4 Discussion

The double-pass method has been proven to be a direct and easy-to-use technique to evaluate the retinal image quality in different clinical studies. In the particular case of IOL implantation, the use of the ocular MTF obtained from the double-pass method may be a better predictor of clinical success than visual acuity or contrast sensitivity tests. In addition, the use of this method in conjunction with bench measurements of the lenses would permit to improve the design of IOLs. In this paper, we show that this method can be applied on some routine basis to control the optical performance of eyes implanted with IOLs.

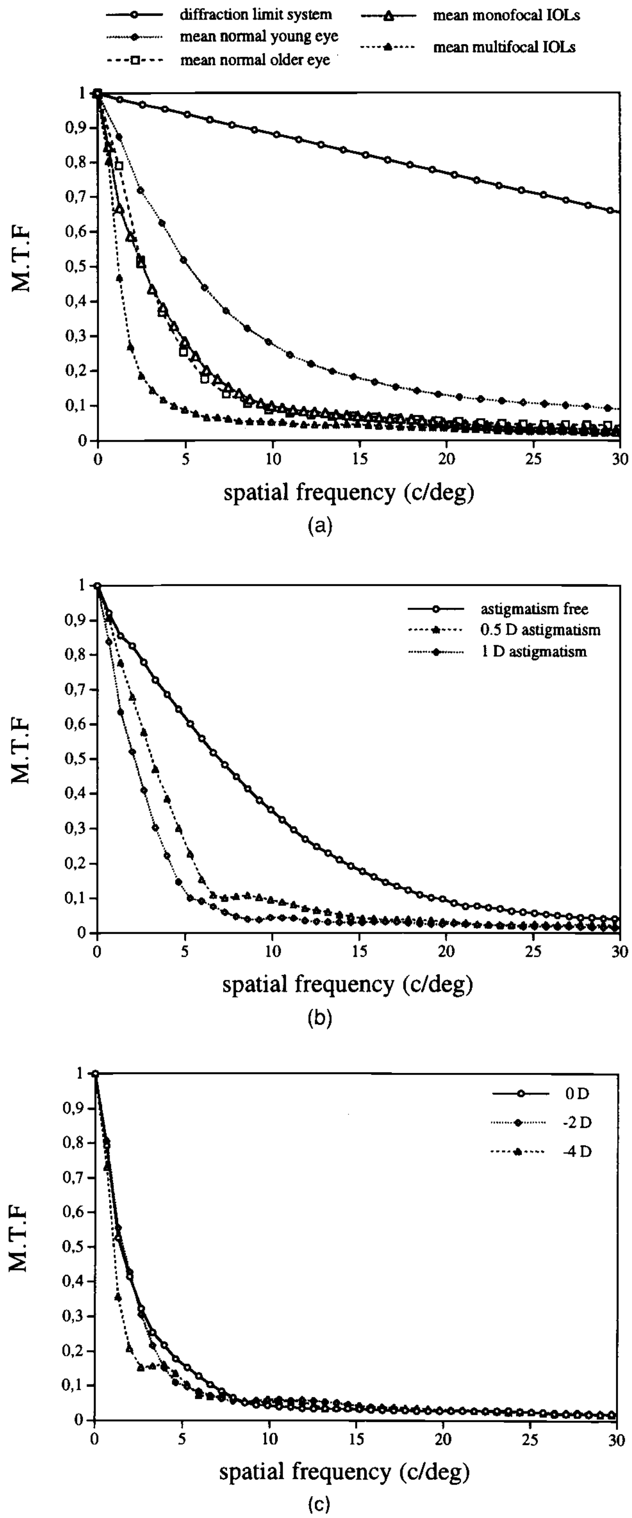

Fig. 5 (a) One-dimensional MTFs (radial profiles) for a diffraction limited system, mean normal young and older eyes (from Ref. 14), and mean monofocal and three types of multifocal IOLs (from Ref. 4). All these MTFs correspond to 4 mm of pupil diameter. (b) One-dimensional MTFs (radial profiles) for three eyes implanted with monofocal IOLs and different amounts of astigmatism (from 0 to 1 D) in the best state of focus and in the circle of least confusion in the cases with astigmatism. (c) One-dimensional MTFs (radial profiles) for an eye implanted with multifocal IOLs at different foci: 0, −2, and 4 D.

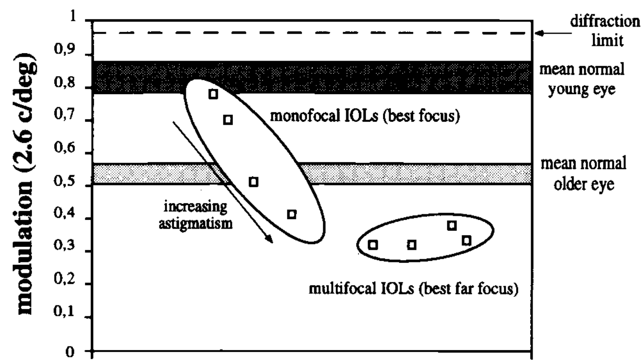

Fig. 6 Mean modulation in the retinal image for 2.6 c/deg. Dashed line represents the value corresponding to a 4-mm-diam pupil diffraction-limited system, shadow stripes are the range of values for normal young and older eyes, and squares correspond to the implanted eyes of this study.

The double-pass method offers several advantages over other methods to estimate the retinal image quality: it is an objective (optical) method, providing direct optical image quality results, and it is comfortable for the subject. However, some possible sources of error in measuring MTFs with the double-pass method should be noted; for example, the effect of the reflection of light from different retinal layers[13,17] and the effect of the field of view over which the aerial image is collected[18] on the MTF estimates. To validate the double-pass results, a series of experiments were performed. We recorded the retinal image of a test consisting of two points, one at the center of the fovea and the other at one degree of eccentricity.[13] Although the thickness of the retina is different at these two locations, the MTFs computed from both images were similar. These results suggest that the effect of the retinal reflection on the double-pass estimates of image quality remains relatively small in the fovea. In another experiment, the MTFs were measured both by the double-pass and psychophysical methods under the same conditions.[19] The results from the two techniques agree reasonably well, although the double-pass MTF is slightly lower for high spatial frequencies than the psychophysical MTF.

In addition, it has been recently shown[20] that the double-pass imaging configuration produces only even aerial images. In consequence, the double-pass method loses the phase of the optical transfer function, and odd aberrations, such as coma or distortion, can not be measured. It was also shown, however, that this loss of phase information does not influence the correct estimation of the ocular MTF, which is the most widely used function to estimate the eye's image quality. On the other hand, the amount of light reflected back from the IOL surfaces in implanted eyes is higher than in the lens. This results in a larger average value in the halo of the aerial retinal image. This problem is easily avoided by subtracting a constant value (the average value in the four corners of the image) to the averaged aerial retinal image prior to computing the MTF. The technique in its present form provides monochromatic image quality results. Under normal conditions, white light evaluation should be considered by including chromatic aberrations measurements both in optical bench and *in vivo*.

In what follows we summarize the main findings of this study. We confirm that the average image quality in the best

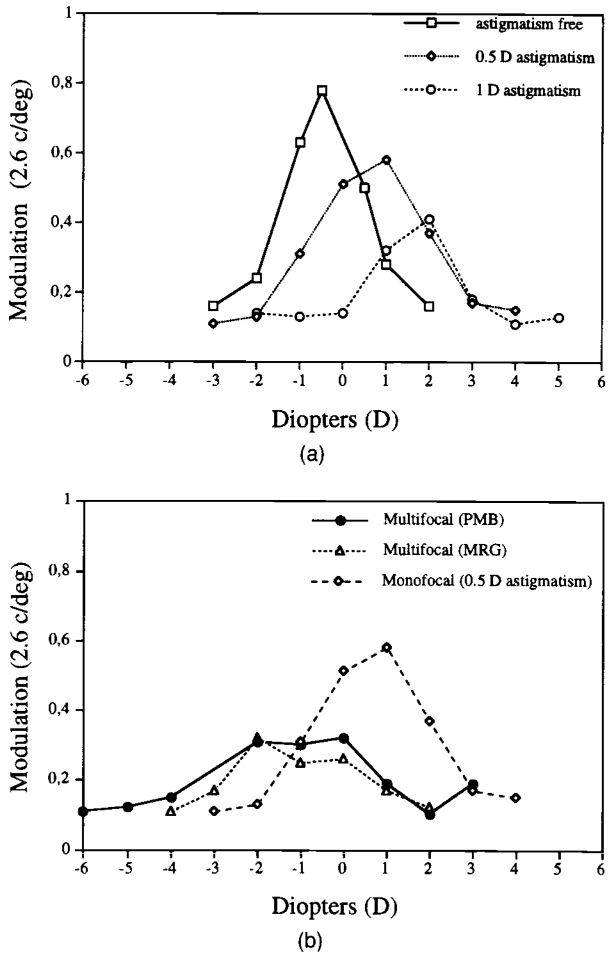

Fig. 7 Mean modulation in the retinal image for 2.6 c/deg as a function of focus. (a) The results correspond to three eyes implanted with monofocal IOLs with different amount of astigmatism. (b) The results correspond to two eyes implanted with multifocal IOLs and one eye with a monofocal IOL (square symbols).

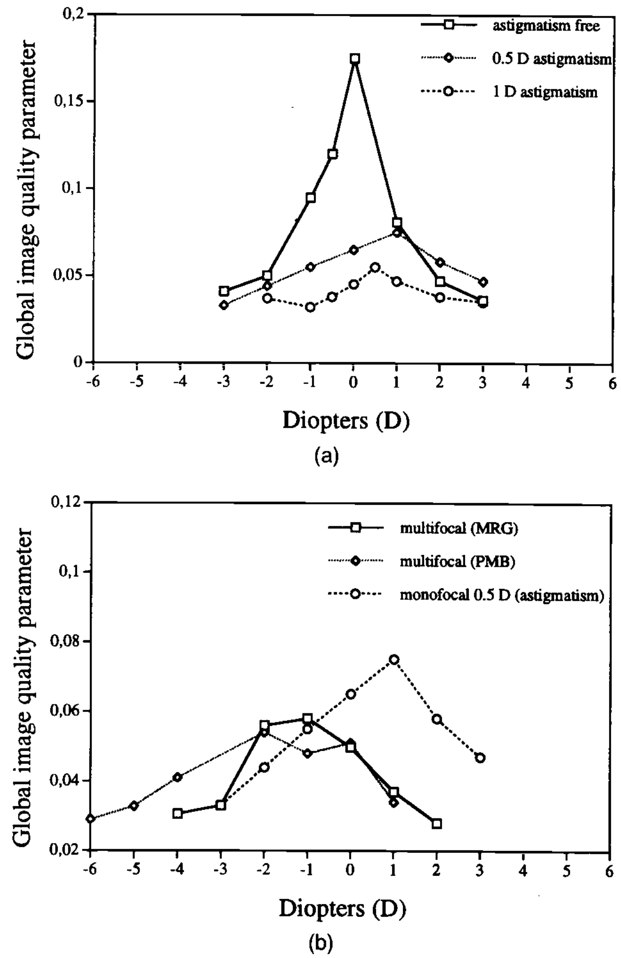

Fig. 8 Image quality parameter (computed as the volume under the aerial retinal images, more details in the text) as a function of focus. (a) Results for three eyes implanted with monofocal IOLs with different amount of astigmatism. (b) The results correspond to two eyes implanted with multifocal IOLs and one eye with a monofocal IOL (circles symbols).

focus is reduced from multifocal to monofocal IOLs. One interesting result is the large difference in retinal image quality among subjects implanted with the same kind of IOLs. If after IOL implantation, there is no amount of residual astigmatism, middle-aged patients (around 50 years old or younger) present a retinal image quality close to that obtained in normal young eyes. However, typically small amounts of astigmatism are present in eyes implanted with monofocal IOLs. This reduces the overall image quality but as a positive aspect increases the depth of focus. Slight tilt or decentering in the implanted IOLs can produce astigmatism, in addition to the possible patient corneal astigmatism.

The retinal image quality results in the case of multifocal IOLs are more homogeneous. On average, eyes implanted with monofocal IOLs have a modulation in the retinal image a factor of 2 larger than that in multifocals. On the other hand, the range of depth of focus in the multifocal IOLs is double that in astigmatism-free monofocal IOLs. However, the image quality in the monofocal IOLs with slight astigmatism is better than that of the multifocal IOLs in a range of defocusing of about 4 D, around the best focus. This means that the effective depth of focus should be approximately the

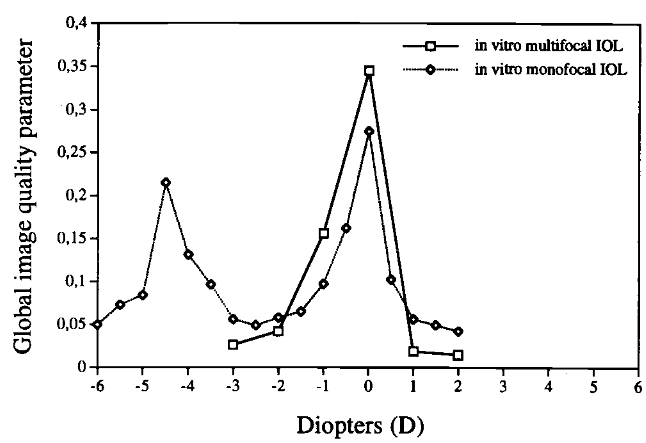

Fig. 9 Image quality parameter as a function of focus measured *in vitro* (optical bench) for one monofocal and one multifocal IOL.

same in eyes with multifocal IOLs and in some patients implanted with monofocal IOLs. Depth of focus depends on pupil size. The results presented in this paper correspond to a 4-mm pupil diameter. This is a typical pupil size for indoor situations common in normal conditions for reading. All the results of depth of focus will be different for smaller or larger pupil diameters.

Image quality results as a function of focus are qualitatively different when obtained *in vitro* and *in vivo* measurement. The implantation process and the effect of the eye's dioptrics reduce the final image quality in the eye in comparison with the intraocular lens. In the case of bifocals IOLs, *in vitro* measurements show clearly defined peaks for near and far focus, whereas in the implanted eye, there is a range with a similar image quality.

In conclusion, this paper demonstrates the usefulness of the double-pass method in assessing the image quality in eyes after implantation of IOLs in cataract surgery.

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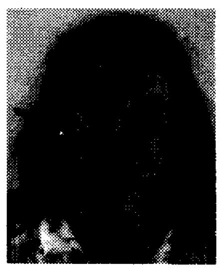

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