Modulation transfer function: Rigid versus foldable phakic intraocular lenses

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PURPOSE: To study in a standard eye model the changes in modulation transfer function (MTF) of a monofocal intraocular lens (IOL) when a phakic IOL (pIOL) is placed in the anterior chamber, compare the MTFs of the rigid Artisan pIOL and foldable Artiflex pIOL, and evaluate the temporal evolution of the MTF of the foldable pIOL after the mechanical stress the pIOL undergoes when injected.

SETTING: Fundación Oftalmológica del Mediterráneo, Valencia, Spain.

METHODS: The MTF values of the IOLs were calculated from the cross-line spread function recorded with the Opal Vector System. The measurements were taken using an eye model following the British and EN-ISO standards with 2.0 mm, 3.0 mm, 4.0 mm, and 5.0 mm pupils. A 28.00 diopter (D) Ophtec monofocal IOL was used as the crystalline lens. The 2 pIOLs were −9.00 D.

RESULTS: The MTF of the rigid pIOL was slightly better than the MTF of the foldable pIOL with all pupil sizes. Both pIOLs provided good optics quality when compared with the monofocal IOL. The injection effect of the foldable IOL disappeared after 2 hours.

CONCLUSIONS: The MTF of the monofocal IOL was slightly reduced with implantation of a negative pIOL in the anterior chamber. The rigid pIOL provided better optical performance than the foldable pIOL with all pupil sizes, as shown by the MTF values. The decrease in MTF caused by the mechanical stress on the foldable pIOL was nullified after 2 hours with no effect on optical quality.

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The use of phakic intraocular lenses (pIOLs) to correct high-power refractive problems, principally myopia, is increasing.[1–9] In general, there are 2 types of pIOLs —rigid and foldable. For implantation, the rigid poly(methyl methacrylate) (PMMA) pIOL requires a 6.2 mm posterior corneal incision. Because it is smaller when folded, the foldable silicone pIOL requires a smaller incision (3.2 mm).[10–12] The smaller incision induces less astigmatism than the rigid pIOL.[13] Beltrame et al.[14] found a mean surgically induced astigmatism (SIA) of 0.70 diopter (D) in 60 eyes with a 3.5 mm incision. Steinert et al.[15] report an SIA of approximately 1.00 D with 4.0 mm incisions. Moreover, the placement of the incisions is important. Barequet et al.[16] found that 3.5 mm temporal incisions yielded a mean SIA of 0.70 D and nasal incisions, of 1.50 D. Guirao et al.[17] report that temporal incisions induced less aberration effects than nasal incisions.

Coullet et al.[13] compared the visual results with an iris-supported rigid pIOL (Artisan, Ophtec) and a foldable pIOL (Artiflex, Ophtec). They found that although the results were similar, the visual capabilities were slightly better in eyes with the foldable pIOL. The authors suggest that this result is mainly explained by the low SIA with the foldable IOL. Nevertheless, in general, rigid PMMA pIOLs might have better optics quality than foldable silicone pIOLs. Moreover, the

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mechanical stress caused by the injection procedure in the fixation of the foldable IOL within the eye could influence the final quality of the optics.[18]

Modulation transfer function (MTF) measurements using an eye model have become the internationally accepted standard for evaluating the performance of the image quality of an IOL.[18–22] Variations in the MTF involve variations in the contrast of the image, which can affect visual performance.[20] Nevertheless, to our knowledge, there are no published data on the amount of decrease in MTF that would produce a significant reduction in visual acuity.

The MTF of IOLs can be obtained using the International Organization for Standardization (ISO) standards[23–25] and an artificial eye. In this way, the optics quality of the IOL can be ascertained and it is possible to compare the optics quality between 2 IOLs.

The MTF of monofocal IOLs is well known. In general, monofocal IOLs give good image quality with all pupil sizes,[19,20] and this depends on the level of illumination. In this study, we used a monofocal IOL as a crystalline lens in an eye model and placed a pIOL between the cornea and crystalline lens to measure the MTF with different pupil diameters. We had 3 goals in this study. The first was to ascertain how much the MTF decreased when a second IOL, in this case a pIOL, was implanted. The second was to compare a rigid pIOL and foldable pIOL. The third was to assess the possible influence of mechanical stress on optics quality by measuring the MTF of a foldable pIOL before the injection procedure and at different intervals after injection. This information on optics quality, together with SIA values, can help explain the visual results obtained with the 2 pIOLs in patients.

MATERIALS AND METHODS

Intraocular Lenses

The Artisan (referred to here as the rigid pIOL) is a single-piece pIOL of Perspex CQ-UV, an ultraviolet light–blocking PMMA. The pIOL is designed for implantation in the anterior chamber of a phakic eye for the correction of high myopia between −5.00 D and −20.00 D. The lens has a 6.0 mm convex–concave optic that is incorporated into an 8.5 elliptically shaped lens design. The pIOL has a slight anterior vault to provide adequate space for aqueous flow and avoid iris chaffing. The Artiflex pIOL (referred to as the foldable IOL) is based on the Artisan iris-claw principle. It has a silicone optic and PMMA haptics. Because of its foldable optic, the IOL is suitable for small-incision surgery. The power of the 2 pIOLs used in this study was −9.00 D. The monofocal IOL used as the crystalline lens in the eye model was a 28.00 D Ophtec.

Modulation Transfer Function Measurement

The MTF was calculated from the cross line-spread function recorded with the Opal Vector System (Image Science Ltd.) using fast Fourier transform techniques.[20] The artificial eye model simulated in vivo conditions of the anterior chamber, including an artificial cornea and a wet cell containing physiological solution where the IOL was positioned, following the setup required by ISO 11979-2.[23] The apparatus and other details of this technique have been described.[20]

First, only the monofocal IOL was placed in the wet cell and its MTF measured. Continuing with the measurements, a pIOL (rigid or foldable) was situated 2.0 mm behind the cornea and 1.5 mm in front of the monofocal (crystalline) lens, thus determining the MTF. The light source was confined to 546.0 nm in the vector system. The detector type used the Reticon K series silicon linear photodiode array, which is 12.8 mm long with 512 pixels. The best focus position was determined by measuring the variation in the MTF with focus at a spatial frequency of 20.0 c/mm. The MTF values were formed with an average of 16 array scans. The MTF measurements conformed to the requirements of the ISO[23,24] except for the effective aperture because the pupil diameters analyzed varied from 2.0 to 5.0 mm in steps of 1.0 mm. For comparison of the MTFs of the pIOLs by pupil size, the foldable pIOL was not folded; rather it was measured under the same conditions as the rigid pIOL.

To make the comparison between the pIOLs easier, each MTF was summarized by the average modulation value. The average modulation is the modulation averaged for all frequencies from 0.0 to 100.0 c/mm. The average modulation is then proportional to the area under the MTF between 0.0 c/mm and 120.0 c/mm, which is an optical quality parameter similar to the one used by other authors.[26]

To determine the evolution of average modulation over time, injection of the foldable pIOL into the eye was simulated using the same instrument used to fold the pIOL. The evolution would indicate the effect of mechanical stress on optics quality and how long the pIOL requires to reach its original optics quality. The MTF was measured 1 minute and 5 minutes after the simulated injection and then at intervals of 5 minutes until 30 minutes elapsed. The next measurement was 45 minutes after the simulated injection, which was followed by intervals of 15 minutes until 90 minutes. Then, measurements were performed at 30-minute intervals until 210 minutes had elapsed. All these MTF values were obtained with a 3.0 mm pupil.

RESULTS

Figure 1 shows the MTFs of the rigid pIOL and flexible pIOL with small pupils (2.0 mm and 3.0 mm), which can be similar to photopic conditions in many individuals, and Figure 2, with large pupils (4.0 mm and 5.0 mm), which can generally correspond to lower photopic or mesopic conditions of illumination.

Figure 3 shows the mean modulation as a function of the pupil diameter.

Figure 4 shows the Strehl ratio versus pupil diameter for the 2 pIOLs and the monofocal IOL.

Figure 5 shows the variation in the MTF of the foldable pIOL with time. The effect of the mechanical stress was apparent for a few minutes after injection but decreased quickly. The MTF curve tended, over time, to revert to the shape of the MTF measured before the injection.

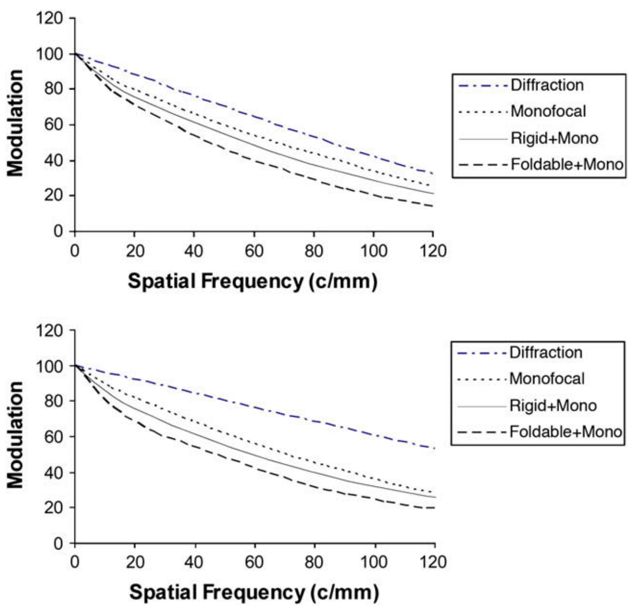

Figure 1. The MTF curves measured with small pupils. *Top*: 2.0 mm pupil. *Bottom*: 3.0 mm pupil (Diffraction = theoretical result for a perfect system with each pupil; Foldable+Mono = MTF when foldable pIOL Artisan placed between cornea and monofocal IOL; Monofocal = MTF with only monofocal IOL in model eye; Rigid +Mono = MTF when rigid pIOL Artisan placed between cornea and monofocal IOL).

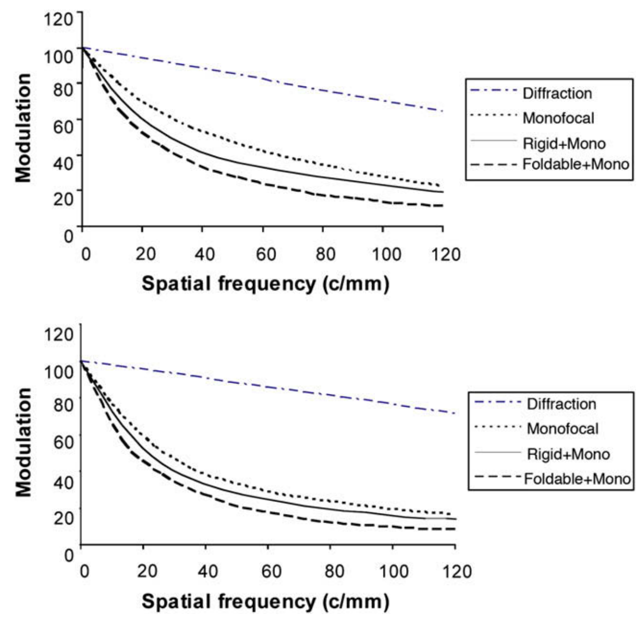

Figure 2. The MTF curves measured with large pupils. *Top*: 4.0 mm pupil. *Bottom*: 5.0 mm pupil (Diffraction = theoretical result for a perfect system with each pupil; Foldable+Mono = MTF when foldable pIOL Artisan placed between cornea and monofocal IOL; Monofocal = MTF with only monofocal IOL in model eye; Rigid +Mono = MTF when rigid pIOL Artisan placed between cornea and monofocal IOL).

Figure 6 shows the evolution of average modulation in time. As in the previous cases, the other optical surfaces remained unaltered; thus, the variations in the MTF were due to the foldable pIOL only.

DISCUSSION

The MTF provides information about the band of frequencies that passes through the system (limited by the cutoff frequency) and also about how the optical system reduces modulation of different frequencies in its pass-band. Thus, by knowing the MTF of an IOL implanted in the eye, we can determine the optics quality of the optical system, which is a first step in analyzing the quality of vision.[26] The curves in Figures 1 and 2 do not correspond to the MTF of the pIOL alone but rather to the monofocal IOL plus the pIOL; therefore, it is possible that the MTF of the pIOL and monofocal IOL together was better than the MTF of the monofocal IOL alone and the MTF of the pIOL alone. However, as the optical performance of the wet cell

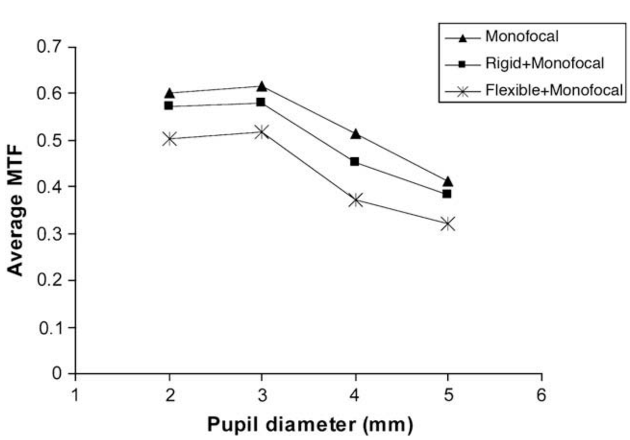

Figure 3. Average modulation values as a function of pupil size for the monofocal IOL, the rigid pIOL with the monofocal IOL, and the foldable pIOL with the monofocal IOL.

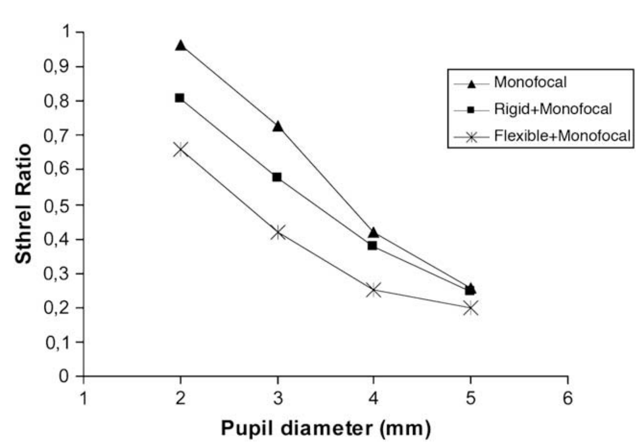

Figure 4. The Strehl ratio as a function of pupil size for the monofocal IOL, the rigid pIOL with the monofocal IOL, and the foldable pIOL with the monofocal IOL.

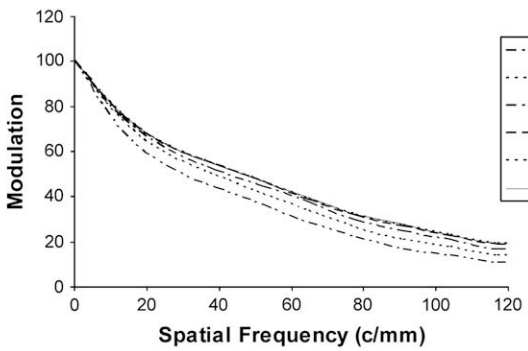

Figure 5. The MTF of the foldable pIOL measured with a 3.0 mm pupil at different times after being folded.

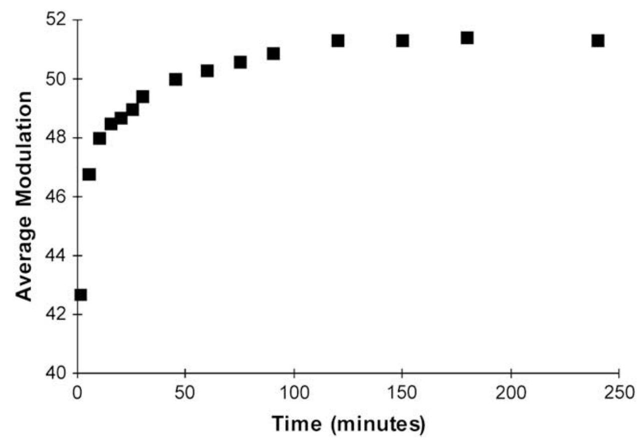

Figure 6. Average modulation values of the foldable pIOL over time with a 3.0 mm pupil, showing the performance of the pIOL when it is folded for injection.

with the monofocal IOL was close to the diffraction limit for small pupils (2.0 to 3.0 mm), we expected the MTF of the pIOL to be similar to that obtained when in conjunction with the monofocal IOL.

The optics quality of the monofocal IOL was good with small pupils (low aberration effect), seen by its curve being close to the diffraction curve (Figures 1 and 2). The optics quality decreased with large pupils (high aberration effect), as shown in previous studies.[19,20] However, to introduce a new pIOL, rather rigid or foldable, into the system means having another filter, which ideally would maintain the MTF or, more commonly, reduce the MTF significantly and thus the optics quality of the system. Both the rigid pIOL and foldable pIOL reduced the MTF of the monofocal system; however, the reduction appeared to be slight. This reduction can be explained by the optical quality of the pIOLs as well as the reduction in the diffraction limit cutoff frequency due to the increase in the focal length of the monofocal IOL and pIOL together.[27] Also, the optics quality was better with the rigid pIOL than with the foldable pIOL, considering that the foldable pIOL was not folded for this comparison. The difference was probably due to the different design, different material, or both of the pIOLs.

The variation in optics quality (given by the average modulation value) with pupil size showed that the best image quality was obtained with a 3.0 mm pupil. This is easily explained because very small pupils produce wide diffraction (low cutoff frequency) and large pupils produce more aberration effects.[28] The rigid pIOL reduced the monofocal average modulation with all pupil sizes by approximately 5%; the exception was with the 4.0 mm pupil, when the reduction was 10%. Similarly, the foldable pIOL reduced the monofocal average modulation with all pupil sizes by approximately 16%, with the reduction increasing up to 24% with 4.0 mm pupils. The absolute differences in average modulation between the rigid pIOL and the foldable pIOL were similar with all pupil sizes. The aberration effect occurred with all IOL setups; the Strehl ratio was very similar (a poor value) for the 3 IOLs with the 5.0 mm pupil because of the great aberration effect. However, the difference in the Strehl ratio values increased as pupil size decreased, with the monofocal IOL being almost perfect at 2.0 mm. The better optics quality of the rigid pIOL is shown in Figure 3.

A question arises when the pupil of the eye becomes larger than the pIOL or IOL diameter (6.0 mm); that is, what happens to the MTF and therefore the image quality? In this case, the effective pupil would be the pIOL, which is the diaphragm limiting the entrance of the light beam into the optics system; nevertheless, light passes around the pIOL (although the light does not pass through the system) which goes toward the focus of the cornea and reaches the retina, as shown in Figure 7. Thus, an object point, at infinite distance from the cornea, produces on the retina the point

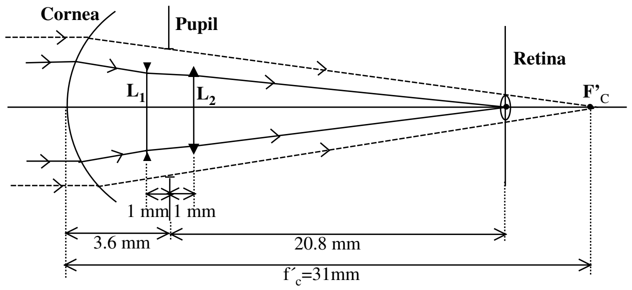

Figure 7. The pupil does not limit the beam that performs the image point in the retina when its diameter exceeds the diameter of the IOLs. The beam from a distant object point (*solid line*) is shown passing through the eye optics system. The pupil only limits the halo around the image point (*dashed line*) (F'_C = focus of cornea; f'_C = corneal focal length).

imaged by the optics system, and moreover a defocused point that performs as a halo of light around the image point. The MTF in this case would be worse than that obtained with a 5.0 mm pupil because aberrations increase with the diameter of the pupil. Moreover, the presence of the halo around each image point would affect the image quality, reducing the contrast of the image; in other words, the modulation is still more attenuated.

With regard to the quality of optics of the foldable pIOL after it is folded for injection, the MTF decreased at first but tended to revert over time to the MTF before folding. After 2 hours (120 minutes), the average modulation (as well as the MTF) almost reached an asymptotic value. After 30 minutes, the IOL had recovered most of its quality. Rawer et al.[18] studied the effect of injectors used in the implantation of different IOLs in the posterior chamber. They found that mechanical stress affected the optics quality of the IOL but that the effect disappeared by about 40 minutes. Our result with the foldable pIOL is similar to that of Rawer et al., but with a longer recovery time, perhaps because of the different IOL material.

The reduction in MTF produced by the addition of the rigid or foldable pIOL would likely not affect the patient's visual performance. The pIOL inserted avoids the use of negative lenses, thus producing a large benefit in magnification. Clinical measurements in patients are necessary to determine the magnitude of change in optical quality that would be reflected by a change in visual performance.

In conclusion, both the rigid pIOL and the foldable pIOL slightly decreased the MTF in the model eye but provided good optics quality. Loss of optics quality with the foldable pIOL due to the injection procedure recovered almost fully in 30 to 50 minutes and recovered fully in 2 hours.

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