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RESEARCH NOTE

Double-pass measurements of retinal image quality in monofocal contact lens wearers

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Summary

The double-pass method is applied to determine the optical image quality in monofocal contact lens (CL) wearers. This is an objective non-invasive technique that permits *in vivo* testing of the optical performance of CL wearers' eyes. Retinal image quality was measured for three subjects wearing two types of monofocal CLs: a rigid gas permeable (RGP) CL and a soft contact lens (SL), for pupil diameters of 3 mm and 5 mm.

Results show the importance of ocular astigmatism regarding retinal image quality. In eyes presenting corneal astigmatism, the best results are obtained when wearing RGP CLs, because the lens compensates the corneal astigmatism. The modulation transfer function (MTF) is considerably smaller when no lens or soft lenses are worn, even for small amounts of astigmatism (0.5 D).

When the astigmatism is corrected, the retinal image quality obtained with both types of CLs and with no lens is similar. © 1997 The College of Optometrists. Published by Elsevier Science Ltd.

Introduction

Contact lenses (CLs) are a widely used method for correcting refraction problems (Gasson and Morris, 1993). Nowadays basically two kinds of monofocal contact lenses are used: rigid gas permeable (RGP) CL or soft contact lens (SL).

The type and design of CL used can influence the wearer's quality of vision, as the lens modifies the overall optical characteristics of the visual system and the total amount of astigmatism. In clinics, the amount of astigmatism when wearing CLs is called residual astigmatism.

Several kinds of studies on the optical performance of different types of CLs have been performed: optical bench testing, ray tracing and clinical studies on visual performance in subjects with CLs (Collins *et al.*, 1989; Guillon and Schock, 1991; Young *et al.*, 1990; Charman and Walsh, 1986). Clinical studies are based on visual acuity measurements and especially the Contrast Sensitivity Function (CSF), which is nowadays a commonly accepted way to measure spatial vision.

The image quality of CLs measured outside the eye by optical bench testing or ray-tracing is difficult to extrapolate to the situation in the eye. Clinical tests can be affected by non-optical problems in the subjects' visual system (i.e. retinal and neural phenomena affecting the CSF cannot be separated from optical ones). All these factors contribute to create a need for direct optical measurements of

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retinal image quality in CL wearers' eyes to obtain a complete evaluation of the optical performance of the contact lens-eye system.

In this study we applied the double-pass technique to determine the Modulation Transfer Function (MTF) of the CL wearer's eye. The MTF, which measures how contrast is transmitted from the object to the image, is probably the most appropriate criterion for assessing optical image quality. The double-pass method is an objective optical non-invasive technique that makes it possible to obtain the MTF of the CL-eye system and therefore to test *in vivo* the optical performance of CL wearers' eyes.

Methods

The double-pass method is based on imaging an object onto the retina; a fraction of the light is reflected back and the external retinal image (aerial image) is used to estimate the point spread function and the ocular MTF.

The double-pass technique has in most cases been used for basic research in vision. However, it shows interesting possibilities for applications in ophthalmology, optometry and the CL field. Recently, studies on the eye's relative image quality as a function of age (Artal *et al.*, 1993), across the visual field (Navarro *et al.*, 1993a) and the measurement of the ocular MTF in subjects implanted with intraocular lenses (Navarro *et al.*, 1993b; Artal *et al.*, 1995a) or CL wearers (Pujol *et al.*, 1996) have been developed.

Apparatus

The experimental system used in this study has been described in detail elsewhere (Pujol *et al.*, 1996). It is based on the one developed by Artal, Navarro *et al.* (Santamaria *et al.*, 1987; Artal and Navarro, 1992), and is depicted in *Figure 1*. It consist of two parts: the first one, recording the aerial image O of the point object O after a double-pass through the optical media of the eye, and the second one, a digital process which includes averaging short-exposure images and computation of the square root of the Fourier transform to obtain the MTF.

The exposures had a duration of about 100 msecond. The maximum laser energy in the pupil plane for a 5 mm pupil diameter that we measured in our expositions is approximately 0.025 mJ/cm^2. This is the worst case, because this level is lower when the pupil diameter is smaller, and is about 1/150 of the maximum level allowed by the safety standards (Sliney and Wolbarsht, 1980).

The pupil size is monitored and controlled with an IR camera that takes an image of the iris, which is displayed on a TV monitor with a calibrated reticle attached. With this procedure we can measure the pupil diameter with a precision better than 0.1 mm. Changes in pupil diameter can be obtained by varying the intensity of a light illuminating the contralateral eye.

Experimental procedure

The short-exposure aerial retinal images recorded are averaged on the computer to remove speckle (coherent noise). We averaged 32 images, by taking four series of eight exposures each. This number avoids excessive discomfort to the subject and allows one to obtain a good signal-to-noise ratio (Santamaria *et al.*, 1987). All the images are 256 × 256 pixels 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 aerial images. After this subtraction, aerial images typically contain a dim, nearly uniform, remaining background that is removed by substrating the average value in the four corners of the image. The MTF is computed by the square root of the Fourier transform of the aerial image.

The measurements were performed with 3 mm and 5 mm artificial pupils projected on the natural subject's pupil, which is kept in both cases larger than the artificial pupil. The subject's head was stabilized by a chinrest, which is mounted on a positioner, used to align the centre of the artificial pupil to the centre of the subject's natural pupil. The subject's pupil is carefully centred by the experimenter throughout the obtainment of aerial images in the experiment, to avoid the influence of misalignments in the optical performance of the eye (Walsh and Charman, 1988; Artal *et al.*, 1996).

Images were obtained in optimum spherical correction reached by moving the lens L_{T1} (see *Figure 1*) of the Thorner optometer, (Le Grand and El Hage, 1980) and with or without ocular astigmatism correction. The point source O was used as a fixation target. As the subjects considered presented central fixation, the MTFs obtained correspond to the centre of the fovea. During the experiment the centring of the CL was controlled by looking at the horizontal and vertical distance between the iris edge and the CL edge on the TV monitor where the iris image was visualized.

Measurements were obtained for three subjects with different refractive conditions (ATG, JGP, MRG) (*Table 1*). Subjects were not usually CL wearers. They showed a corrected visual acuity of at least 6/6 and were free of ocular pathology.

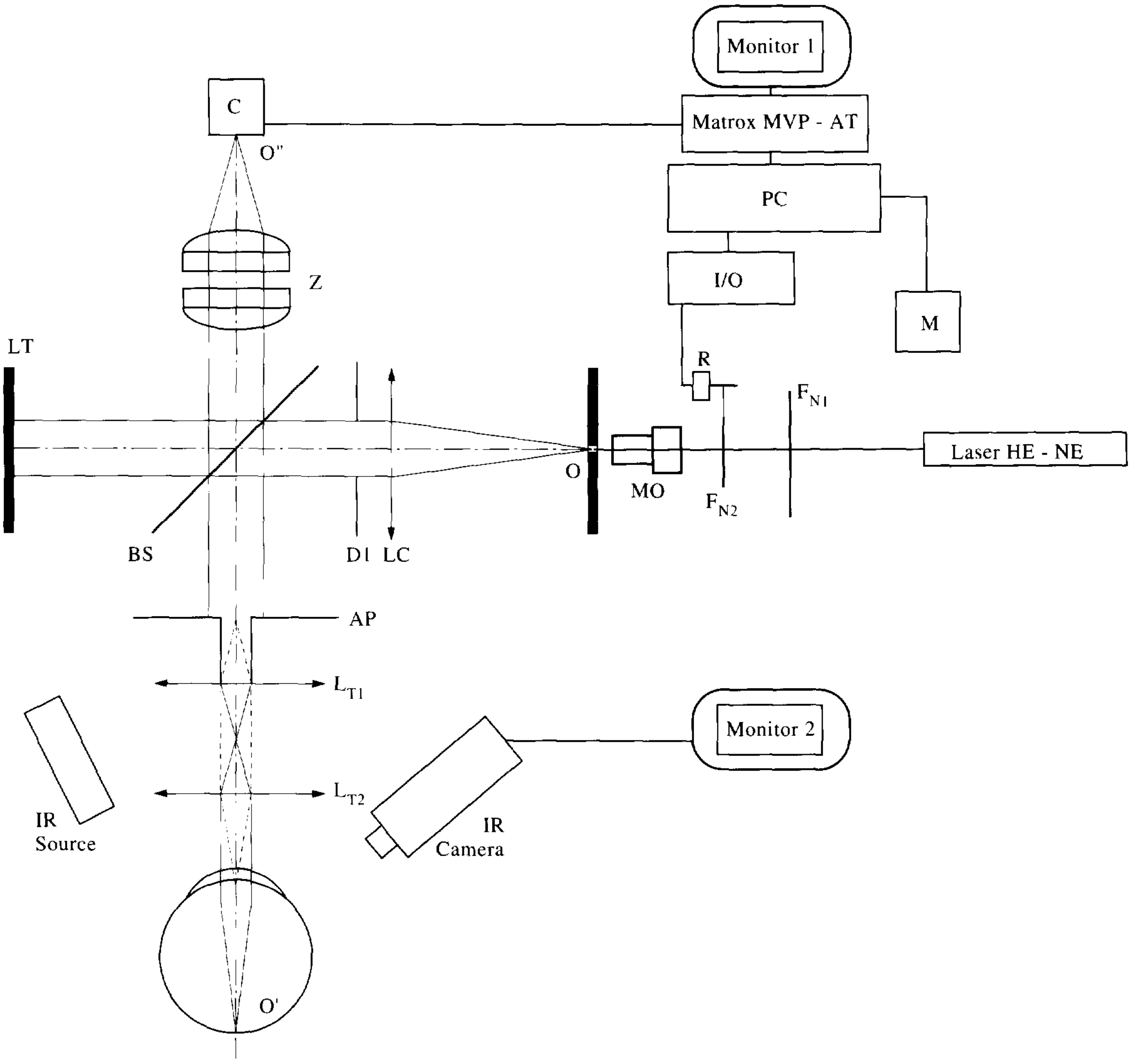


Figure 1. Experimental double-pass system used to record and process the retinal images of a point test. the He–Ne laser is the light source. F_{N1} and F_{N2} are neutral density filters; MO is a microscope objective and P is a pinhole; L_c is a collimator lens; L_{T1} and L_{T2} are the Thorner's optometer lenses; BS is a pellicle beam splitter; LT is a light trap; AP is an artificial pupil and Z a zoom lens. O′ is the retinal image of the point O, and O″ is the double-pass aerial image of O formed on a CCD camera (C). M is a mouse and R a rotary solenoid to move in and out of the beam the neutral filter F_{N2}. An IR source, a camera and a TV display constitute a system to control the pupil size.

Types of contact lenses

Two different types of monofocal CLs were studied: a rigid gas permeable CL and a soft CL.

Table 1. Reflective errors of the three subjects that took part in the experiment.

Subject	*Refractive error*
JGP	−2.50−1.00 × 5°
ATG	−3.00−0.50 × 90°
MRG	+1,00 D

Rigid gas permeable CL (BOSTON RXD) is made of fluorosilicone acrylate with an oxygen permeability (DK) of 45×10^{-11} (cm^2/seg) (ml O_2 × mm Hg) at 35 °C, a density of 1.27 and a refraction index of 1.435. The one used in the experiment had a total diameter of 9.60 mm and an optic zone diameter of 8.20 mm.

The soft CL (ALPHA 46) is made of homopolymer of hydroxyethyl methacrylate with a water content of 45.7%, an oxygen permeability (DK) of 17×10^{-11} (cm^2/seg) (ml O_2 × mm Hg) at 35 °C, a density of 1.14, a refraction index of 1.4225 to 1.4330, a total diameter of 14 mm and an optic zone diameter of 8 mm.

Because of their characteristics, these lenses were considered to be good samples to represent the variety of monofocal lenses fitted nowadays.

Results

Figure 2 shows aerial retinal images for the subject JGP corresponding to compensation with different CL types and for the two pupil diameters considered: 3 mm and 5 mm. These results are presented as grey-level images (series (a) and (c)) and their horizontal sections (series (b) and (d)). All the images and sections are normalized in intensity to the same value to permit a direct comparison. These figures give a clear qualitative picture of how retinal image changes with pupil diameter and with the monofocal CLs used to correct the ametropia.

The images, corresponding to 3 mm pupil diameter (a), are smaller and more concentrated than the images, corresponding to 5 mm pupil diameter (c). Therefore, horizontal sections of the aerial images corresponding to 3 mm (b) are smaller than those corresponding to 5 mm (d). These results show the well-known effect of decreasing retinal image quality as the pupil diameter increases (Campbell and Gubrisch, 1966; Artal and Navarro, 1994).

Subject JGP shows a clinically significant amount of astigmatism in his left eye (test eye) −2.50–1.00 × 180°. We can clearly appreciate the influence of astigmatism on the aerial retinal image quality. The total amount of corneal astigmatism is corrected by the RGP lens, and consequently the image is better (i.e. smaller and more concentrated) than the rest. We shall consider that the RGP lens substitutes the first corneal surface, commonly the origin of ocular astigmatism, for a perfectly spherical surface. The images for the no lens and the soft lens wearing eye do not show any large differences because the soft lens does not correct the total amount of corneal astigmatism.

For the other subjects the results are similar as a function of their refractive conditions. Subject ATG displays a refraction of −3.00–0.50 × 90° in the analysed eye. The aerial image when the RGP lens is worn is slightly better than the SL or no lens image. The effect can be attributed to the correction, with the RGP lens, of the small amount of astigmatism exhibited by the subject. Subject MRG shows a low grade hyperopia and no astigmatism. In this case aerial retinal images without a lens, with soft and with RGP lenses are similar.

Ocular astigmatism is an important factor that affects retinal image quality. *Figure 3* shows three-dimensional plots corresponding to the intensity distribution of the aerial images of JGP (3 mm pupillary diameter) on an arbitrary linear scale for different types of CL correction and with or without corrected astigmatism. The intensities of each image have been normalized to the same value, so that all the peaks have the same height. The x,y-axes are quantified by an arc min. scale to obtain information on the aerial image extension. From the figures, it is obvious again that the influence of the astigmatism correction is absolutely definitive on the retinal image quality. The plots for the RGP lens wearing eye are exactly the same because no additional correction of astigmatism was required for this kind of lens. The figure shows a fairly good distribution of the energy with a high, thin single peak that indicates a high amount of energy concentrated at the central point. SLs only correct a small fraction of the total amount of astigmatism, and therefore when the SL is worn a certain amount of residual astigmatism exists. When this residual astigmatism is not corrected, the aerial image spreads out and shows several small peaks around the principal one indicating a wider distribution of the energy around the central point. For the no lens case obviously a difference also exists between non-corrected and corrected astigmatism, as in the soft lens case, the aerial image corresponding to corrected astigmatism showing a thinner peak.

Computing the MTF from the averaged aerial retinal images as explained above enables quantitative measurements to be obtained. Radial profiles of the ocular MTF obtained by averaging the 2-D MTFs over all orientations corresponding to subject JGP are shown in *Figure 4*. These MTF results correspond to the different situations studied: when no CL is worn, RGP lens and SL are worn and without corrected astigmatism, for 3 mm pupil diameter (*Figure 4*a) and 5 mm pupil diameter (*Figure 4*b). In all cases the MTF corresponds to optimum spherical correction obtained by moving the Thorner's optometer lens L_{T1} (see *Figure 1*). The two graphs are plotted on the same scale of spatial frequency to allow a comparison of the results. For the two pupil diameters the influence of the CL type is similar. The MTF for the SL wearing eye is slightly better than for the no lens wearing eye due to the small fraction of corneal astigmatism corrected by the SL. However, the differences are far greater for RGP lens. In this case the MTF is better for all the spatial frequencies, due to correction of the corneal astigmatism by these lens.

For subjects with astigmatism, aerial retinal images can show either of the two possible typical shapes: elongated in one direction, when the retina is close to one of the two Sturm foci, or circular when the retina is close to the least confusion circle. For elongated

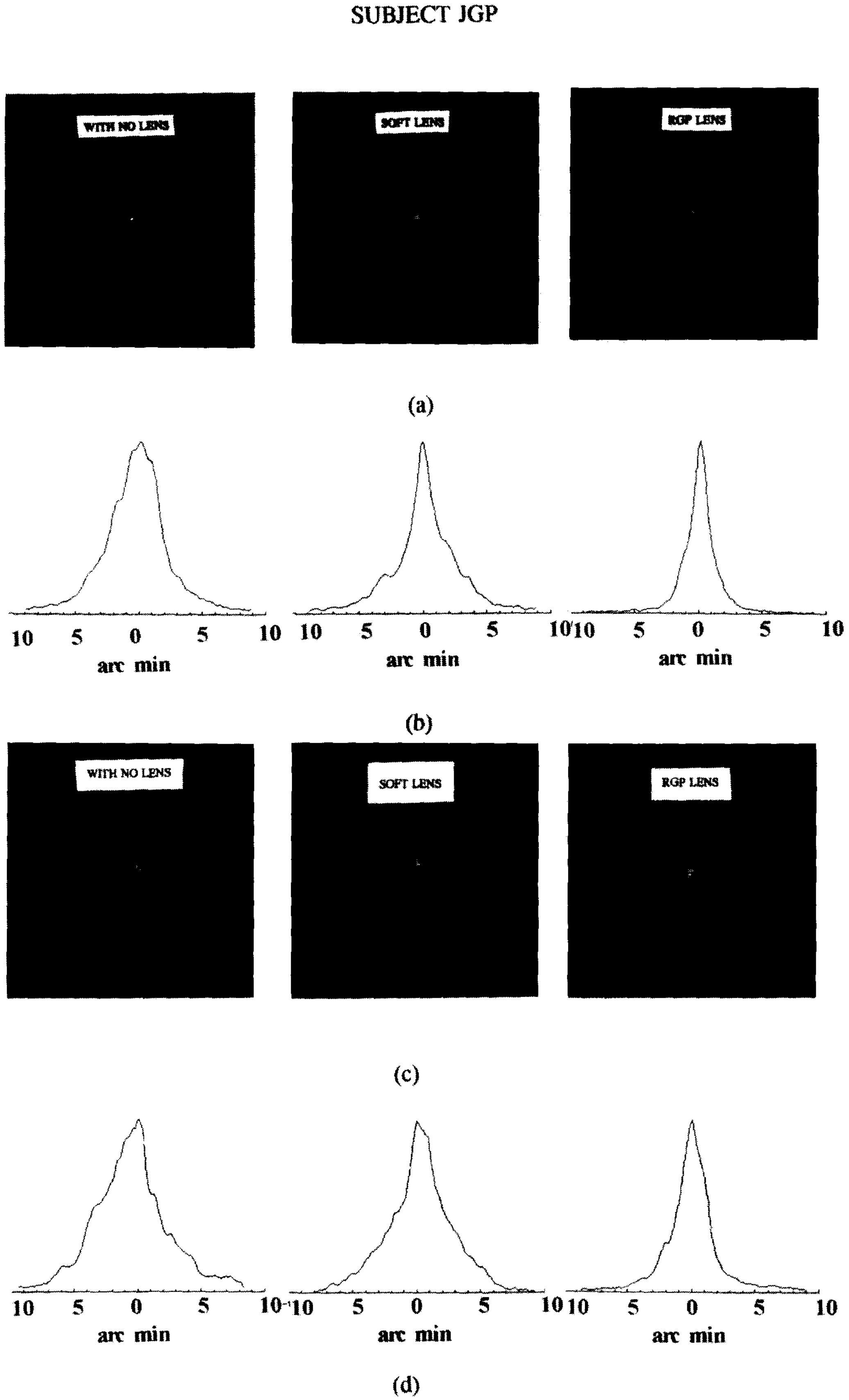
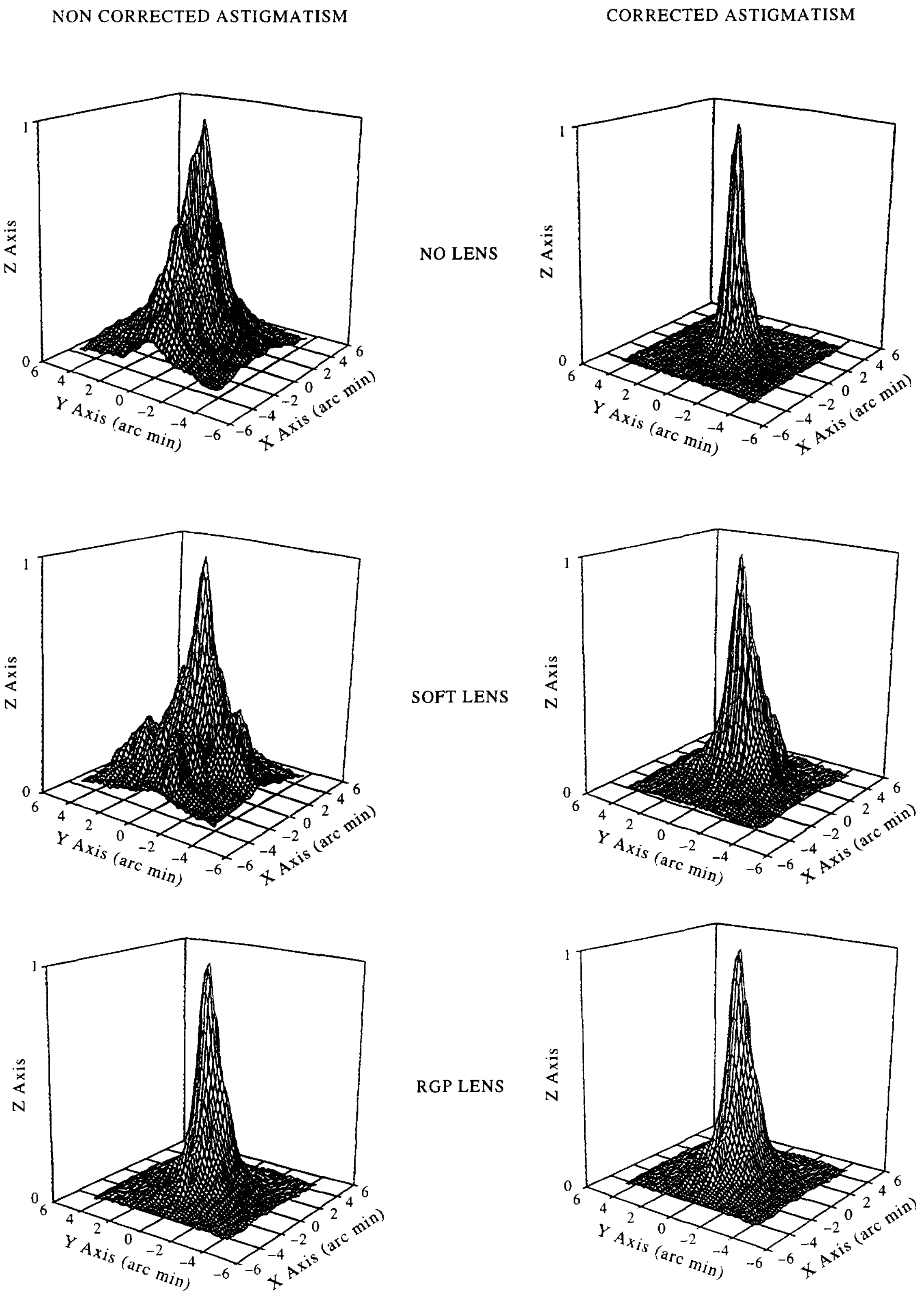


Figure 2. Aerial images of a point test and horizontal sections (normalized to the same arbitrary value) of the aerial images for the subject JGP. (a) and (c) Aerial images for 3 mm and 5 mm pupil diameter. (b) and (d) Horizontal sections for 3 mm and 5 mm pupil diameter.



NON CORRECTED ASTIGMATISM

CORRECTED ASTIGMATISM

NO LENS

SOFT LENS

RGP LENS

Figure 3. Three dimensional plots of the intensity distribution of aerial images for JGP a pupil diameter of 3 mm, astigmatism corrected and non-corrected.

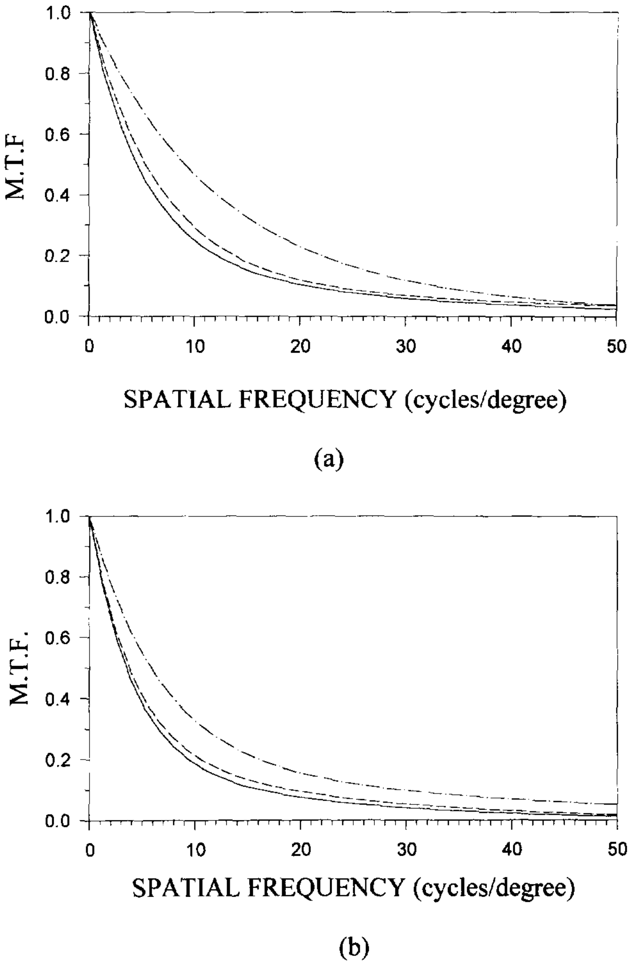


Figure 4. Radial profiles of the two-dimensional MTF corresponding to the subject JGP when no contact lens (solid curves), soft contact lens (SL) (dashed curves) or rigid gas permeable lens (RGP) (pointed and dashed curves) is worn, without compensating the astigmatism. (a) Pupil diameter 3 mm. (b) Pupil diameter 5 mm.

shapes, it is possible to obtain an MTF profile for the maximum and for the minimum elongation of the aerial image. This profiles represent an upper-bound and a lower-bound to the radial profile (Navarro *et al.*, 1993a). To estimate the retinal image quality we have considered radial profiles of the MTF, because in our study stimuli was viewed with natural accommodation and we have obtained a haphazard sampling of images with different refractive states across the Sturm interval and the apparence of the aerial images suggest that in most cases the mean refractive state is close to the circle of least confusion.

As for the other subjects considered, MRG does not show astigmatism and therefore the MTFs obtained are similar when no CL is worn and SL or RGP lenses are worn. ATG displays a small amount of astigmatism (0.5 D) and the MTF is slightly better when a CL is worn than when no lens is worn, but the variation is smaller than for the case of JGP.

To analyse the influence of monofocal CLs on the retinal image quality, independently of the influence of astigmatism, we represent the MTFs with corrected astigmatism for the three subjects considered with no lens, RGP lens and SL. *Figure 5* shows the curves corresponding to a 3 mm pupil diameter and *Figure 6* those corresponding to a 5 mm pupil diameter. In these cases all the MTFs are similar. This can be explained by the fact that the most important contribution of the CL to the retinal image quality lies in the compensation of the corneal astigmatism, and therefore when the astigmatism is compensated, the MTFs without lens or with RGP or SL show small differences.

The differences in the retinal image quality when RGP or SL are worn can be evaluated by analysing the subtraction of the MTFs obtained with these two types of lenses. In *Figure 7*, these subtractions are shown for the three subjects considered, with a pupillary diameter of 3 mm (*Figure* 7a) and 5 mm (*Figure* 7b). We can appreciate that the difference

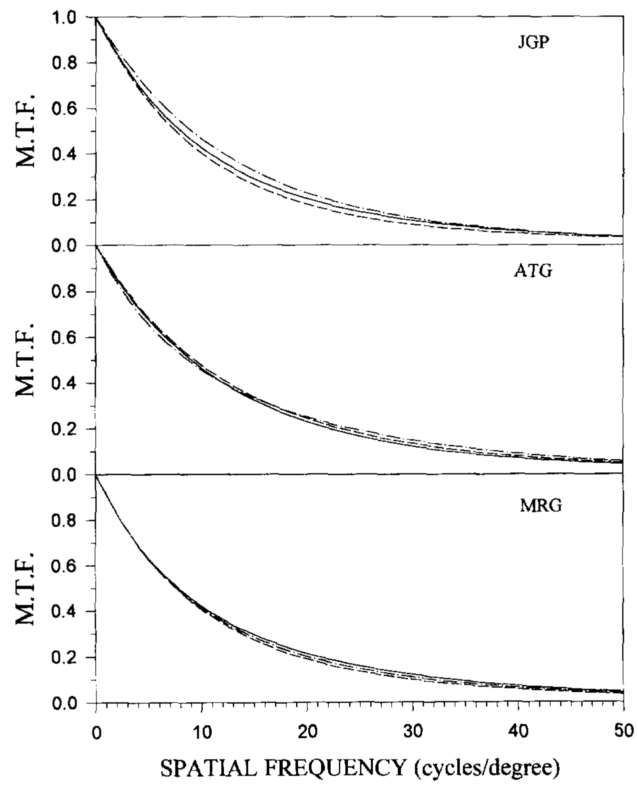


Figure 5. Comparison of the MTF obtained for a 3 mm pupil diameter with rigid gas permeable contact lens (RGP) (pointed and dashed curves), soft contact lens (SL) (dashed curves) and without contact lens (solid curves) when the astigmatism is corrected. The results correspond to the three subjects considered.

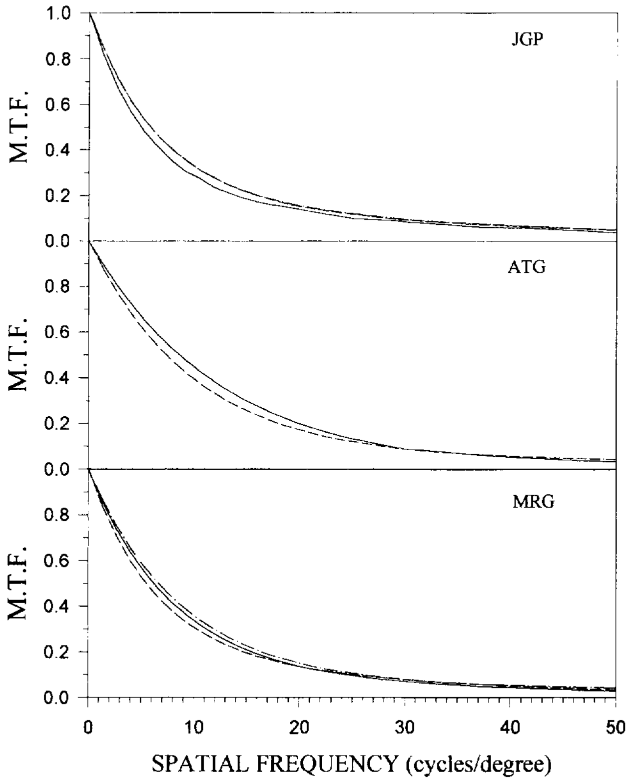


Figure 6. Comparison of the MTF obtained for a 5 mm pupil diameter with rigid gas permeable contact lens (RGP) (solid and dashed curves), soft contact lens (SL) (dashed curves) and without contact lens (solid curves) when the astigmatism is corrected. The results correspond to the three subjects considered.

between the two MTFs is greater when the eye is not corrected of astigmatism (upper plots) than when the astigmatism is corrected (lower plots). When the astigmatism is not corrected the difference always possesses a positive sign. Therefore, when residual astigmatism exists, RGP lenses provide better retinal image quality than SLs. When the residual astigmatism is compensated the situation changes: the differences between the MTF obtained with RGPs and SLs are lower and although generally of positive sign we can appreciate a negative difference for the subject ATG for 3 mm pupil diameter and spatial frequencies lower than 25 cycles/degree.

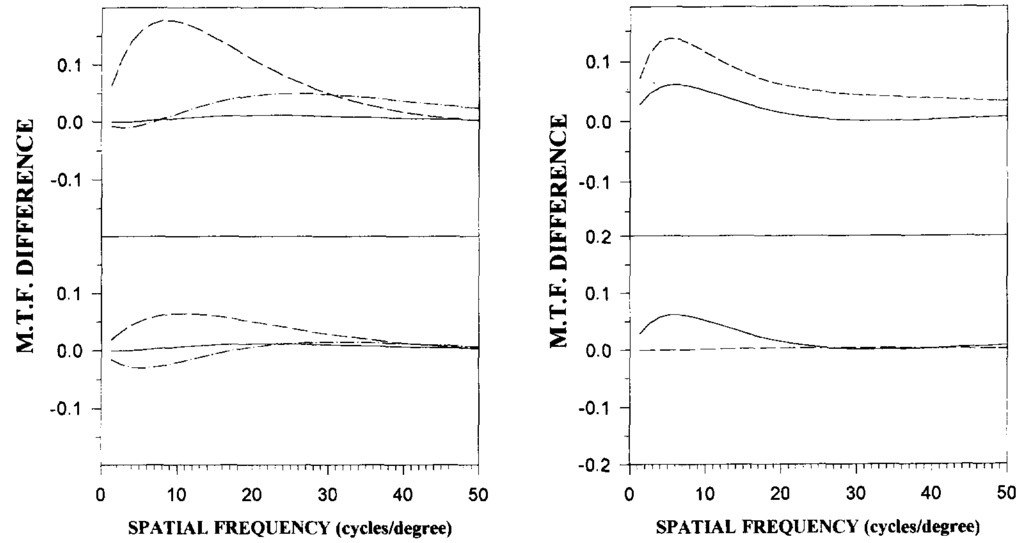
Discussion

The double-pass method has been shown to be a useful technique for evaluating optical performance in various situations (Artal and Navarro, 1992; Artal *et al.*, 1993; Navarro *et al.*, 1993a,b). In the particular case of CL wearing, double-pass measurements may provide more complete information related to the optical quality of the CL-eye system than other parameters normally used, such as visual acuity or the CSF. In addition, this method could be used to control the quality of new designs of CLs.

The double-pass method offers several advantages over other methods for estimating the retinal image quality: it is an objective (optical) non-invasive method, providing direct optical image quality results, and it is comfortable for the subject. In effect, with an adapted routine, recording only a sufficient number of images to obtain a good signal-to-noise ratio, the duration of the measurement diminishes, increasing the comfort of the subject. In recent years several experiments have been performed to validate the double-pass results (Artal and Navarro, 1992; Artal *et al.*, 1995b) and to determine the influence on the results of several factors such as reflection of light from different retinal layers (Artal and Navarro, 1992; Gorrand, 1989) or the field of view from which the aerial image is collected (Simon and Denieul, 1973). The results obtained show a small influence of these factors on the fovea. Also, the MTF measured by double-pass and psychophysical methods under the same conditions have been compared (Williams *et al.*, 1994). The results obtained agree reasonably well, although the double-pass MTF is slightly lower for high spatial frequencies than the psychophysical MTF.

When the double-pass method is used to measure the optical quality of CL wearing eyes, other factors such as the CL centring and light reflection on the CL surface could potentially affect our measurements. In this study, light reflection on the CL has no affect because we did not observe any light artifacts that can be attributed to these reflections. During the experiment the centration of the CL is controlled by looking at the horizontal and vertical distance between the iris edge and the CL edge on the TV monitor where the iris image is displayed.

The results show the importance of ocular astigmatism on both the aerial retinal image quality and the MTF of the eye. When the eye is astigmatism free, the aerial images obtained in the best focus condition without contact lens or with RGP or SL are similar. When the eye shows some amount of astigmatism the best retinal image quality is obtained when wearing an RGP CL, because this lens compensates the corneal astigmatism. When a SL is worn the eye can display a certain amount of residual astigmatism due to adaptation of lens shape to the corneal surface. Even for small amounts of astigmatism (0.5 D, subject ATG) appreciable differences can be obtained, but when the astigmatism is greater (1 D, subject JGP) the difference becomes more noticable. Those variations are translated to the MTF, where clear differences can also be appreciated for the subject JGP. In further studies, it could be of interest to evaluate to what extent these



(a) (b)

Figure 7. Subtraction of the MFTs obtained with rigid lens and soft lens for the three subjects considered: MRG (solid curves), JGP (dashed curves) and ATG (pointed and dashed curves). The upper plots correspond to the non-corrected astigmatism case and the lower plots correspond to the corrected astigmatism case for 3 mm pupil diameter (a) and 5 mm pupil diameter (b).

variations in the MTF correlate with variations in the Contrast Sensitivity Function (i.e. a psychophysical measurement).

In order to compare the retinal image quality wearing soft and RGP lenses, the subtraction of the MTFs obtained has been made. When the astigmatism is not corrected the difference is always positive, which demonstrates that the MTF when wearing the RGP lens is higher. The greatest differences can be found in spatial frequencies lower than 20 cycles/degree. As the astigmatism is corrected the differences are smaller, or even negative in some cases.

We made measurements for 3 and 5 mm pupil diameter. The results show that the MTF decreases when the pupil diameter increases (Campbell and Gubrisch, 1966; Artal and Navarro, 1994). Comparing the results obtained as a function of the astigmatism compensation, the differences for 5 mm pupil diameter are smaller. This effect could be due to the increase in ocular aberrations as the pupil diameter increases.

In conclusion, we have determined the retinal image quality of monofocal CLs wearers using the double-pass technique. The results obtained show that for observers presenting astigmatism, the retinal image quality is substantially better when wearing an RGP lens than a soft one. This phenomenon is explained by the corneal astigmatism compensation with the two types of CLs. When the astigmatism is compensated with ophthalmic lenses or the observer does not display ocular astigmatism, the MTFs obtained with the two types of CLs are very similar.

In the near future we shall apply this technique to multifocal (aspheric, diffractive, concentric, etc) CL wearers.

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