Ophthal. Physiol. Opt. 2002 **22:** 221–233

Image quality in wearers of a centre distance concentric design bifocal contact lens

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Abstract

The optical performance of eyes wearing bifocal concentric contact lens was studied using the double-pass technique. Retinal image quality was measured for four subjects wearing CIBA Bisoft contact lenses presenting the central zone for correcting distance vision. Lenses with two different central optic zone diameter (COZD), 3.2 and 3.8 mm, were studied and the influence of pupil diameter and viewing distance were analysed. Results show that the best optical performance is obtained for far vision conditions when no lens is worn even if the pupil coverage by the COZD is complete. For near vision conditions, the optical performance when the lens is worn is, in general, better than when no lens is worn. When the lens is worn the best optical performance corresponds to a pupil diameter of 3 mm and far vision conditions. For this pupil diameter, variations in the situations analysed can be explained by changes in the percentage of pupil coverage corresponding to the far or the near vision zone of the lens. For a pupil diameter of 5 mm, the retinal image quality is more similar in all situations studied and pupil coverage alone cannot explain the results obtained and the influence of other parameters related to the design or contact lens fitting characteristics must be considered.

Keywords: contact lenses, double-pass technique, image quality, optometry, physiological optics.

Introduction

Using multifocal lenses is a possible strategy for correcting presbyopia with contact lenses. Nowadays several types of multifocal contact lens designs are available: bifocal concentric contact lenses (BCCLs), with their front surface divided into two or more concentric zones with different spherical shapes, diffractive contact lenses and varifocal contact lenses based on refractive aspherical surfaces (Gasson and Morris, 1993).

When designing the BCCL, if it presents only two optic zones two possibilities exist: centre distance (CD) design, i.e. a central zone for correcting distance vision and a peripheral annular zone for correcting near vision or centre near (CN) design, i.e. a central zone for correcting near vision and a peripheral zone for correcting distance vision. The BCCLs are based upon the simultaneous vision principle. The two corrective zones are simultaneously maintained in front of the pupil and therefore both optic zones simultaneously focus light onto the retina. The subject attends to the clear image of interest but the other optic zone produces a superimposed out-of-focus image. The optical and visual performance when BCCLs are worn mainly depends on four factors: lens design (CN or CD), central optic zone diameter (COZD), pupil diameter and decentration (Woods *et al*., 1993a, b, 1994).

Several studies on the optical and visual performance of BCCL have been performed. The investigation of optical performance of BCCL is based on geometrical considerations (Borish, 1988; Erickson *et al*., 1988), ray-tracing techniques (Wesley, 1971; Charman and Walsh, 1986; Charman and Saunders, 1990) or optical bench testing (Young *et al*., 1990; Woods *et al*., 1993a, c). The results obtained show a marked diminution when an out of focus image exists that changes with pupil size. Measures of the modulation transfer function (MTF) of the lenses in order to establish the influence of COZD,

Received: 19 February 2001
Revised form: 17 October 2001
Accepted: 19 December 2001

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lens design, pupil diameter and lens decentration have been reported (Young *et al*., 1990; Woods *et al*., 1993a, c). The measured MTFs of bifocal contact lenses have been shown to be similar to the theoretically calculated MTFs, and the shape of the MTF appears to vary with lens design and spatial frequency, but typically it can only be half the value of an optimally corrected single vision contact lens.

Visual performance has been evaluated in terms of contrast sensitivity function, high- and low-contrast visual acuity and stereopsis (Lowther, 1982; Erickson and Robboy, 1985; McGill *et al.* 1987; Back *et al*., 1989; Collins *et al*., 1989; Jones and Lowther, 1989; Sheedy *et al*., 1991; Back *et al*., 1992; Woods *et al*., 1993b). Most of these studies compared the visual performance of BCCL with monovision, aspheric multifocal lenses, distance contact lenses combined with reading spectacles, or spectacles. Normally the simultaneous vision contact lenses reduced all the visual functions tested. But in some conditions, such as under low illumination, contrast sensitivity and visual acuity can be similar for simultaneous vision bifocal contact lenses and monovision.

With concentric design bifocal contact lens centred over the pupil, the optimum COZD (equal distance and near optical performance) is near to 40% of the pupil area for pupil diameters from 3 to 6 mm (Woods *et al*., 1993a). Previous reports indicated 50% (Erickson *et al*., 1988).

The effect of altering the COZD, as can be expected (Erickson and Robboy, 1985; Jones and Lowther, 1989; Woods *et al*., 1993b), improves visual performance for the relevant viewing distance as the COZD increases. Normally, CN are preferred to CD, because visual performance should be better, especially in near vision conditions because of the convergence-related pupil constriction. Decentration of the contact lenses causes major changes in optical performance that are only partly explained by changes in the proportion of the aperture covered by the central optic zone.

In general, there is good agreement between the optical and visual performance when a BCCL is worn. Taking into account optical measurements visual performance has been predicted (Woods *et al*., 1994). Recently (Chateau and Baude, 1997) a model of presbyopic eye in various viewing conditions was derived as a combination of average clinical findings with a non-aberrated monochromatic eye model. The use of theoretical calculation may allow a preliminary selection of designs but cannot completely replace optical and clinical measurements.

At the moment, no direct optical measurements of the retinal image quality in BCCL wearers' eyes are reported. There are only few papers related to monofocal contact lenses wearing eye (Lorente *et al*., 1997; Torrents *et al*., 1997). In this study, we have obtained *in vivo* objective measurements of the optical quality of the BCCL-eye system applying the double-pass technique. These measurements allow us to know and analyse the retinal image quality for far vision and near vision conditions and to compare the image quality obtained with and without BCCL. We also studied the influence of pupil diameter in the optical quality of the BCCL-eye system and therefore the influence of illumination on the quality of vision when BCCLs are worn. Finally, by comparing the results obtained for two different COZD lenses we can analyse the influence of COZD on the retinal image quality.

Experimental methods

Experimental procedure

The experimental system used has been described in detail elsewhere (Pujol *et al*., 1996). It is based on the double-pass system for measuring the ocular MTF developed by Artal *et al.* (Santamaria *et al*., 1987; Artal and Navarro, 1992) and is depicted in *Figure 1*.

To measure the optical MTF, we recorded series of eight small duration exposures (about 100 ms), of a monochromatic red point (He–Ne laser, $\lambda = 632.8$ nm) after double passage through the eye. In order to remove

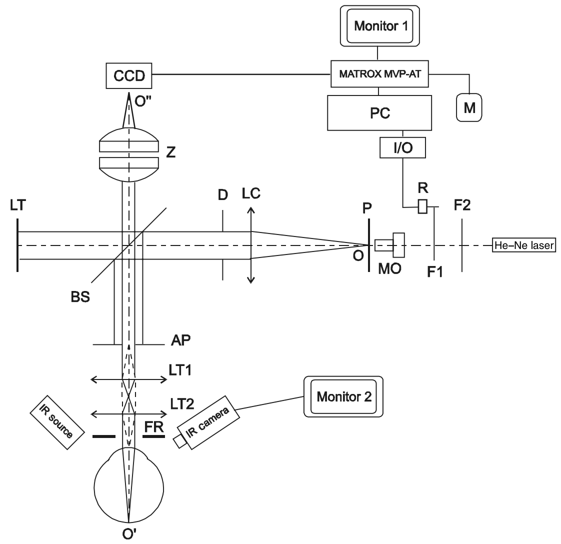

Figure 1. Experimental double-pass system used to record and process the retinal images of a point test. The He–Ne laser is the light source. F1and F2 are neutral density filters; MO is a microscope objective and P is a pinhole; LC is a collimator lens; LT1 and LT2 are the Thorner's Optometer lenses; FR is a frame to place lenses to correct the astigmatism of the subject; BS is a pellicle beam splitter; LT is a light trap; AP is an artificial pupil and Z a zoom lenses. O' is the retinal image of the point O, and O'' is the double-pass aerial image of O formed on a CCD camera. M is a mouse and R a rotary solenoid to move the neutral filter F1 in and out of the beam. An IR source, a camera and a TV display constitute a system to control the pupil size.

the speckle we averaged 16 images, taking two series of eight exposures each. We obtained the ocular MTF for two subjects (JPR and JGP) in different conditions, and averaging 32 or 16 images, the MTF here practically the same. Moreover, 16 images have been used in most clinical studies (Artal *et al.*, 1995; Navarro *et al.*, 1993). A background image, obtained by placing a black diffuser in the pupil plane instead of the eye, is subtracted from aerial images. The MTF is computed by the square root of the Fourier transform of the aerial image.

The maximum laser energy in the pupil plane that we measured in our exposures is of the order of 0.025 mJ cm^{-2}, corresponding to the worst case, when the pupil diameter is high. This energy level falls as the pupil diameter decreases. These exposure values are clearly below the limits allowed by safety standards (ANSI, 2000).

Types of contact lens and subjects

In this study, we used soft BCCLs (Bisoft, CIBA Vision) with a total diameter of 13.8 mm, refractive power according to the subjects refraction (*Table 1*) and an addition of + 2D, presented in a CD design. We studied lenses with two different values of COZD: 3.8 and 3.2 mm.

Measurements were obtained for four subjects: two women (ATG, ECG) aged 28 and 37 years and two men (JPR, JGP) aged 37 and 25 years. Subjects presented different refractive conditions (*Table 1*) and were not habitual contact lens wearers. They showed a corrected visual acuity of at least 6/6 and were free of ocular pathology.

Experimental conditions

To analyse the influence of pupil diameter, distance of observation and COZD in the retinal image quality in concentric bifocal contact lens wearers, we performed measurements with pupil diameters of 3 and 5 mm, in far vision and near vision conditions and with the two COZD considered: 3.8 and 3.2 mm.

Pupil diameter values were obtained with artificial pupils projected on the dilated natural pupil. The subject's head was stabilised by a chin-rest, which is mounted on a positioner, used to align the centre of the artificial pupil to the centre of the subject's natural pupil. Carefully centring the subject avoids the influence of misalignments in the optical performance of the eye (Walsh and Charman, 1988; Artal *et al.*, 1996).

Table 1. Refractive error of the four subjects that took part in the experiment

Subject	Refractive error
JGP	−2.50/−1.00 × 5
ATG	−3.00/−0.50 × 90
ECG	+0.50
JPR	+0.75

Images were obtained in far vision and near vision conditions in foveal vision, using the point source O (*Figure 1*) as a fixation target. To avoid its influence the accommodation was paralysed and the pupil was dilated by instilling two drops of tropicamide 1% in the subjects' eye, with a 5-min interval between drops and 15 min before taking measurements. It is commonly known (O'Connor Davies, 1989) that other drugs, such as cyclopentalate (1%) paralyse the accommodation more effectively, but create more discomfort to the subject because of their longer effect. For one subject (JPR) we obtained aerial images under the same experimental conditions using two drops of tropicamide (1%) or two drops of cyclopentalate (1%) to paralyse the accommodation and no difference was found with the two types of drugs.

Far vision conditions were obtained by moving the lens LT1 of the Thorner Optometer (Le Grand and El Hage, 1980) (*Figure 1*) until the best retinal image O'of the point O for a 3-mm artificial pupil diameter was obtained. In this case, light passes only through the long distance optic zone. The point O is imaged by the Thorner Optometer in the eye far point. When the 5 mm artificial pupil diameter is used the position of the LT1 lens is not changed.

To obtain near vision conditions we used an annular aperture (AP, *Figure 1*) with a 5-mm external diameter and a 4-mm internal diameter. In this case, light passes only through the near distance optic zone and when the best retinal image O' of the point O is obtained this point is imaged by the Thorner Optometer in the near vision far point. When the 3-mm artificial pupil diameter is used the position of the LT1 lens is not changed.

With these procedures to obtain far vision and near vision conditions the measurements were performed in the best focus condition. Another possibility to achieve near vision conditions could have been to shift the object vergence 2D from the far vision conditions (2D is the nominal addition of the lenses used in this study). Actually, during the experimental process very small differences were detected between both methods when the near vision point was asserted. However, only shifting the object vergence 2D, a small defocus could exist in the retinal image and therefore the MTFs obtained would be slightly reduced as compared with those obtained under the best focus condition.

Optimum fitting of the contact lens was checked by observing the eye with a slit-lamp. Movement was observed and centration was measured for each subject using a calibrated grid three times an hour on three different days. Results obtained were very similar in each observation and the mean and standard deviations values of the decentration are displayed in *Table 2*.

When no lens is worn the spherical refractive error of the eye is corrected by the Thorner Optometer and astigmatism is corrected by means of a toric ophthalmic lens placed in a frame (FR, *Figure 1*). When the contact lenses are worn, small amounts of residual astigmatism are also corrected by means of a toric ophthalmic lens. Correcting the residual astigmatism is important because small amounts of astigmatism can make the retinal image quality drop, as we have reported in a previous study (Torrents *et al*., 1997).

A complete session of measurements was carried out, recording aerial images of the eye without the contact lens. After the contact lens was placed on the eye and before starting measurements, we waited for half an hour to achieve a correct fitting of the lens. Two series of eight aerial images were recorded for a pupil diameter of 5 mm, and two more for a pupil diameter of 3 mm in far vision conditions. Finally, images for the two pupil diameters under near vision conditions were obtained. A complete session of measurements took about 2 h.

For the two lenses analysed (COZD = 3.8 mm and COZD = 3.2 mm) we carried out a minimum of two complete measurements in order to ensure the repeatability of the results.

Results

Pupil coverage

Optical and visual performance for different observation distances with simultaneous vision concentric bifocal contact lenses depends on the area of pupil occupied by the far or the near optic zone of the lens. For a fixed value of COZD, pupil coverage depends on contact lens decentration.

The values of decentration obtained for each subject are different for the two lenses analysed (*Table 2*). Horizontal decentration is, in general, greater than vertical decentration. For two subjects (JGP and ATG) decentration values are always smaller than 0.5 mm, but for the other two subjects (ECG and JPR) decentration values are greater than 0.5 mm, except for one case, and greater than 1 mm when ECG wears the lens presenting COZD = 3.8 mm and when JPR wears the lens presenting COZD = 3.2 mm.

The changes in pupil coverage by the central optic zone with decentration for both lenses analysed can be obtained using a simple geometrical model and are shown in *Figure 2* (COZD = 3.2 mm) and *Figure 3* (COZD = 3.8 mm). The pupil coverage corresponding to the measured values of decentration for the subjects that took part in this experiment are also shown.

Retinal image quality

Figure 4 shows aerial images for the subject ECG corresponding to far vision and near vision conditions, for the two pupil diameters considered (3 and 5 mm) and for the lens with COZD = 3.2 mm. These results are

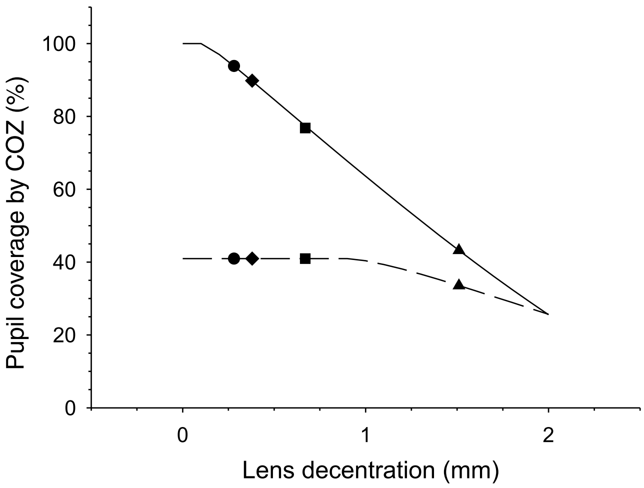

Figure 2. The proportion of pupil coverage by the central optic zone for the lens presenting COZD = 3.2 mm for a pupil diameter of 3 mm (solid curve) and 5 mm (dashed curve) as a function of lens decentration. The proportion corresponding to each subject according to the measured decentration values is also indicated with different symbols [JGP (◆), ATG (●), ECG (■), JPR (▲)].

Table 2. Mean and standard deviation values of horizontal and vertical decentration measured for the four subjects that took part in the experiment and for the two lenses analysed (COZD = 3.2 and 3.8 mm)

	Lens with COZD = 3.2 mm				**Lens with COZD = 3.8 mm**			
	Horizontal decentration (mm)		**Vertical decentration (mm)**		**Horizontal decentration (mm)**		**Vertical decentration (mm)**	
Subject	**Mean**	**S.D.**	**Mean**	**S.D.**	**Mean**	**S.D.**	**Mean**	**S.D.**
JGP	0.32	0.02	0.20	0.03	0.24	0.02	0.08	0.02
ATG	0.28	0.02	0.00	0.00	0.30	0.02	0.32	0.05
ECG	0.68	0.04	0.08	0.01	1.00	0.05	0.28	0.04
JPR	1.28	0.08	0.80	0.04	0.16	0.01	0.16	0.01

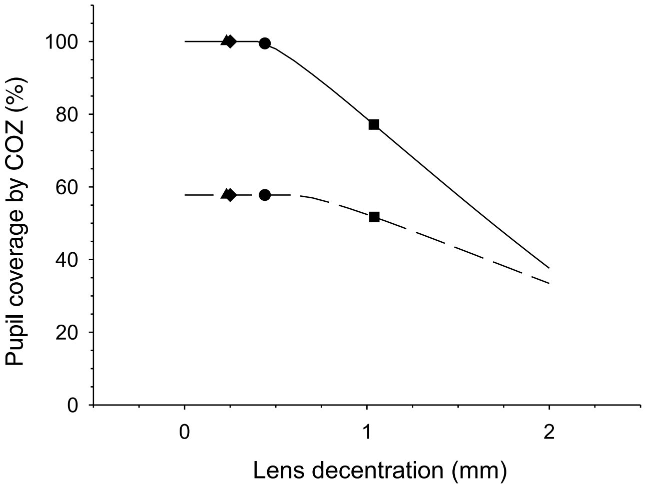

Figure 3. The proportion of pupil coverage by the central optic zone for the lens presenting COZD = 3.8 mm for a pupil diameter of 3 mm (solid curve) and 5 mm (dashed curve) as a function of lens decentration. The proportion corresponding to each subject according to the measured decentration values is also indicated with different symbols [JGP (◆), ATG (●), ECG (■), JPR (▲)].

presented as grey-level images. All the images are normalised to the same value to allow direct comparison. This type of representation shows qualitatively how the image quality changes with pupil diameter and observation distance.

Computing the MTF from the averaged aerial images as explained above enables quantitative measurements to be obtained. Radial profiles of the ocular MTFs obtained by averaging the 2D MTFs over all orientations corresponding to the subjects that took part in the experiment are shown in *Figures 5–8*. These MTF results correspond to far vision and near vision conditions for the different conditions studied: pupil diameter of 3 mm and both designs tested [COZD = 3.2 mm (*Figures 5–8a*) or COZD = 3.8 mm (*Figures 5–8b*)], and pupil diameter of 5 mm and both designs [COZD = 3.2 mm (*Figures 5–8c*) or with COZD = 3.8 mm (*Figures 5–8d*)]. The MTF when no lens is worn is also shown in all these figures for comparison.

Retinal image quality when no lens is worn for far vision conditions is higher than that when a contact lens is worn in all the cases studied. The difference depends on the subject considered. Subjects ATG and JPR show the greatest and the smallest difference, respectively.

Comparing the MTFs when the contact lenses are worn, for a pupil diameter of 3 mm (*Figures 5–8a* and *5–8b*) the MTFs corresponding to far vision conditions are much better than MTFs corresponding to near vision conditions for both lenses studied. In general, the difference is greater for the lens with COZD = 3.8 mm than for the lens with COZD = 3.2 mm. Only for the subject ECG the difference is similar. For a pupil

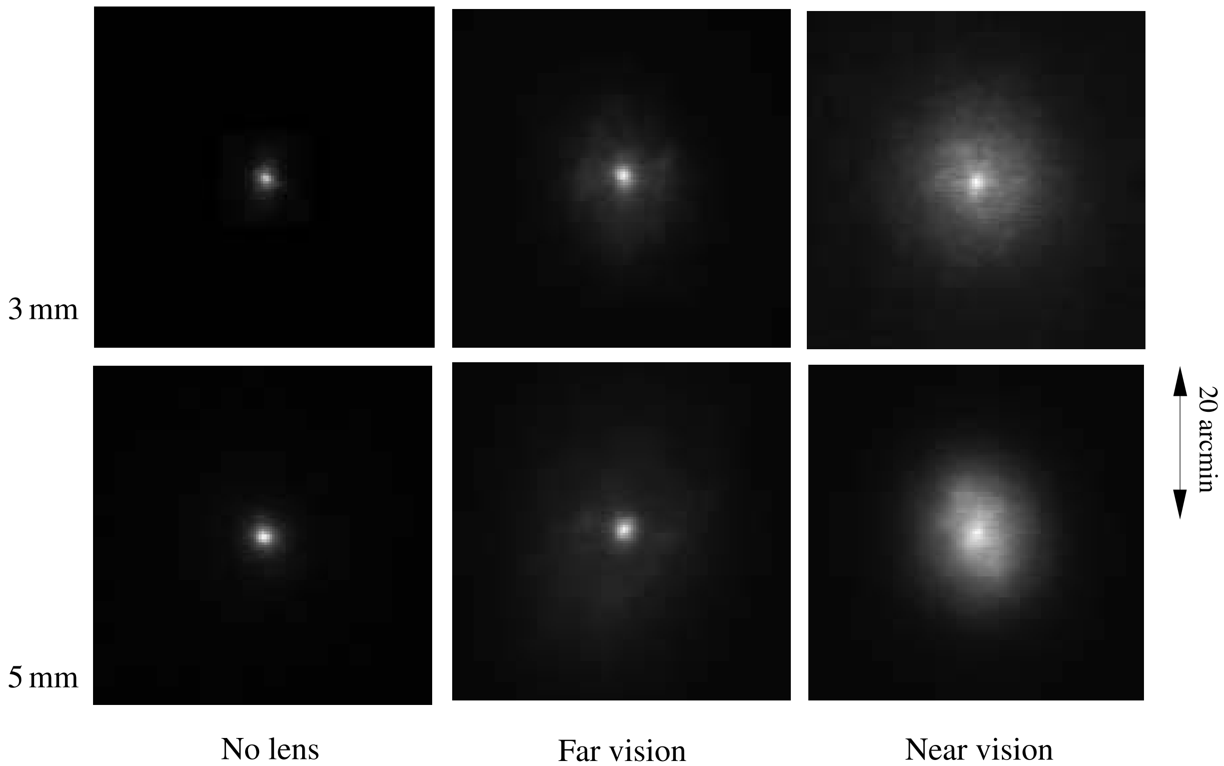

Figure 4. Aerial images for the subject ECG for a pupil diameter of 3 and 5 mm, corresponding to the case when no lens is worn, far vision and near vision conditions when the lens with COZD = 3.2 mm is worn.

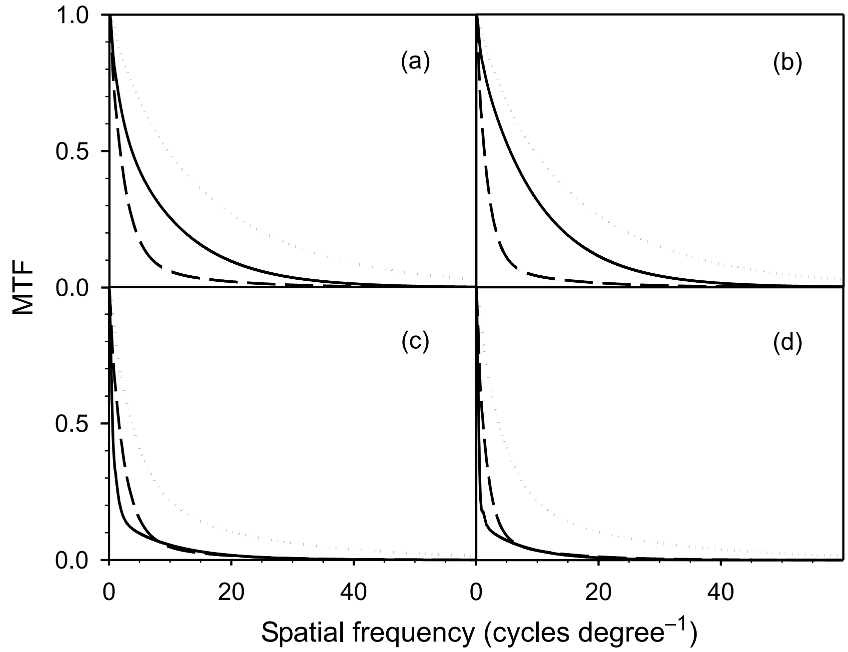

Figure 5. Radial profiles of the two-dimensional MTFs corresponding to the subject ATG in far (solid curves) and near (dashed curves) vision conditions for a pupil diameter of 3 mm and lens with COZD = 3.2 mm (a) or COZD = 3.8 mm (b), and a pupil diameter of 5 mm and lens with COZD = 3.2 mm (c) or COZD = 3.8 mm (d). The MTFs when no lens is worn are also shown (dotted curve).

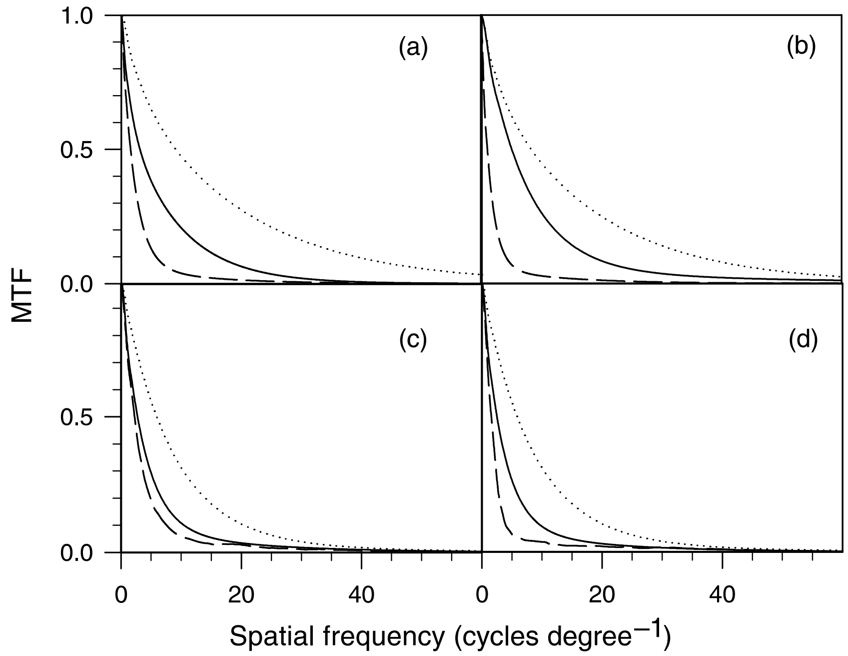

Figure 6. Radial profiles of the two-dimensional MTFs corresponding to the subject JGP in far (solid curves) and near (dashed curves) vision conditions for a pupil diameter of 3 mm and lens with COZD = 3.2 mm (a) or COZD = 3.8 mm (b), and a pupil diameter of 5 mm and lens with COZD = 3.2 mm (c) or COZD = 3.8 mm (d). The MTFs when no lens is worn are also shown (dotted curve).

diameter of 5 mm (*Figures 5–8c* and 5–8*d*) the MTFs corresponding to far and near vision conditions are more similar than for a pupil diameter of 3 mm. Subjects ATG and JPR show slightly higher MTFs for near vision conditions than for far vision conditions while subject JGP shows an opponent behaviour, i.e. the MTFs are slightly higher for far vision conditions than for near vision conditions. Subject ECG presents very

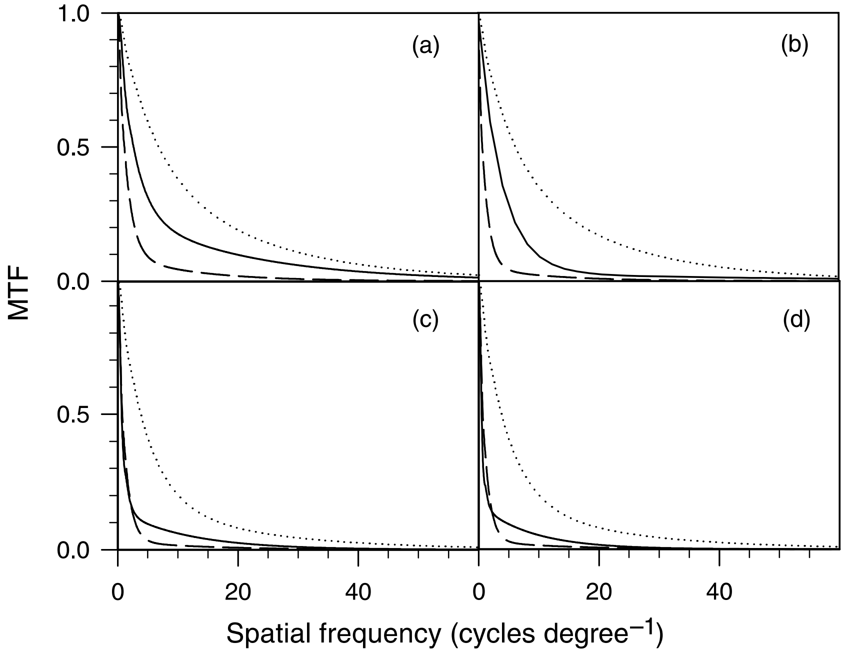

Figure 7. Radial profiles of the two-dimensional MTFs corresponding to the subject ECG in far (solid curves) and near (dashed curves) vision conditions for a pupil diameter of 3 mm and lens with COZD = 3.2 mm (a) or COZD = 3.8 mm (b), and a pupil diameter of 5 mm and lens with COZD = 3.2 mm (c) or COZD = 3.8 mm (d). The MTFs when no lens is worn are also shown (dotted curve).

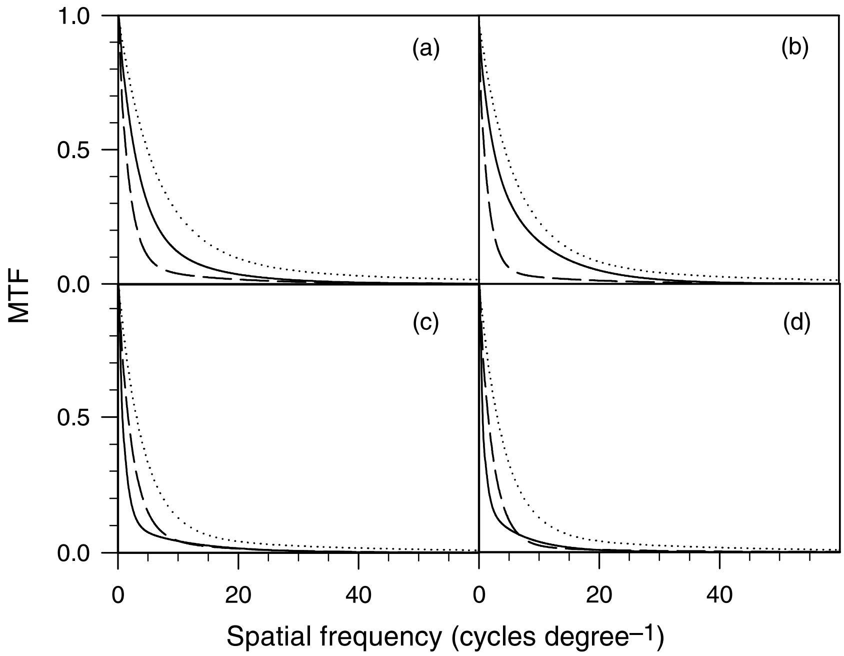

Figure 8. Radial profiles of the two-dimensional MTFs corresponding to the subject JPR in far (solid curves) and near (dashed curves) vision conditions for a pupil diameter of 3 mm and lens with COZD = 3.2 mm (a) or COZD = 3.8 mm (b), and a pupil diameter of 5 mm and lens with COZD = 3.2 mm (c) or COZD = 3.8 mm (d). The MTFs when no lens is worn are also shown (dotted curve).

similar values for the MTFs corresponding to near and far vision conditions for low spatial frequencies. For mean and high spatial frequencies, MTF values for far vision are slightly higher than the ones obtained for near vision conditions.

The influence of decentration of the lenses also becomes apparent when analysing quantitative parameters such as the MTF. For example, the subject JPR presented a high value of decentration for the lens with COZD = 3.2 mm and therefore the difference between the MTFs corresponding to the far and near vision conditions for a pupil diameter of 3 mm are smaller than the ones obtained for the other subjects (*Figures 5–8a*). In the same way, subject ECG presented a high value of decentration for the lens with COZD = 3.8 mm and therefore the difference between the MTFs corresponding to the far and near vision conditions for a pupil diameter of 3 mm are smaller than for the other subjects (*Figures 5–8b*).

In order to evaluate the benefit of the lenses in near vision conditions, we measured the MTF for the naked eye under these conditions in the subjects JPG and JPR. *Figures 9* and *10* show the MTFs for near vision conditions for naked eye or when the lens is worn for these subjects corresponding to 3-mm pupil diameter (*Figures 9* and 10*a*) and 5 mm pupil diameter (*Figures 9* and 10*b*). For 3 mm of pupil diameter the MTFs for the naked eye situation and the ones obtained when the lens of COZD = 3.8 mm were worn are very similar, being slightly higher than the one obtained for the lens with COZD = 3.2 mm. For a pupil diameter of 5 mm, the MTF when the lens is worn is clearly higher than the one for the naked eye situation. When the two COZD studied are compared the best MTF corresponds to COZD of 3.2 mm for the subject JGP. For the subject JPR the MTFs are very similar.

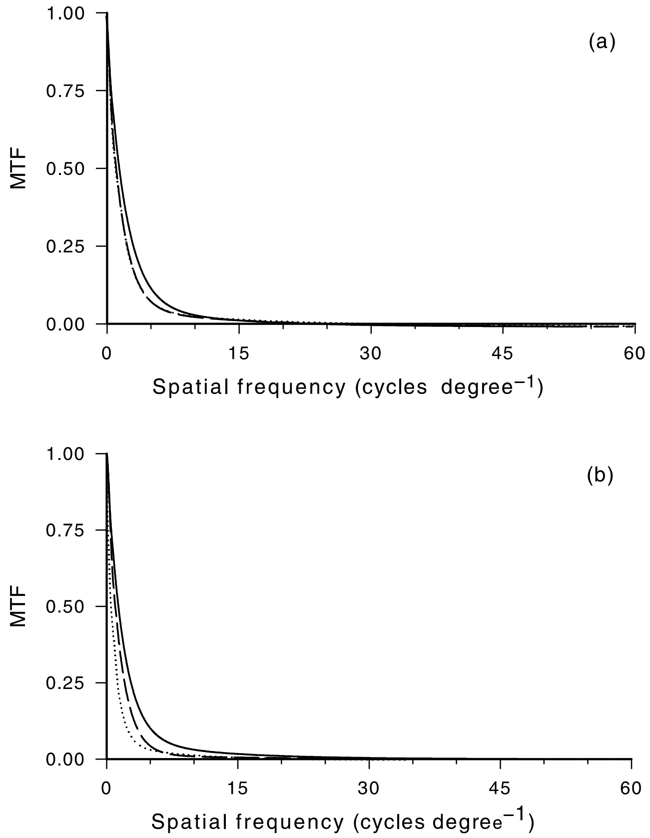

Figure 9. Radial profiles of the two-dimensional MTFs corresponding to the subject JGP for the naked eye (dotted line), when the lens with COZD = 3.2 mm is worn (solid line) and when the lens with COZD = 3.8 mm is worn (dashed line) for near vision conditions. (a) Corresponds to a pupil diameter of 3 mm and (b) to a pupil diameter of 5 mm.

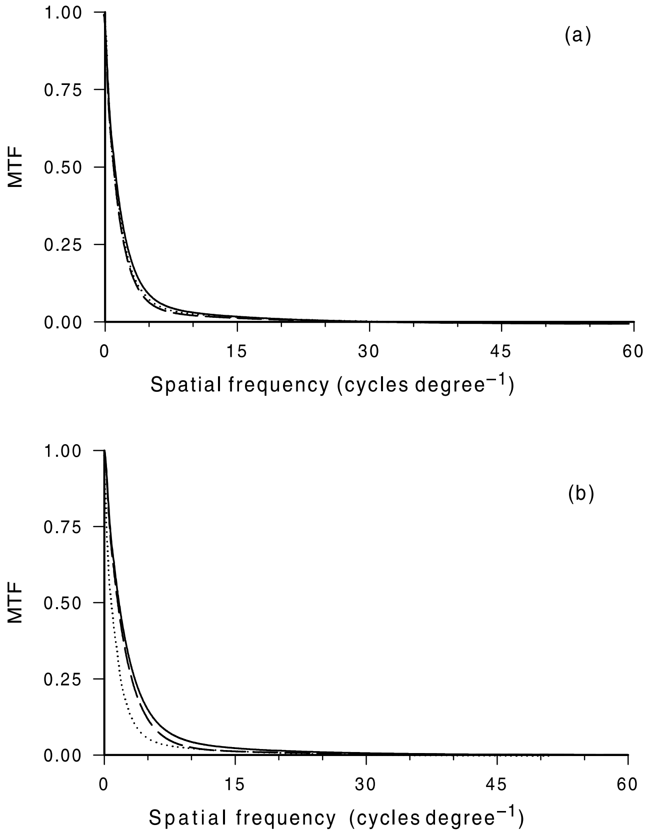

Figure 10. Radial profiles of the two-dimensional MTFs corresponding to the subject JGP for the naked eye (dotted line), when the lens with COZD = 3.2 mm is worn (solid line) and when the lens with COZD = 3.8 mm is worn (dashed line) for near vision conditions. (a) Corresponds to a pupil diameter of 3 mm and (b) to a pupil diameter of 5 mm.

In order to analyse more directly the influence of pupil diameter on the retinal image quality for the two different COZD lenses the MTF corresponding to the subject JPR are plotted for far vision (*Figure 11a* and 11*b*) and near vision conditions (*Figure 11c* and 11*d*). For far vision conditions the MTF corresponding to a pupil diameter of 3 mm is clearly better than the MTF corresponding to a pupil diameter of 5 mm for both COZD considered. For near vision conditions the MTFs obtained for pupil diameters of 3 and 5 mm are very similar for the two COZD considered. This behaviour is similar in the other analysed subjects as it can be appreciated when the MTFs corresponding to 3 and 5 mm of pupil diameter (*Figures 5–7*) are compared.

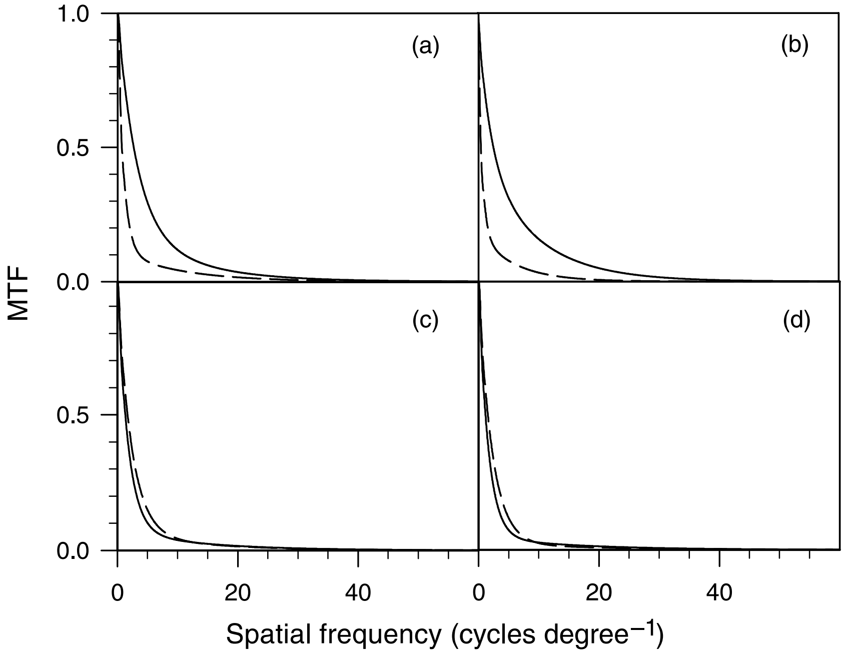

Figure 11. Radial profiles of the two-dimensional MTFs corresponding to the subject JPR for 3 mm (solid curve) and 5 mm (dashed curve) pupil diameter obtained for far vision conditions when the lens with COZD = 3.2 mm is worn (a), when the lens with COZD = 3.8 mm is worn (b), near vision conditions when the lens with COZD = 3.2 mm is worn (c), when the lens with COZD = 3.8 mm is worn (d).

For easy comparison of retinal images or their MTFs, it is useful to have a single parameter that evaluates the overall image quality and provides quantitative information of the optical quality. We used the quotient between maximum and mean irradiance (I_{max}/I_{med}) of the image, which has been shown to be one of the most discriminatory image quality parameters (Pujol *et al.*, 1998). We computed this parameter for the images obtained for the four subjects that took part in the experiment in all the situations analysed. The results obtained have been normalised for each subject. *Figure 12* shows the mean values and the standard deviation of the normalised quotient between maximum and mean irradiance corresponding to the conditions analysed, i.e. for a pupil diameter of 3 or 5 mm, when no lens is worn for far vision conditions and for contact lenses of both designs worn, for far or near vision conditions.

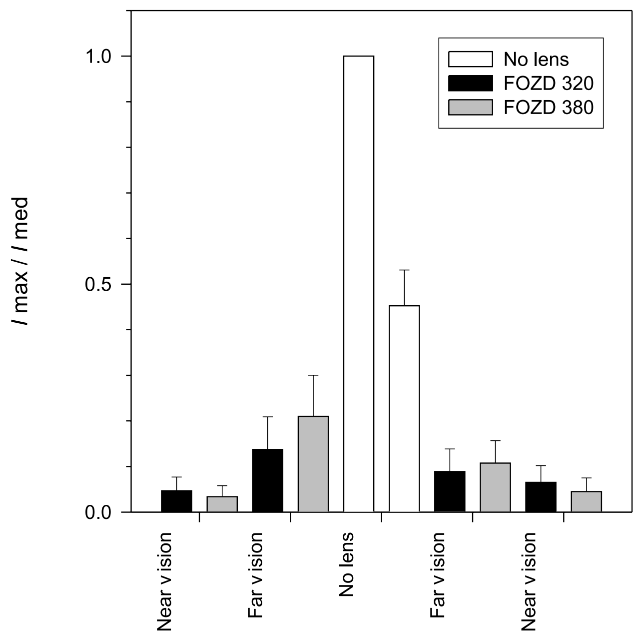

Figure 12. Mean values and standard deviation of the normalised maximum divided by the mean irradiance corresponding to all the conditions studied. White bars correspond to the no lens condition for far vision, black bars correspond to the COZD = 3.2 mm lens and grey bars correspond to the COZD = 3.8 mm lens for far and near vision conditions.

Discussion

For far vision conditions, retinal image quality when no lens is worn is higher than that when a contact lens is worn in all the cases studied, even when the central optic zone covers the entire pupil (*Figures 5–8*). This may be the result of several factors related to the optical quality of the lenses or the contact lens fitting characteristics. We have already shown in a previous work (Torrents *et al.*, 1997) that, with monofocal contact lens, the retinal image quality is similar when no lens is worn and when one is worn. When no lens is worn the MTF is clearly higher for pupil diameter of 3 mm than for pupil diameter of 5 mm because of the diminution of retinal image quality when the pupil diameter increases as a consequence of an increase in the ocular aberrations. In order to understand the drop of the MTF when the lens is worn and other results that we have obtained to have information about optical quality of the lenses would be of interest. To know the exact optical characteristics (e.g. monochromatic aberrations) of the contact lenses used would allow us to separate the contribution of factors related with the optical quality of the lenses and factors related with contact lens design and fitting.

When the lens is worn and for a pupil diameter of 3 mm the MTF for far vision conditions is clearly higher than the one obtained for near vision conditions for both COZD considered (*Figures 5–8a, b*). For this pupil diameter, if the lens was perfectly centred, the COZD would cover the entire pupil. Taking into account the design of the analysed lenses, the light goes only through the optical zone that corrects distance vision. Therefore, for far vision conditions, a focused image is formed on the retina while for near vision conditions the image is out-of-focus. Because of the possible decentration of the lens the condition in which light goes only through the far optic zone can be better achieved when the difference between the diameter of the central optic zone and the pupil diameter is greater. According to this for far (near) vision conditions the MTF for a COZD = 3.8 mm lens is higher (lower) than for COZD = 3.2 mm and therefore the difference between far and near vision conditions is more evident for a COZD = 3.8 mm than for a COZD = 3.2. Only for the subject ECG the difference is similar, but this can be explained by the high value of decentration presented for this subject with the lens of 3.8 mm COZD. The high value of decentration can also explain the small difference for the subject JPR, compared with the other subjects, between far and near vision conditions for the lens of 3.2 mm COZD.

When the pupil diameter is 5 mm (*Figures 5–8c, d*), light passes through the far and the near optic zones for both designs, i.e. COZD = 3.2 and 3.8 mm. Therefore, two superimposed images, one focused and the other out-of-focus, are simultaneously formed on the retina. As a consequence, the MTFs in the four situations shown in *Figures 5–8c, d* are more similar than those for the same situations when the pupil diameter is 3 mm (*Figures 5–8a, b*). Two subjects (ATG and JPR) show slightly higher MTFs for near vision conditions than for far vision conditions, one subject (JGP) shows a slightly higher MTF for far vision conditions than for near vision conditions and another subject (ECG) shows very similar values of the MTFs corresponding to near and far vision conditions for low spatial frequencies and slightly higher MTF values for far vision than for near vision conditions for mean and high spatial frequencies. Taking into account the values of decentration, the percentages of pupil coverage on their own, cannot explain the results obtained, and therefore, the influence of other factors related to the contact lens design, the optical quality of the lens and the increase in aberrations of the lenses and the eye with pupil diameter should have a considerable influence on the larger pupil diameter tested.

For near vision conditions, the MTF when the lens is worn is clearly higher than the one for the naked eye for a pupil diameter of 5 mm (*Figures 9* and 10*b*). In this case, considering the design of the analysed lenses, an amount of light may go through the optic zone that corrects near vision and therefore a focused image is formed on the retina. As the amount of light that passes through this zone is higher for COZD = 3.2 mm than for COZD = 3.8 mm the best MTF is obtained, generally, for the former lens. For the subject JPR (*Figure 10b*) the MTFs for the two lenses are practically equal probably because of the high value of decentration that presents this subject for the COZD = 3.2 lens. For a pupil diameter of 3 mm the behaviour is a little different (*Figures 9* and 10*a*). In this case the MTFs for the naked eye and when the lens of COZD = 3.8 mm is worn are very similar because light only passes through the zone that corrects distance vision and therefore, the effect of the lens is imperceptible. For COZD = 3.2 mm a small amount of light can pass through the zone that corrects near vision becauses of factors such as decentration, contact lens fitting characteristics and contact lens design, that can explain the increase of the MTF obtained.

When it comes to analyse the influence of pupil diameter on the retinal image quality for the two different design lenses, for far vision conditions the MTF corresponding to a pupil diameter of 3 mm is clearly better than the one corresponding to a pupil diameter of 5 mm for both COZD considered. For near vision conditions the MTFs obtained for pupil diameters of 3 and 5 mm are very similar. (*Figure 11*). These performance can be explained considering that for pupil diameter of 3 mm light goes only through the far optic zone, and therefore, a focused (out-of-focus) image is formed on the retina for far (near) vision conditions. For 5 mm of pupil diameter the light passes simultaneously through both optic zones of the lens and therefore, two superimposed images form on the retina, one of them in focus but the other one out-of-focus, as a consequence the optical performance of the lens is similar for far and near vision conditions.

Considering the results for all the analysed subjects, those are similar for all the subjects when no lens is worn and for a pupil diameter of 3 mm when the lens is worn.

However, some differences are to be noted for a pupil diameter of 5 mm when the lens is worn. In this case, when the lens presenting a COZD = 3.8 mm is worn, the averaged results show that the highest and the lowest I_{max}/I_{med} values correspond to far and near vision conditions, respectively (*Figure 12*). These averaged results agree with the percentage of pupil coverage by the far vision zone that, without taking into account lens decentration, are 41% for the lens presenting the small COZD and 58% for the lens presenting the large COZD.

Generally speaking, the results obtained in all the studied conditions show a diminution in optical quality of the system formed by the BCCL and the eye. This diminution depends on different factors as observation distance, COZD, eye and contact lens aberrations or fitting characteristics. This diminution in the optical quality probably will be correlated with a diminution in visual performance. The reduction of visual functions as visual acuity or contrast sensitivity function when a simultaneous vision contact lens is worn have been reported in some papers as we indicated in the Introduction. To obtain the correlation between optical and psychophysical measurements could be a very interesting work to carry out in the future.

Conclusions

We measured the optical image quality of the contact lens-eye system, using the double-pass technique. This is an objective non-invasive method that permits *in vivo* testing of the optical performance of contact lens wearing eyes. The lenses analysed were soft BCCLs with a total diameter of 13.8 mm and presenting the far optical zone in the centre. For these types of lenses the factors that can have most influence on the optical performance of the contact lens-eye system are the pupil diameter, the observation distance, factors related to lens design (specially the COZD), optical quality and factors related to the lens fitting (mainly the lens centration).

Decentration of the contact lens affects the portion of pupil surface covered by the central optic zone of the lens. The percentage of pupil coverage can be obtained using a simple geometrical model (*Figures 2* and 3) and regarding the subjects that took part in the experiment, the measured decentration (*Table 2*) greatly affected the percentage of pupil coverage for one of them in each of the two lenses studied. Because of decentration, the retinal image quality decreases, as shown for example when *Figure 8a* is compared with *Figures 5–7a* or when *Figure 7c* is compared with *Figures 5, 6* and 8*c*. These figures show the radial profiles of MTFs corresponding to the different subjects in the same conditions of pupil diameter and observation distance. The difference between the MTFs corresponding to far and near vision conditions is smaller for the subjects presenting high values of lens decentration than for the ones presenting low values of lens decentration.

In general, retinal image quality is better when no lens is worn under far vision conditions than in the bifocal contact lens wearing situation. This can be shown qualitatively, by means of aerial image comparison (*Figure 4*), or quantitatively, when MTFs are compared (*Figures 5–8*). This result is clearly understood when two images, one in focus and the other out-of-focus, are formed on the retina because of the different power corresponding to the far and near optic zones of the lenses. However, for a pupil diameter of 3 mm and far vision conditions this result is unlikely, because the pupil coverage by the far vision zone is total and there is no agreement with previous results obtained using monofocal lenses (Torrents *et al*., 1997). The influence of factors related to the optical quality and lens fitting may explain these differences.

For near vision conditions the retinal image quality is, in general, better when the lens is worn than for the naked eye (*Figures 9* and 10). Only for a small pupil diameter (3 mm) and large COZD (3.8 mm) are the MTFs obtained similar. Therefore, excluding this case, these lenses have a clear clinical benefit in order to improve the near vision qualities of eyes with reduced accommodation capacity.

The pupil diameter clearly affects the optical performance of the contact lens-eye system (*Figure 11*). For far vision conditions the retinal image quality corresponding to a 3 mm pupil diameter is clearly better than that corresponding to 5 mm. This can be explained because, as a general rule, in far vision conditions, for a pupil diameter of 3 mm there is only one focused image on the retina, while for a 5-mm pupil diameter two superimposed images, one focused and the other out-of-focus, form on the retina. For near vision conditions retinal image quality is more similar for the two pupil diameters analysed. In some cases the difference in optical performance obtained between the two pupil diameters studied cannot be explained only taking into account the percentage of pupil coverage by the central optic zone of the contact lens. This shows the influence of factors such as the increase in the eye-contact lens system aberration with aperture or the design of the transition region between the far and the near optic zones in the optical performance obtained.

When all the situations analysed for contact lens wearing eyes are compared either using the MTF or computing a single parameter that evaluates the overall image quality as the quotient between maximum and mean irradiance (I_{max}/I_{med}) of the image (*Figure 12*), it is clearly demonstrated that for a pupil diameter of 3 mm, a clearly higher retinal image quality was obtained for far than for near vision conditions. This behaviour can be explained by the percentage of pupil coverage corresponding to far and near vision zones of the lens. Therefore, in far vision conditions, the retinal image quality is higher for the larger COZD lens design and vice versa in near vision conditions. For a pupil diameter of 5 mm the retinal image quality measured for all the situations studied is more similar than for a pupil diameter of 3 mm. However, the results obtained cannot only be explained by considering the percentages of pupil coverage by each zone of the lens, and therefore, the importance of the other factors as mentioned above become apparent.

Acknowledgements

The authors are grateful to Aurora Torrents and Ester Cervelló for their valuable cooperation and to CIBA Vision for providing the contact lenses.

This research was supported by the Comisión Interministerial de Ciencia y Tecnologia, Spain, under grant TAP96-0887.

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