Clinically Relevant Optical Properties of Bifocal, Trifocal, and Extended Depth of Focus Intraocular Lenses

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ABSTRACT

PURPOSE: To experimentally compare the optical performance of three types of hydrophobic intraocular lenses (IOLs): extended depth of focus, bifocal, and trifocal.

METHODS: The tested IOLs were: TECNIS ZMB00 (bifocal; Abbott Medical Optics, Abbott Park, IL), TECNIS Symfony ZXR00 (extended depth of focus; Abbott Medical Optics), and FineVision GFree hydrophobic (trifocal; PhysIOL, Liège, Belgium). Their surface topography was analyzed by optical microscopy. Modulation transfer function (MTF) and spherical aberrations were determined on optical bench for variable pupil apertures and with two cornea models (0 μm and +0.28 μm). United States Air Force target imaging was analyzed for different focal points (near, intermediate, and far). Point spread function (PSF) and halos were quantified and compared.

RESULTS: The three lenses presented step-like optic topography. For a pupil size of 3 mm or greater, clearly distinctive MTF peaks were observed for all lenses: two peaks for the extended depth of focus and bifocal lenses with +1.75 and +4.00 diopters (D) addition, respectively, and three peaks for the trifocal lens with +1.75 and +3.50 addition for intermediate and near vision, respectively. The extended depth of focus and bifocal lens had slightly higher MTF at best focus with the +0.28 μm cornea model than with the 0 μm model, whereas the trifocal lens was likely to be more independent of the corneal spherical aberrations.

CONCLUSIONS: It appears that the three lenses rely on light diffraction for their optical performance, presenting halos with comparable intensities. For small pupil apertures (< 3 mm), the MTF peaks for the far and intermediate focal distances of the trifocal and extended depth of focus lenses overlap, but the trifocal lens presented an additional MTF peak for the near focal points.

[*J Refract Surg.* 2016;32(4):273-280.]

Multifocal intraocular lenses (IOLs) with two or more foci can be used to replace the opacified natural lens during routine cataract surgery. They are recommended by cataract surgeons as the replacement lenses of choice when patients wish to avoid wearing spectacles. However, some patients implanted with multifocal IOLs report glare and halos at night, and the assessment of the objective optical quality of these lenses deserves interest.

Differences in the design of diffractive IOLs translate into differences in optical quality at their foci, through-focus performance, and halo features, which can offer further information to surgeons when selecting which IOL to implant. In addition to being objective and patient independent, optical bench testing of multifocal IOLs has the ability to control factors that are difficult to address in clinical essays such as pupil diameter, lens alignment and tilt, and level of corneal spherical aberration on the multifocal IOL.

The International Organization for Standardization (ISO) standards 11979-2 and 11979-9 define the guidelines for the in vitro measurement of the optical quality of an IOL. Optical bench evaluation of the modulation transfer function (MTF) provides valuable information about the optical quality of IOLs.[1-3] The correlations existing between a trifocal IOL, a varifocal IOL, and a monofocal IOL using the "ex vivo" optical bench through-focus image quality analysis and the clinical visual performance in real patients by study of the defocus curve were investigated. Significant correlations were found between logMAR visual acuity and image quality metric for the multifocal and monofocal IOLs analyzed. Ex vivo find-

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Submitted: July 1, 2015; Accepted: January 6, 2016

Dr. Gatinel has a proprietary interest in the trifocal diffractive optic (Patent WO2011092169). Dr. Loicq has no financial or proprietary interest in the materials presented herein.

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doi:10.3928/1081597X-20160121-07

TABLE 1

Features of the Three Studied Lenses

Characteristic	TECNIS ZMB00 IOL	TECNIS Symfony ZXR00 IOL	FineVision GFree IOL
Optical/total diameter (mm)	13/6	13/6	6/11.4
Haptic design	one-piece/C-loop	one-piece/C-loop	one-piece/double C-loop
Power addition at the IOL plane (D)	+4.00	+1.75	+1.75 and +3.50
Spherical aberration (μm)	-0.27	-0.27	-0.11
Refractive index/Abbe number	1.47/55	1.47/55	1.52/42
UV-blue filter	UV	UV	UV/violet-blue
Indicated far optical power (D)	+20.00	+20.00	+20.00

IOL = intraocular lens; D = diopters; UV = ultraviolet
The TECNIS ZMB00 and Symfony ZXR00 are manufactured by Abbot Medical Optics, Abbott Park, IL, and the FineVision GFree lens is manufactured by PhysIOL, Liège, Belgium.

ings may enable surgeons to predict visual outcomes from the optical bench analysis.[4]

The MTF describes how the transfer of contrast information by an optical system decreases with increasing spatial frequency. It describes the amount of contrast that is transferred by the system for a given frequency or object size. The contrast decrease is more pronounced at higher spatial frequencies (ie, the number of line pairs per millimeter [lp/mm], cycles per degree, or for smaller object size). The overall contrast sensitivity depends on ocular optics (MTF) and retinal–brain function: contrast sensitivity = MTF × retinal–brain function.[5] If retinal–brain function does not change after cataract removal and IOL implantation, then postoperative functional vision (contrast sensitivity) improvement is directly influenced by the improvement in visual optics (MTF).

Using a United States Air Force (USAF) 1951 Resolution Target, it is also possible to document and compare the quality of the image at a focus plane. Maxwell et al.[6] and Kim et al.[7] presented the imaging of a USAF target through multifocal IOLs. Such characterization is more representative for the quality of the patient's retinal image than MTF measurement alone and cross-correlation curves. Gatinel and Houbrechts later reported the comparison of the optical bench of seven multifocal IOLs.[8] The through-focus MTFs and the images of the USAF targets were compared for distance, intermediate, and near focal points.

Recently, an extended depth of focus IOL (TECNIS Symfony ZXR00; Abbott Medical Optics, Abbott Park, IL) was introduced on the market with a patented novelty.[9] This IOL with a diffractive step-like optical profile is claimed to extend the range of vision and to correct the linear chromatic aberrations of the phakic eye (cornea) for a reinforced contrast sensitivity. In this study, we measured clinically relevant optical properties (MTF and USAF targets) of this new IOL in comparison with diffractive bifocal and trifocal lenses.

MATERIALS AND METHODS

IOL DESCRIPTION

The following IOLs were tested: bifocal TECNIS ZMB00 (Abbott Medical Optics), extended depth of focus TECNIS Symfony ZXR00, and trifocal FineVision GFree (PhysIOL, Liège, Belgium). **Table 1** lists the main features of the three studied lenses.

The TECNIS ZMB00 is a pupil independent fully diffractive bifocal IOL with a +4.00 D addition. It succeeds the ZM900 silicone implant, the first to be approved by the U.S. Food and Drug Administration and whose quality of vision was previously reported.[10]

The TECNIS Symfony ZXR00 IOL is claimed to be designed with a new optical technology for providing an extended range of focus. The diffractive step-like optic profile is intended to extend the range of vision while being combined with a proprietary technology to correct chromatic aberrations for contrast sensitivity enhancement. Moreover, this product is claimed to induce less dysphotopsia phenomena with similar incidence as a standard monofocal IOL.

The TECNIS ZMB00 and Symfony IOLs are both manufactured by lathing and milling out of a hydrophobic raw material with a refractive index of 1.47. These lenses are dry packed and sterilized.

The optical features of the lens are identical to those of its hydrophilic commercially available counterpart, the FineVision IOL, which has been comprehensively described previously.[11,12]

The trifocal hydrophobic FineVision GFree is a fully diffractive IOL that uses a combination of two bifocal diffractive patterns for far/near and far/intermediate vision, respectively. The diffractive structure is apodized with a continuous decrease of the diffractive steps height from the optic center to the periphery. This makes the lens more far vision dominant at larger pupils for diminution of photic phenomena under dim conditions. The lens is made of the proprietary glistening-free hydrophobic material GFree from PhysIOL with refractive index of 1.52.[13]

SURFACE TOPOGRAPHY

The surface topography of the three lenses was analyzed with a high-resolution VHX-5000 microscope (Keyence, Itasca, IL).

OPTICAL QUALITY

The optical quality of the three IOLs was evaluated by measurement on optical test benches of the USAF target image resolution, the through-focus MTF, and the objective quantification of photic phenomena (halos), as described hereafter.

OPTICAL BENCHES

PMTF. The optical bench used for this series of measurements is the PMTF developed by Lambda-X (Nivelles, Belgium) to measure image quality—MTF and PSF of diffractive multifocal IOLs.[11,14-16]

The device complies with ISO 11979-2 and 11979-9 requirements. The equipment disposes of two model corneas with different preset values of spherical aberrations, as described in ISO 11979-2: the ISO1 model cornea with zero spherical aberrations and the ISO2 model cornea with +0.280 µm spherical aberrations at 5-mm pupil aperture. Indeed, the ISO2 model cornea aims at simulating the average human cornea spherical aberrations measured by Beiko et al.[17]

The PMTF enables MTF measurement at different apertures (2, 3, 3.75, and 4.5 mm), focal planes (through-focus curve), and spatial frequencies.

In the experimental set-up, the IOL is placed in an 11-mm diameter lens holder before being inserted in a glass cuvette filled with balanced salt solution (refractive index: 1.335; Baxter, Deerfield, IL). The front (anterior) surface of the IOL faces the incident light. The holder enables a tilt-free orientation of the IOL. The instrument detects the IOL optical axis automatically with a lateral precision of 0.2 mm. The collimated light through the artificial cornea singlet is focused onto the IOL, thereby simulating the vergence of a human eye. The charge coupled device camera is able to shift along the optical axis and record the best focus at 50 lp/mm, thus giving rise to signal intensity peaks for all focal points.

The curves were obtained for a spatial frequency of 50 lp/mm, approximating the visual function assessment with an optotype for a 0.50 decimal (20/40 Snellen) visual acuity. The through-focus MTF curves were generated at 2-, 3-, and 3.75-mm pupil apertures with the two ISO1 and ISO2 model corneas.

Despite the fact that diffraction effects are influenced by the wavelength of the light in consideration, it is well known that the human eye has a peak sensitivity in the range of 530 to 560 nm.[18] Therefore, a wavelength of 543 nm has been selected for performing this set of experiments.

NIMO. The NIMO TR0815 instrument (Lambda-X) is based on phase shifting Schlieren principle. It reconstructs the light wavefront after passing through the lens under measurement. This bench is not suited to fully characterize the diffractive lenses. However, it can be used in the case of diffractive optics for investigating phase effects related to the refractive component of the transmitted light (ie, the distance vision) after adjusting the frequency resolution of the instrument. The NIMO instrument was used to measure spherical aberrations of the three lenses at apertures varying from 2 to 5 mm. Experimental set-up for IOL positioning on the optical bench is identical to that used with the PMTF instrument.

USAF RESOLUTION IMAGES

USAF target images were obtained at a position simulating distance to closer viewing distances per 0.50-D increments and at 3-mm pupil aperture. The spherical aberration-free ISO1 model cornea was applied for this analysis to characterize the range of vision as provided by the IOL itself, without the contribution of the corneal spherical aberrations. Indeed, the amount of spherical aberrations would influence the depth of focus of the whole optical system.

HALO QUANTIFICATION

The evaluation of the magnitude of the halos was performed from the PSF measurement obtained at each focal spot location on PMTF optical bench. The amplitude of the off-axis peaks of the radial profile of the PSF enables quantification of the percentage of energy of the halos with respect to the height of the central peak.

PSFs were obtained by measurement performed on the PMFT bench, by using a 2.5-µm pinhole (as a secondary light point source) instead of the USAF target. PSF is recorded by the PMTF charge coupled device camera. The resulting light intensity was coded into pixel with values between 0 and 255. The camera integration time was adjusted to avoid any saturations in the recorded images, especially in the brightest central spot. The annular zone surrounding the central peak corresponding to the halo was analyzed. These measurements were done with the ISO1 model cornea to

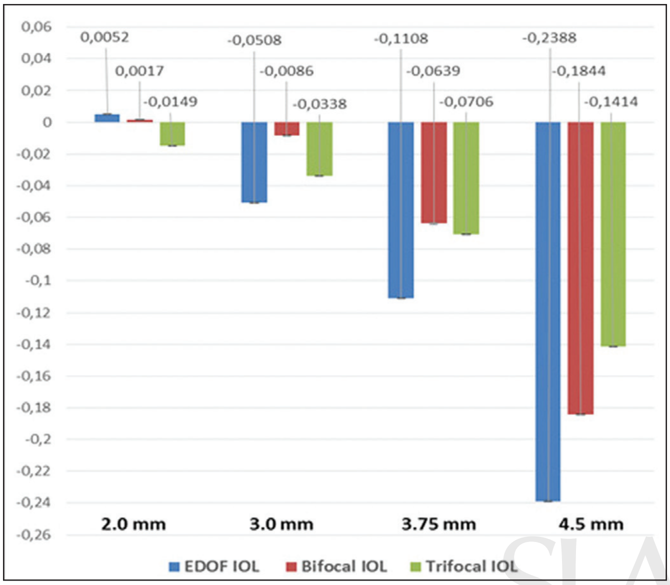

Figure 1. Spherical aberrations (μm) at 2-, 3-, 3.75-, and 4.5-mm apertures for the extended depth of focus (EDOF), bifocal, and trifocal intraocular lenses (IOLs).

eliminate the contribution of the cornea and highlights the IOL contribution only.

To avoid any lack of homogeneity due to measurement or IOL lens misalignment, the radial variation of intensity was averaged using an annular numerical mask. This mask is concentric to the center of the central spot. The radial intensity was evaluated on the mask and averaged on the surface of the ring. The radius of the mask was increased to cover the radial coordinate space. The width of this mask was defined as one pixel. The results obtained in terms of power per pixel in the units of bmp image were converted into percentage of the central spot, which is weighted 100%.

RESULTS

LENS SURFACE TOPOGRAPHY

Figure A (available in the online version of this article) shows the surfaces of the three lenses under microscopy. The three IOLs present rings (steps) that are prone to be involved in a diffraction mechanism of light propagation. The number of rings varies for the different lenses as follows: the bifocal lens displays 22 steps on the 6-mm optic, the trifocal lens 23 steps on the 6.15-mm optic, and the extended depth of focus lens only 9 steps on the 6-mm optic. The trifocal lens shows two types of diffractive steps for even and odd rings, respectively. Note that the extended depth of focus and bifocal IOLs display micro-rings in addition to more pronounced diffractive steps. These micro-rings must not be considered as a diffractive pattern but rather as traces of the cutting toll revolution during optic manufacturing by lathing, the lens not being polished after machining.

SPHERICAL ABERRATIONS

Figure 1 presents the spherical aberration values of the three IOLs measured with the NIMO instrument. In all cases, at apertures higher than 2 mm, the tendency is toward more negative spherical aberrations with the pupil enlargement. However, the bifocal and extended depth of focus IOLs show significantly higher absolute values of spherical aberrations in comparison with the trifocal IOL, especially for large pupil diameters. Bifocal and extended depth of focus aspherical lenses are claimed to compensate the average corneal spherical aberrations, whereas the trifocal IOL corrects only partly the positive corneal spherical aberrations, leaving the pseudophakic eye with residual positive aberration that may contribute to providing some depth of focus. To take into account these differences, the optical performance of the three IOLs was estimated by their MTF values using two different cornea models: ISO1 (aberration free) and ISO2 (with +0.28 μm spherical aberrations).

THROUGH-FOCUS MTF CURVES

The through-focus MTF curves of the three IOLs, collected at 50 cycles/mm and pupil apertures of 2, 3, and 3.75 mm, are shown in **Figures 2-3** with the ISO1 and ISO2 model cornea, respectively.

The ISO standard provides a tolerance on the IOL power: any IOL with a power between 19.75 and 20.25 would be labelled 20.00 D. For this reason, the peaks of the though-focus MTF of the three IOLs were not originally exactly at 20.00 D. To be able to compare the depth of focus, we translated the through-focus curves so that the distance peak of the through-focus MTF for the three IOLs is exactly at 20.00 D.

At a 2-mm aperture and in either the model cornea, the extended depth of focus lens shows two partly overlapping MTF peaks at two focal points, +20.00 and +21.75 D, corresponding to far and intermediate vision distances in accordance with the power addition of +1.75 D claimed by the manufacturer (**Figures 2A** and **3A**). Similarly, the trifocal IOL shows partly merged MTF peaks for far and intermediate vision, but displays an additional peak for near vision at the +3.50 D power addition in respect to the distance vision power. As anticipated, the bifocal lens gives rise to two well-discriminated MTF peaks for far and near vision with a power addition of +4.00 D.

For a pupil aperture larger than 2 mm, the MTF peaks became more discriminated, revealing the number and power positions of all focal points for a given optical design (**Figures 2B** and **3B**). The trifocal lens showed three MTF peaks for far, intermediate, and near distances, and thus two power additions of +1.75

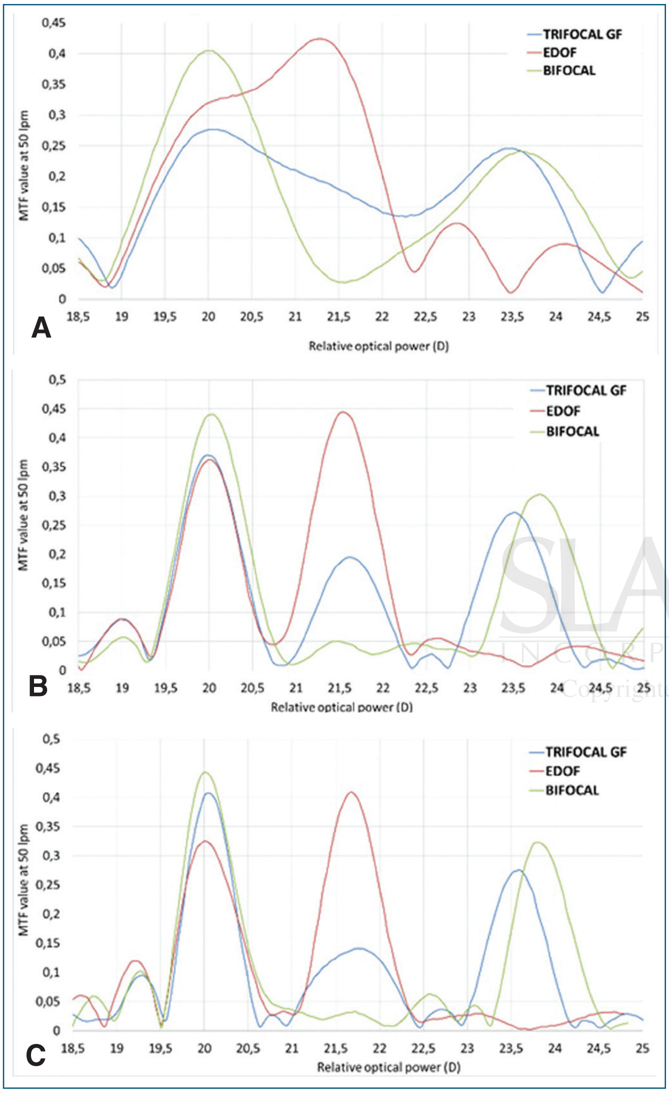

Figure 2. Through-focus modulation transfer function (MTF) using ISO1 model cornea at (A) 2-, (B) 3-, and (C) 3.75-mm pupil aperture. EDOF = extended depth of focus; D = diopters

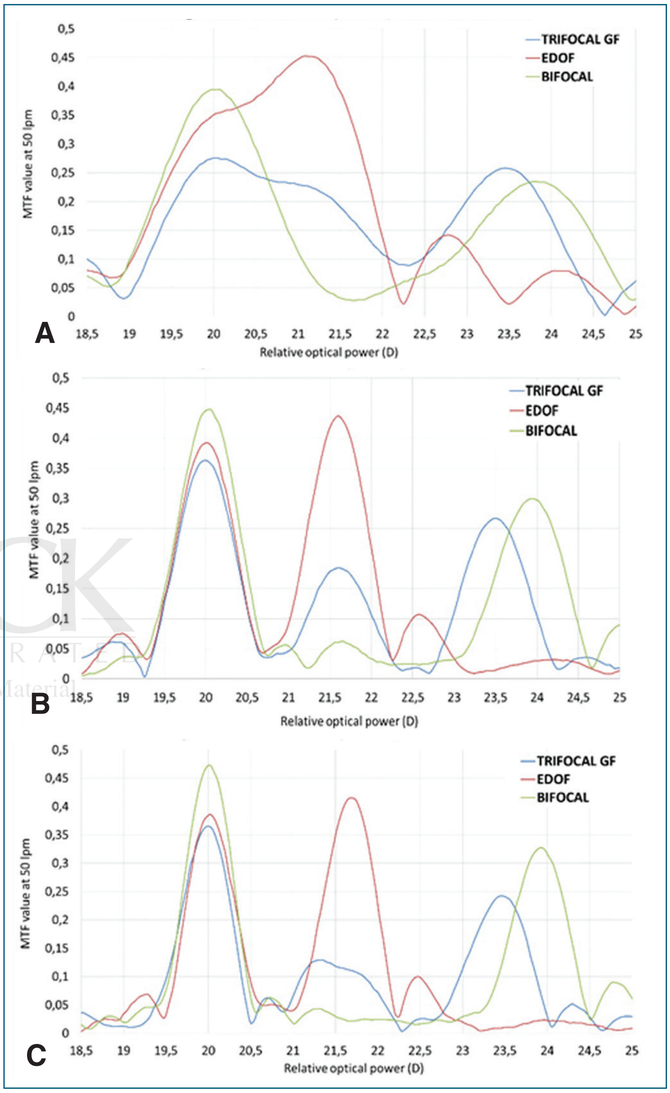

Figure 3. Through-focus modulation transfer function (MTF) using ISO2 model cornea at (A) 2-, (B) 3-, and (C) 3.75-mm pupil aperture. EDOF = extended depth of focus; D = diopters

and +3.50 D in respect to the far focal point. The far vision was dominant, as shown by the relative intensities of the three MTF peaks, followed by near and intermediate vision.

From **Figures 2B** and **3B**, it is obvious that the bifocal and extended depth of focus lenses showed similar bifocality with a lower power addition for the extended depth of focus lens (+1.75 D instead of +4.00 D) and different relative intensities between the focal points. The far vision appeared to be dominant for the bifocal IOL, whereas the closer distance vision appeared to be dominant for the extended depth of focus lens. It is worth noting that, for the intermediate focal point, an identical power addition of +1.75 D in respect to the far focal point was measured for both the extended depth of focus and the trifocal lenses.

Outcomes at the 3.75-mm pupil aperture were similar to those obtained at 3 mm for the three lenses, when the same model cornea was used. However, a slightly more intense MTF peak for far distance was observed in the case of the trifocal lens.

The use of the ISO2 model cornea, with +0.28 µm spherical aberrations, for a same pupil aperture, was likely to result in slightly higher MTF at best focus for the far and add distances, compared to its ISO1 counterpart (with 0 µm spherical aberrations) in the case of the extended depth of focus and bifocal lenses, both having spherical aberrations of -0.27 µm.

This seems to not be the case for the trifocal lens. However, the through-focus MTFs at the 2-, 3-, and 3.75-mm pupil aperture were similar when using the ISO1 and ISO2 model corneas.

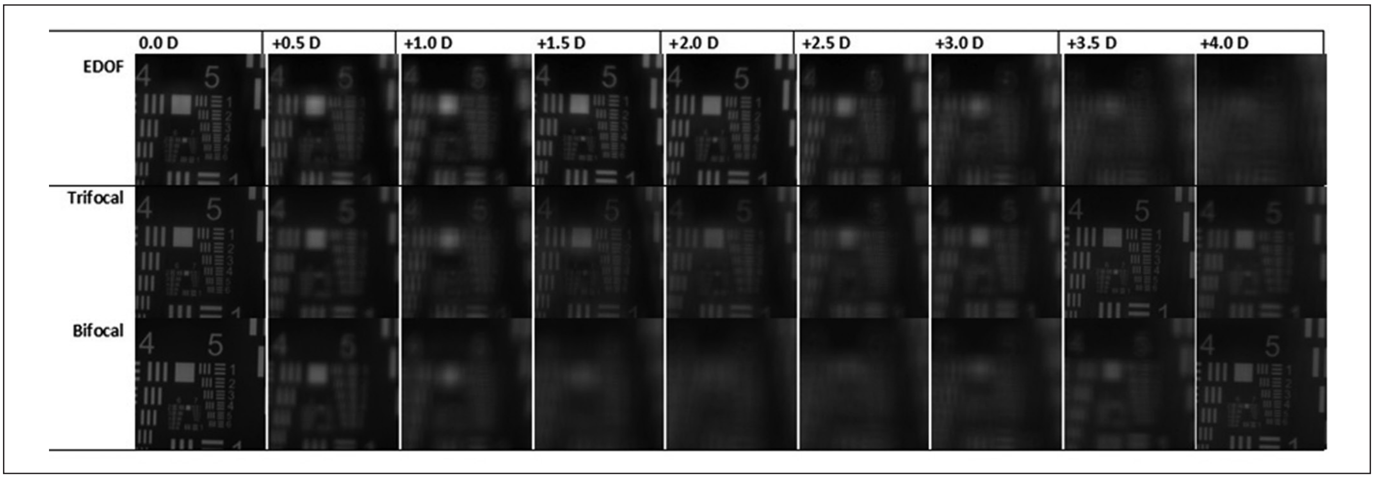

Figure 4. United States Air Force targets with the three tested intraocular lenses (through-focus imaging: per increment of 0.50 diopters (D) from 0.00 D to +4.00 D). EDOF = extended depth of focus

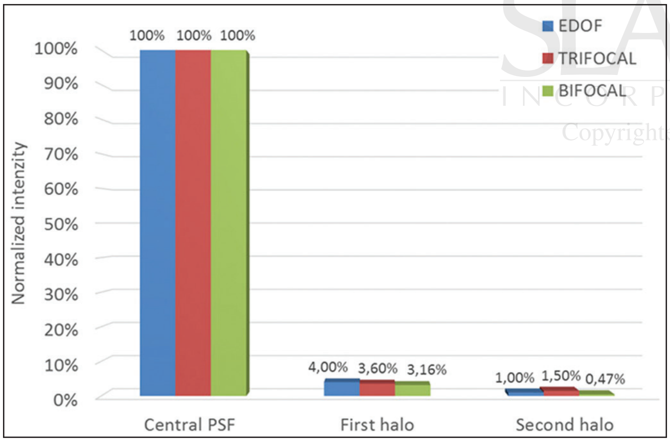

Figure 5. Histograms of halos for far focal point. EDOF = extended depth of focus; PSF = point spread function

IMAGE RESOLUTION

The USAF target imaged through the three different IOLs is presented in **Figure 4** for power additions from 0.00 to +4.00 D by an increment of +0.50 D. Obviously, the three IOLs showed extended range of vision, but exhibited significant differences in terms of range extension between the distance, intermediate, and near vision zones.

The extended depth of focus lens displayed a range of vision with sufficient resolution from 0.00 to +2.00 D (ie, from far to 50 cm distances) and a dramatic drop of contrast resolution at near distances.

The bifocal IOL provided a good image resolution at far (0.00 D) and near (+4.50 D, or 25 cm) distances with, however, a marked gap of image resolution in between for intermediate distances.

The trifocal IOL offered the most extended range of image resolution among the three studied lenses from far to near vision at +3.50 D, or 28 cm, without a too marked gap in resolution at intermediate distance, or approximately +1.50 to +2.00 D, or 50 to 66 cm.

ANALYSIS OF HALOS

Point spread function images of the far focal point of the three IOLs are illustrated in **Figure B** (available in the online version of this article). In these figures, the image gray level was non-linearly amplified to make visible the halos that actually correspond to the annular zones surrounding the central spot (best focus for far vision). The maximum amplitude of the light intensity of the PSF along the optic radial axis corresponds to the central spot (ie, the far focal point at best focus) observed in **Figure B**, whereas the two off-axis secondary peaks correspond to the first and second halos (first and secondary annular zones in **Figure B**). For the sake of comparison between the three lenses, the absolute values of light intensities for the central spot and the surrounding halos were normalized in respect to the central spot, which is weighted at 100%. Results of the three IOLs are given in the histogram (**Figure 5**). The first halo relative intensities for the three lenses were similar and fall in the range of 3% to 4% of the far focus intensity. The second halos were less intense than the first halos (0.5% to 1.5% of the far focus intensity). However, there were no obvious differences in halo intensity between the three IOLs.

DISCUSSION

The through-focus MTF curves showed multiple and distinct peaks corresponding to different focal points. If the presence of more than one MTF peak is considered as a criterion to define multifocality, the three IOLs (bifocal, trifocal, and extended depth of focus) can be considered multifocal IOLs. For bifocal and trifocal lenses, this statement can be viewed as evidence, but it is not the case for the extended depth of focus IOL, for which the multifocality was not claimed in any available data. In the tested conditions, the extended depth of focus IOL behaved as a bifocal IOL, with one focal point for far vision and one for intermediate vision, with an add-power of +1.75 D.

The three IOLs presented a step-like pattern in the optical zone. It can therefore be speculated that the diffraction mechanism of light propagation is at the origin of the multifocality found for the three lenses (ie, two focal points for the bifocal and extended depth of focus IOLs and three focal points for the trifocal lens).

The effect of the aperture is of utmost importance and affects the results of the three lenses in different ways for the through-focus. For large apertures (> 3 mm), the three lenses showed well-discriminated MTF peaks corresponding to multiple focal points. The power addition was computed from the interval between the “far MTF peak“ and the “closer distance MTF peak” for all lenses. The bifocal IOL has an add-power of +4.00 D, whereas the trifocal IOL displays two power additions at +1.75 and +3.50 D, respectively. The trifocal IOL displays the same three focal points as those already published for the hydrophilic version of the FineVision IOL.[8,11,16]

It is interesting to note that the extended depth of focus lens has a power addition of +1.75 D, which is identical to the first power addition of the trifocal lens. It is known that the power addition of a diffractive lens is theoretically fixed by the spacing between two consecutive diffractive rings. The number of rings observed on the three lenses matches with the theory that nine rings have been identified for the extended depth of focus lens versus more than 20 rings for the bifocal and trifocal lenses.

For smaller apertures (< 3 mm), the MTF peaks can merge and partially overlap if they are sufficiently close to each other. This is the case for the extended depth of focus lens, which shows a single and broad MTF peak at the 2-mm aperture. Similarly, the trifocal lens in the same conditions shows partly merged far and intermediate MTF peaks. In contrast, the bifocal lens with a larger power addition (+4.00 D) also displays peak enlargement, but peaks cannot merge due to their distance.

Thus, at the 2-mm aperture, both the trifocal and extended depth of focus lenses give rise to a continuum of MTF from far to intermediate focus. This contributes to extending of the depth of focus of the two IOLs, possibly due to the pinhole diffraction effect. The reduction of the addition power to +1.75 D allows the two MTF peaks for far and intermediate focal points to overlap when the pupil constricts to less than 2 mm, according to the pinhole mechanism. The far and intermediate MTF peaks at +1.75 D behave similarly for the trifocal and extended depth of focus IOLs and merge at the small pupil aperture, whereas the near MTF peak of the trifocal IOL remains well discriminated, offering the “last 30 cm” (from 60 to 30 cm), which are essential for reading comfort. Thus, for the extended depth of focus and the trifocal lenses, the reduction of the power addition gives rise to a lens with an extended range of vision in the far to intermediate distance range on pupil constriction, with an additional focus for reading distances in the case of the trifocal lens. Contrarily, the bifocal lens with +4.00 D power addition does not display such an MTF continuum.

The three IOLs are presenting halos, due to the multifocality. Hence, light passing through the tested IOLs is converging in numerous locations, corresponding to the different focal spots along the optical axis.

The halos generated in the vicinity of each focus were evaluated. The main explanation of the presence of such halos is the presence of converging or diverging rays from other focal points. In addition, an airy pattern is generated at each focal point because of pupil diffraction at the entrance plane. Actually, the halos result from the combination of these two contributors, and reflect the reduction in the image quality given by the tested IOL. The relative amount of halos is similar for the three IOLs.

Bifocal and extended depth of focus IOLs behave better in terms of MTF values with the +0.28 µm spherical aberration ISO2 model cornea in comparison with the spherical aberration-free ISO1 model cornea, and vice versa for the trifocal lens. Indeed, the bifocal and extended depth of focus lenses would compensate for the positive corneal aberration more than the trifocal lens, as assessed by the spherical aberrations values of the three IOLs reported in **Figure 1** and in accordance with their claimed -0.27 µm spherical aberrations. Thus, the bifocal and extended depth of focus IOLs should probably yield more frequently negative residual spherical aberrations after implantation than the trifocal IOL. The trifocal lens is close to an aberration-free lens, and is therefore less dependent on the corneal spherical aberration and less sensitive to the optic decentration and tilt.[19]

To the best of our knowledge, no clinical outcomes are yet available in the literature with the extended depth of focus IOL. However, it is reported that reducing the addition power of a bifocal IOL (eg, to +2.50 D) is an effective way to improve the intermediate vision of a multifocal IOL,[20] at the expense of the near vision.[21] On this basis, it might be predicted that the extended depth of focus lens, having a limited power addition of +1.75 D, would provide satisfactory intermediate vision and mediocre near vision. On the other hand, the trifocal lens, in addition to an intermediate focus at +1.75 D, shows a third focal point for near vision offering a more extended vision range, as illustrated on the USAF images, than the extended depth of focus lens. The loss of light energy due to the presence of this third focal point is only perceptible at the 2-mm aperture. In larger pupils, the trifocal IOL displays similar distance MTF, as tested in bifocal and extended depth of focus lenses.

For the sake of comparison and simplicity, the study was performed in monochromatic conditions and the generated results may eventually differ from clinical outcomes.

CONCLUSION

The three lenses offer optical performances in agreement with the addition powers as estimated by the MTF measurements (+1.75 D for the extended depth of focus IOL, +1.75 and +3.50 D for the hydrophobic trifocal IOL, and +4.00 D for the bifocal IOL. Interestingly, within the limits of the experimental conditions, the two lenses with an extended range of vision (trifocal and extended depth of focus lenses) do not show more halos than the bifocal lens.

Familiarity with the optical characteristics of different multifocal IOLs is paramount for their success. These results may be useful for preoperative patient counseling and surgical planning. They were obtained on optical benches at a single wavelength (543 nm) and well-centered scenario, and should conform to clinical outcomes. However, it would be interesting to perform future studies to analyze the optical performances of the tested lenses under polychromatic light and at various levels of tilt and decentration, the latter having been reported to have significant impact on the visual performances of an IOL.[19]

AUTHOR CONTRIBUTIONS

Study concept and design (DG, JL); data collection (DG, JL); analysis and interpretation of data (DG, JL); writing the manuscript (DG, JL); critical revision of the manuscript (DG, JL)

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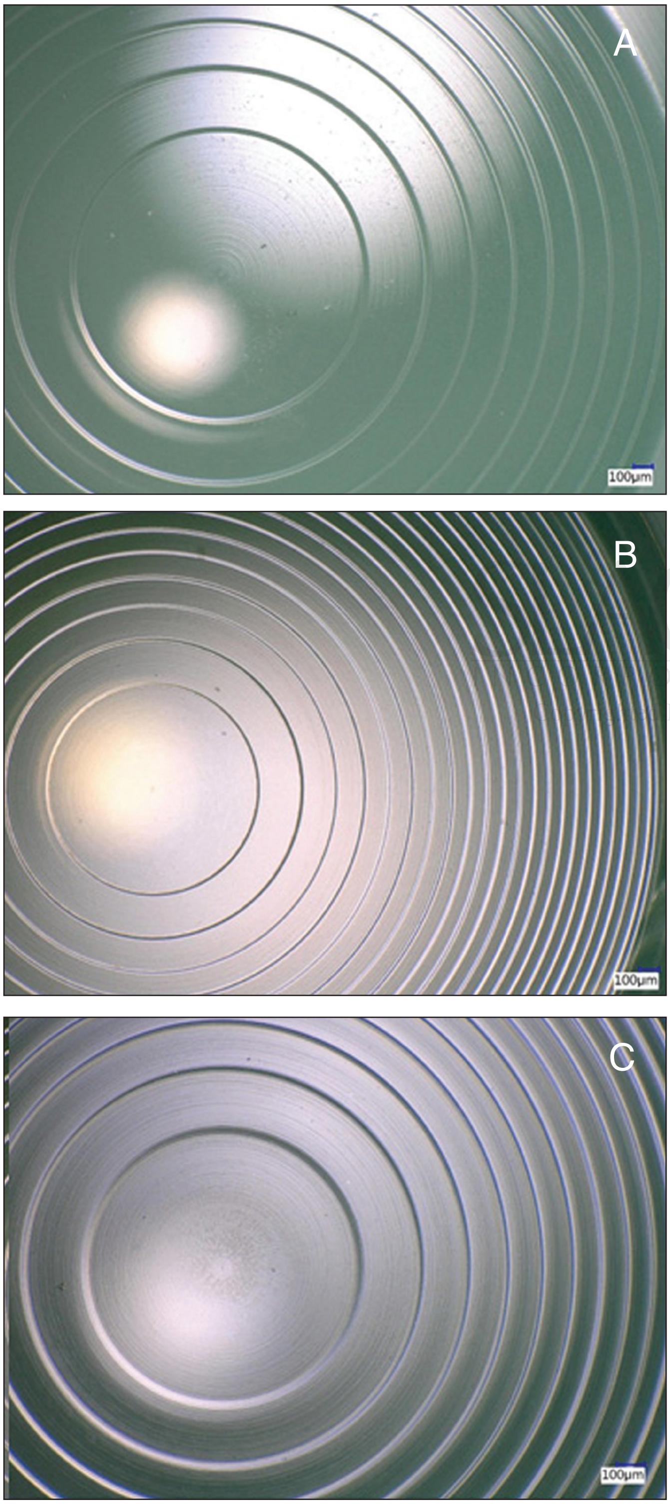

Figure A. Microscopy pictures of the intraocular lens (IOL) surface: (A) extended depth of focus IOL; (B) trifocal IOL; and (C) bifocal IOL.

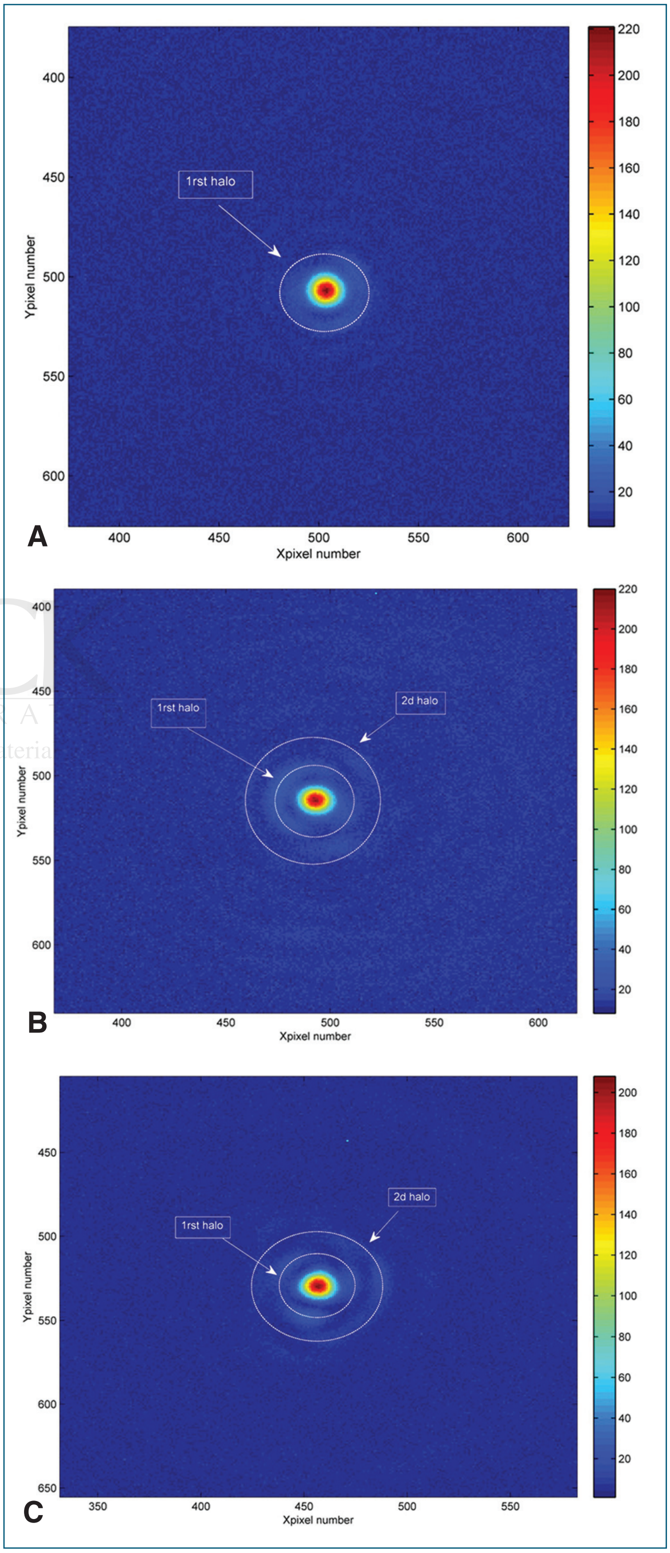

Figure B. Point spread function through a 3-mm pupil aperture for the: (A) bifocal, (B) extended depth of focus, and (C) trifocal intraocular lenses.