Total Depth of Focus of Five Premium Multifocal Intraocular Lenses

Juan F. Zapata-Díaz, PhD; Miguel A. Rodríguez-Izquierdo, MD; Nassima Ould-Amer, BSc (Hons); Jerónimo Lajara-Blesa, MD, PhD; Norberto López-Gil, PhD

ABSTRACT

PURPOSE: To compare the in vitro optical performance of five premium multifocal intraocular lenses (IOLs), including a single-valued metric that shows the total range of distances where a multifocal IOL generates an acceptable image quality.

METHODS: Through-focus modulation transfer function (MTF) and the image of a United States Air Force target were obtained for a 3-mm pupil and a wavelength of 546 nm in five multifocal IOLs (Tecnis Symfony [Johnson & Johnson], FineVision Micro F [PhysIOL], Acrysof IQ PanOptix [Novartis], and Artis Symbiose Mid and Plus [Cristalens Industrie] multifocal IOLs). Total depth of focus (TDOF) is computed by adding the vergence intervals where the through-focus MTF at 50 cycles/mm is 0.15 or greater.

RESULTS: Due to their different optical designs (bifocal, trifocal, or extended depth of focus), energy is distributed differently between far, intermediate, and near focus for each multifocal IOL. The light distribution of the Symbiose Mid and Plus multifocal IOLs was similar, concentrating the energy into far focus and the intermediate into near focus, but extending the intermediate focus more (Plus) or less (Mid) toward the near focus. TDOFs were: 1.58 diopters [D] (FineVision); 1.71 D (Tecnis Symfony); 1.73 D (Artis Symbiose Plus); 1.74 D (Artis Symbiose Mid); and 1.90 D (Acrysof IQ PanOptix).

CONCLUSIONS: TDOFs were similar between multifocal IOLs with a maximum difference of 0.32 D and mean value of 1.73 D. The combination of the Symbiose Mid and Plus IOLs can theoretically provide a TDOF of 2.90 D in case one is implanted in one eye and the other in the fellow eye.

[*J Refract Surg*. 2020;36(9):578-584.]

Premium multifocal intraocular lenses (IOLs) are being developed to compensate for the loss of near and intermediate vision due to presbyopia by restoring functional vision at several distances. Different optical approaches to achieve multifocality in an IOL can be found on the market today. This difference between IOL designs makes it difficult to compare their performance.

Bifocal multifocal IOLs were developed to provide two foci of sharp vision (far and near), because they feature an addition power for near focus, but image quality at intermediate distances was compromised. Trifocal multifocal IOLs were designed to overcome this limitation by providing an intermediate focus for visual tasks such as computer use while keeping good far and near visual acuity. The depth of focus of these foci was limited, so there were gaps of poor image quality between them that caused poor visual acuity in patients implanted with trifocal lenses.[1,2] Extended depth of focus (EDOF) lenses were developed to provide an extended range of sharp vision, covering a continuous interval from far to intermediate distances.[3]

Many in vitro and clinical studies have compared the performance of bifocal, trifocal, and EDOF lenses. In particular, clinical studies comparing bifocal and trifocal multifocal IOLs have shown a statistically significant decrease in visual acuity outside foci, providing patients with a non-continuous depth of focus.[4-6]

From the Departamento de Investigaciones Clínicas, Vista Ircovisión Oftalmólogos, Murcia, Spain (JFZ-D, MAR-I, JL-B); Grupo de Ciencias de la Visión de la Universidad de Murcia, Murcia, Spain (JFZ-D, NO-A, NL-G); Grupo de Investigación Multidisciplinar en Ciencias de la Visión, Universidad Católica San Antonio de Murcia, Murcia, Spain (JL-B); and Groupe Optométrie, LPCMME, Oran, Algeria (NO-A).

Submitted: January 10, 2020; Accepted: June 16, 2020

Dr. López-Gil is a consultant for Cristalens Industrie. The remaining authors have no financial or proprietary interest in the materials presented herein.

Correspondence: Juan F. Zapata-Díaz, PhD, Vista Ircovisión Oftalmólogos, C/ General Gutiérrez Mellado, 2 Bajo, 30008 Murcia, Spain. Email: juanf.zapata.diaz@gmail.com

doi:10.3928/1081597X-20200720-01

Although EDOF IOLs are relatively new compared to bifocal and trifocal IOLs, several comparative clinical studies have been performed showing an extension of the depth of field from far to intermediate distances.[7,8]

Nevertheless, subjective visual outcomes comparison between multifocal IOLs might be challenging due to the intersubject variability in the eye's optical parameters. The International Organization for Standardization (ISO) provided the guidelines to determine the image quality of ophthalmic implants, including two model eyes in which the IOL should be inserted before measurements.[9] In addition, this regulation proposed the use of the modulation transfer function (MTF) as an image quality measure. Most authors have adopted the through-focus MTF at 50 cycles/mm as the standard objective metric to compare the optical quality of different multifocal IOLs because it provides information for several defocus values.[7,10-15]

Several studies have tried to describe the image quality of IOLs with a single-valued metric, because MTF measurements might be difficult to interpret for a non-scientific audience, or to predict clinical outcomes with objective measurements.[16-22] However, most of these studies focus on the best image quality magnitude without providing information about the range of defocus where the image quality is acceptable, which is directly related to the objectively assessed depth of focus. For multifocal IOLs, the distance intervals of sharp vision could be as important as the maximum image quality value or the maximum visual acuity achieved with such multifocal IOLs. As far as we know, only one recent study has objectively assessed the depth of field of patients implanted with several multifocal IOLs.[23] In that study, the authors used aberrometry measurements to calculate the interval of distances above the 90% of the visual Strehl ratio based on the optical transfer function[24] only on the far focus, evaluating from +1.00 to -1.00 diopters (D) of defocus. However, the high wavelength dependence of diffractive multifocal IOLs (with typical higher MTF peaks in red light for far vision and on the contrary higher MTF peaks in blue light for near vision)[25] should also be taken into account when doing such measurements.[26]

We propose a new metric to compare the total depth of focus (TDOF) of different multifocal IOLs objectively, using optical bench measurements of the MTF at 50 cycles/mm for several defocus values. This TDOF metric is intended to provide ophthalmologists and patients with further knowledge to make it easier to select the appropriate IOL to match patient expectations. We also provide three-dimensional maps of the through-focus MTF at all spatial frequencies from 0 to 100 cycles/mm to illustrate the variation of performance of diffractive IOLs according to the size of the details within the object.

MATERIALS AND METHODS

MULTIFOCAL IOLS

Five different types of multifocal IOLs were analyzed in this study, all of them producing multifocality by diffraction of light on one of their surfaces. Descriptions of the multifocal IOLs and their technical specifications follow (**Table 1**).

The FineVision Micro F (PhysIOL) is a one-piece, four closed-loop trifocal IOL made of yellow hydrophilic material. The light energy distribution among the three foci is rendered possible by the patented superposition of two specific diffractive kinoform patterns.[27] Addition powers are 1.75 D (80 cm at corneal plane) and 3.50 D (40 cm at corneal plane) for a 546-nm wavelength (green) and an aberration-free cornea.

The Acrysof IQ PanOptix (Novartis) is a trifocal IOL (a quadrifocal with one suppressed focus) made of ultraviolet light-blocking and blue light-filtering hydrophobic acrylic material. It has a non-apodized diffractive design and provides a near sight point at 40 cm (addition of 3.25 D at IOL plane) and a far sight point identical to the ReSTOR model, presenting the additional benefit of an intermediate focal point at 60 cm (addition of 2.17 D at IOL plane).

The Tecnis Symfony (Johnson & Johnson) is a monobloc C-loop clear hydrophobic IOL designed to provide an EDOF from far to intermediate distances.[28] In monochromatic green light, this IOL delivers two peaks of MTF at far and intermediate foci (approximately 1.75 D at the IOL plane), using the higher diffractive orders +1 and +2 instead of 0 and +1 orders, as is usually the case.[29,30]

The Artis Symbiose Mid (Cristalens Industrie) is a monobloc lens with four closed-loop haptics made of clear ultraviolet light-blocking hydrophobic material. Its diffractive profile is designed with a new patented profile to provide a continuous through-focus phase (the argument of the optical transfer function) from intermediate to near vision, and coupling the Artis Symbiose Plus profile to obtain extended sharp vision from 1.50 to 3.75 D without discontinuity when implanted in the same patient, while keeping high contrasted far vision. The Artis Symbiose Mid lens dedicates a larger amount of light energy to a low addition rather than to a high addition focal plane.

The Artis Symbiose Plus (Cristalens Industrie) has technical characteristics similar to the Artis Symbiose Mid lens, except that it dedicates a larger amount of light at a higher addition focal plane than the Artis Symbiose Mid lens.

OPTICAL QUALITY ASSESSMENT

The image quality of the multifocal IOLs was analyzed using the commercial optical bench PMTF

TABLE 1
Specifications of the Five Multifocal Intraocular Lenses Analyzed

Parameter	FineVision	Acrysof IQ PanOptix	Tecnis Symfony	Artis Symbiose Mid	Artis Symbiose Plus
Far optical power (D)	+20.00	+19.50	+20.00	+22.50	+24.50
Optical zone diameter (mm)	6.00	6.15	6.00	6.00	6.00
Design	Apodized diffractive	Non-apodized diffractive	Posterior achromatic diffractive surface	Apodized continuous phase diffractive	Apodized continuous phase diffractive
Intermediate addition (D)	+1.75	+2.17	+1.75	Continuous and complementary from 1.50 to 3.75 D	
Near addition (D)	+3.50	+3.25	–		
Spherical aberration (μm)	-0.11	-0.10	-0.27	-0.23	-0.23
Pupil dependence	Dependent	Less dependent	Independent	Dependent	Dependent

D = diopters
The FineVision is manufactured by PhysIOL; the Acrysof IQ PanOptix is manufactured by Novartis; the Tecnis Symfony is manufactured by Johnson & Johnson; and the Artis Symbiose Mid and Artis Symbiose Plus are manufactured by Cristalens Industrie.

(Lambda-X). This device is in compliance with the international standard ISO 11979-2.[9]

After a calibration of the apparatus using 10 monofocal IOLs with exact power previously assessed using another instrument based on a different technology (NIMO TR1504; Lambda-X), the lenses were placed in an 11-mm diameter holder before being inserted in the wet cell, which was filled with NaCl 0.9% physiological saline with the anterior side of the IOL facing the incident light. The holder guarantees a tilt-free orientation of the multifocal IOL while being inspected. The device detects the optical axis of the multifocal IOL with 0.2 mm of precision. Centration was carefully checked, ensuring the center of the star object (Siemens target) did not move when the microscope of the PMTF moved along the whole range of vergences tested (usually > 5.00 D).

Optical Quality Parameters

The MTF measurements of each IOL were assessed for a 3-mm pupil and a spherical aberration–free cornea from 0 to 100 cycles/mm (corresponding to a visual acuity of 20/20 in far vision). The through-focus MTF was obtained in 0.10-D steps for approximately 5.00 D, covering all focal planes of the multifocal IOLs. Illustrative images of a United States Air Force (USAF) resolution target were obtained for defocus values between 0.00 and -5.00 D in 0.50-D steps, in addition to an additional step at -1.75 D to include the intermediate focus of the FineVision Micro F and the Tecnis Symfony multifocal IOLs.

Data Processing

Once the through-focus MTF data were obtained and recorded, two types of processing were performed. First, the axial axis of the through-focus MTF at 50 cycles/mm for a 3-mm pupil was shifted to make the first maximum of the MTF value (corresponding to the far focal position) matching 0.00 D. This was a simple procedure in Microsoft Excel (Microsoft Corporation) that allowed us to compare the through-focus MTF among the multifocal IOLs, because they did not have the same nominal power (**Table 1**). Second, all through-focus MTFs at 50 cycles/mm data for each case were parameterized using Matlab software (Mathworks) and its built-in function Piecewise Cubic Hermite Interpolating Polynomial. This new curve was evaluated between -5.00 and 0.00 D in 0.001-D steps. A threshold MTF value of 0.15 was used to calculate the dioptric intervals of defocus in which the interpolated MTF curve was above this value. The sum of these intervals was adopted as the TDOF for each lens (**Figure 1**). It is worth pointing out that the TDOF does not include the dioptric range beyond the infinite (through-focus MTF above 0.15 on the positive part of x-axis, as shown in **Figure 1**) to optimize distance vision, because patients are frequently looking at objects placed far away.

RESULTS

Figure 2 shows the through-focus MTF at 50 cycles/mm of the five multifocal IOLs analyzed in this study for a 546-nm wavelength (green) and a 3-mm pupil. The MTF values of all far foci were between 0.34 (FineVision Micro F multifocal IOL) and 0.43 (Tecnis Symfony multifocal IOL). The FineVision IOL exhibited three local maxima of the MTF corresponding to the three foci, but with gaps with low image quality between them. The Tecnis Symfony multifocal IOL showed two local maxima for far and intermediate distances for these conditions. These maxima presented the highest image quality among all of the multifocal IOLs. The Acrysof IQ PanOptix multifocal IOL created three maxima corresponding to the three foci of the lens, but the intermediate and near foci were continuous, avoiding a gap between them. The Artis Symbiose Mid and Plus multifocal IOLs presented two local maxima each. The Artis Symbiose Plus multifocal IOL showed the highest image quality for near distances among all five multifocal IOLs. The Artis Symbiose Mid multifocal IOL created a wider maximum for the second focus, covering from intermediate to near distances, having higher image quality for intermediate distances. In contrast, the Artis Symbiose Plus multifocal IOL exhibited a second focus with higher image quality for near distances. The through-focus MTF of both Artis Symbiose multifocal IOLs were complementary, showing an intersection of their near and intermediate foci at 2.79 D of defocus (at IOL plane).

Figure A (available in the online version of this article) expands the information shown in **Figure 2**, including the through-focus MTF at all spatial frequencies between 0 and 100 cycles/mm for a 546-nm wavelength, a 3-mm pupil, and a spherical aberration–free corneal model. It can be seen how the performance of the multifocal IOLs depends on the spatial frequency of the object. Thus, for objects with low spatial frequencies, the image quality provided by the multifocal IOLs is higher and more continuous, whereas with objects with higher spatial frequencies these multifocal IOLs present lower image qualities. It is worth noting that at 100 cycles/mm, the FineVision Micro F multifocal IOL has almost no intermediate contrast anymore, whereas the Acrysof IQ PanOptix multifocal IOL was not continuous anymore between near and intermediate foci for such spatial frequency.

The TDOF of the five multifocal IOLs is presented in **Table 2**, along with the depth of focus at each distance zone (far, intermediate, and near). As can be seen, at the far focus all multifocal IOLs had similar depth of focus, ranging from 0.49 to 0.59 D. At intermediate distances, the Artis Symbiose Mid multifocal IOL created the longest depth of focus (1.22 D), whereas the FineVision Micro F multifocal IOL exhibited the shortest one (0.36 D). At the near focus, the Artis Symbiose Plus multifocal IOL showed the longest depth of focus (1.19 D), whereas the FineVision Micro F multifocal IOL presented the shortest one (0.73 D). The TDOF for 50 cycles/mm of the individual lenses ranged from 1.71 D (Tecnis Symfony) to 1.90 D (Acrysof IQ PanOptix). Mean TDOF of all multifocal IOLs tested was 1.73 D. In addition to the TDOF obtained for the standard spatial frequency of 50 cycles/mm, **Table 2** also includes that value for two other spatial frequencies: 25 and 75 cycles/mm. For 25 cycles/mm, the largest TDOF corresponded to the Artis Symbiose Mid lens, whereas for 75 cycles/mm the Tecnis Symfony lens presented the largest TDOF.

Because the Artis Symbiose Mid and Plus multifocal IOLs were designed to be implanted in the same patient in different eyes, we also analyzed the TDOF of both lenses together. For that purpose, we just added both through-focus MTF curves assuming that the visual system would use the the eye with the highest contrast value. Although usually the contrast detected by both eyes is better than that detected by one eye separately,[31] we assumed a more pessimistic scenario for the simulation of binocular vision, finding a TDOF of 2.90, 4.00, and 1.35 D for spatial frequencies of 50, 25, and 75 cycles/mm, respectively. These values are larger than any other value obtained for each of the IOLs analyzed individually.

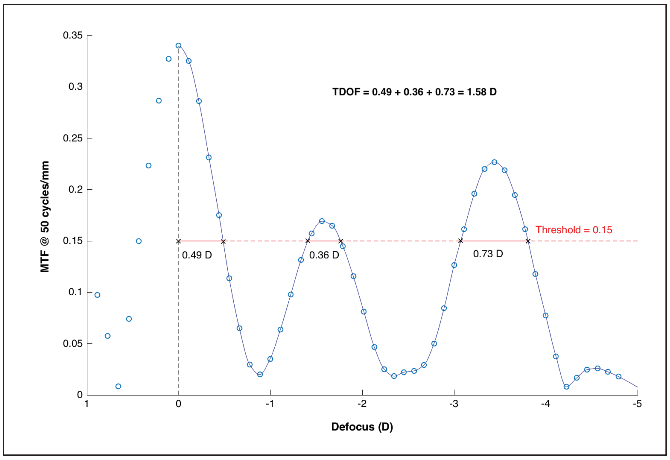

Figure 1. One example of the fitted through-focus modulation transfer function (TFMTF) curve including the different depth of focus (DOF) ranges. Blue circles represent real measurements and the blue line represents data interpolation. The dashed red line is the threshold MTF value between 0.00 and -5.00 diopters (D) of defocus. Black crosses are the intersections between the TFMTF curve and the threshold. Full red lines represent the DOF dioptric intervals (with numerical values below lines). TDOF = total depth of focus

Figure B (available in the online version of this article) is an illustrative matrix of the USAF target imaging for several defocus values. It is aimed to provide the reader with more information about the performance of the multifocal IOLs analyzed in this study.

DISCUSSION

Although other studies of the through-focus MTF performance of the Tecnis Symfony,[7,25] Acrysof IQ PanOptix,[25] and FineVision Micro F[10,12,15] lenses exist, we added to the comparison two new multifocal IOLs (Artis Symbiose Mid and Plus) whose in vitro optical performances were measured for the first time, as far as we know. We also introduced for the first time an objective metric based on a single value (the TDOF), allowing the eye care professional to have a quick idea of the optical performance of a multifocal IOL for the whole range of vergences.

Figure 2 and **Figure A** show that the Tecnis Symfony multifocal IOL presented the largest optical per-

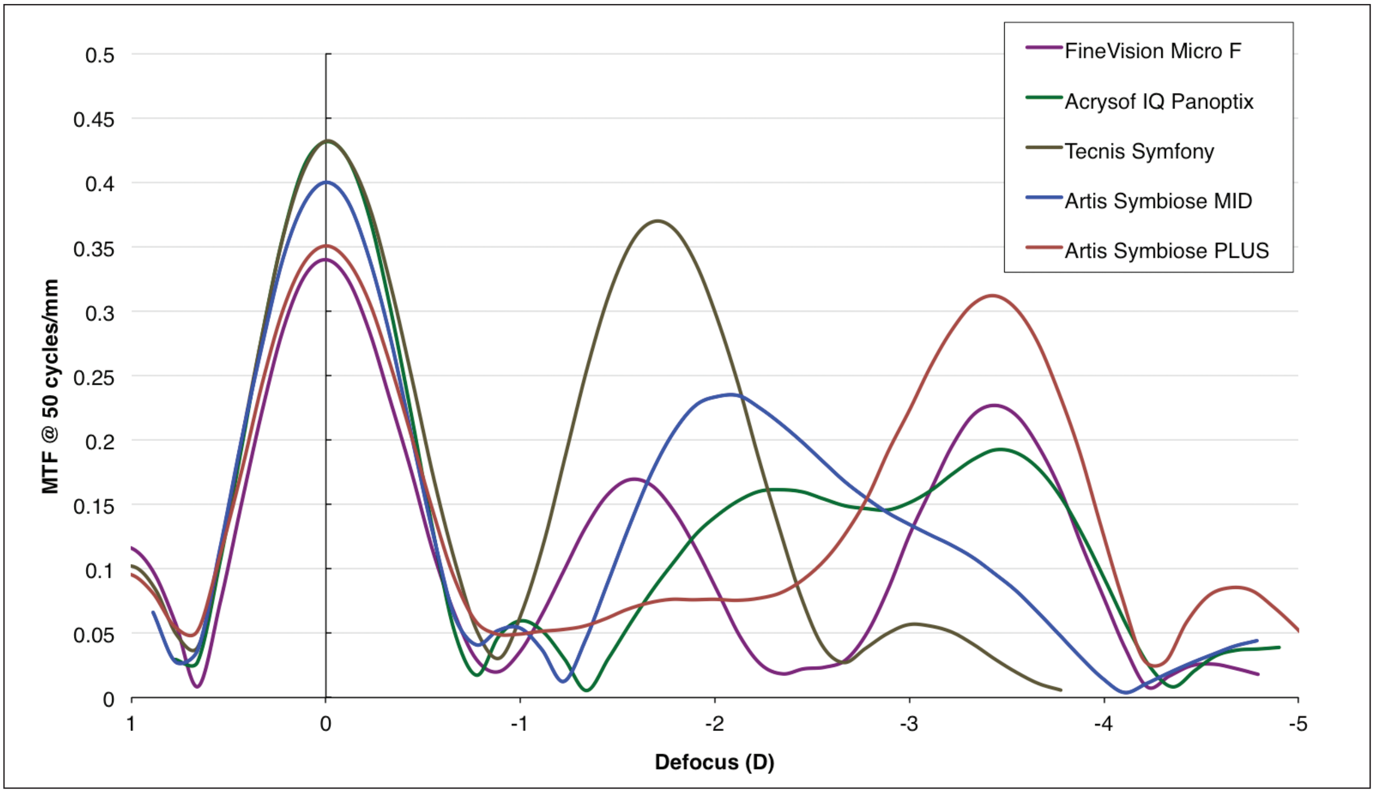

Figure 2. Through-focus modulation transfer function (TFMTF) of the five lenses analyzed in this study in an aberration-free eye model, for a 3-mm pupil and a 546-nm wavelength (green light). The FineVision is manufactured by PhysIOL; the Acrysof IQ PanOptix is manufactured by Novartis; the Tecnis Symfony is manufactured by Johnson & Johnson; and the Artis Symbiose Mid and Artis Symbiose Plus are manufactured by Cristalens Industrie. D = diopters

TABLE 2
DOF Results

	50 cycles/mm				25 cycles/mm	75 cycles/mm
Lens	**Far DOF (D)**	**Intermediate DOF (D)**	**Near DOF (D)**	**TDOF (D)**	**TDOF (D)**	**TDOF (D)**
FineVision Micro F	0.49	0.36	0.73	1.58	2.90	0.71
Acrysof IQ PanOptix	0.53	0.55	0.82	1.90	2.93	0.83
Tecnis Symfony	0.59	1.12	–	1.71	2.92	1.16
Artis Symbiose Mid	0.52	1.22		1.74	3.54	0.75
Artis Symbiose Plus	0.54	1.19		1.73	2.84	1.02
Artis Symbiose Mid + Plus	0.54	2.36		2.90	4.00	1.35

DOF = depth of focus; D = diopters; TDOF = total depth of focus
The FineVision is manufactured by PhysIOL, the Acrysof IQ PanOptix is manufactured by Novartis; the Tecnis Symfony is manufactured by Johnson & Johnson; and the Artis Symbiose Mid and Artis Symbiose Plus are manufactured by Cristalens Industrie.

formance at far (0.00 D) and intermediate (approximately -1.75 D) distances, because it was designed to concentrate the light energy on these two vergences, producing low contrast images at vergences below -2.50 D, thus penalizing near vision. The Acrysof IQ PanOptix lens showed the largest TDOF due to its special quadrifocal design, which redirects its third focus to generate a trifocal multifocal IOL allowing intermediate and near foci to overlap with a relatively high contrast value (**Figure 2**). Both Artis Symbiose multifocal IOLs showed a similar TDOF, although the Mid lens presented a higher contrast value for intermediate vision and the Plus lens concentrated more energy on the near focus, showing a higher performance for near vision. In general, all multifocal IOLs showed similar TDOF, with a mean between-multifocal IOL value of 1.73 D and a standard deviation of 0.11 D. The range of the TDOF between the multifocal IOLs was 0.32 D, slightly higher than the usual clinical significance value of the power of a lens: a quarter of diopter.

Although only in vitro measurements are shown in this study, we can expect the combination of both Artis Symbiose (Mid and Plus) lenses to give the largest clinical TDOF. Through-focus USAF images in **Figure 4** also predict this result when comparing the last two rows corresponding to the Artis Symbiose IOLs. With the exception for a vergence of -1.00 D, it is possible to record a relatively good USAF image with the Artis Symbiose Mid and Plus multifocal IOLs on the rest of vergences. In our simulations, this TDOF value corresponds to almost 3.00 D (**Table 2**), which represents an interval of vision large enough to cover all visual necessities of individuals with presbyopia, taking into account that presbyopia is usually defined when the amplitude of accommodation falls below 3.00 D.[32] Future clinical defocus curves of patients implanted with the Artis Symbiose set of lenses may confirm this prediction based on in vitro measurements.

Finally, there are some limitations of this study. First, only one pupil diameter (3 mm) and only one corneal model have been analyzed in this study. We selected a 3-mm pupil because it represents the typical pupil diameter for a population older than 60 years (usually the age of patients with cataract) in photopic conditions.[33,34] For this pupil size, the effect of any potential spherical aberration of the cornea is small. Future studies should include values for larger pupils and the effect of a cornea with positive spherical aberration to investigate the performance of these lenses in mesopic conditions. In addition, we have used a threshold value of 0.15 in the definition of TDOF. This selection was based on the fact that this value should be higher than a 0.10 threshold, which represents the value for low contrast visual acuity testing, but enough to get a resolving letter at the retinal plane, which have been proved for a contrast of 0.16, which is the value of the intermediate focus of the FineVision multifocal IOL (**Figure 2**).[35]

AUTHOR CONTRIBUTIONS

Study concept and design (JFZ-D, MAR-I, JL-B, NL-G); data collection (JFZ-D, NL-G); analysis and interpretation of data (JFZ-D, MAR-I, NO-A, NL-G); writing the manuscript (JFZ-D, MAR-I, NO-A, NL-G); critical revision of the manuscript (JFZ-D, MAR-I, NO-A, JL-B, NL-G); statistical expertise (JFZ-D); administrative, technical, or material support (MAR-I, JL-B); supervision (MAR-I, JL-B, NL-G)

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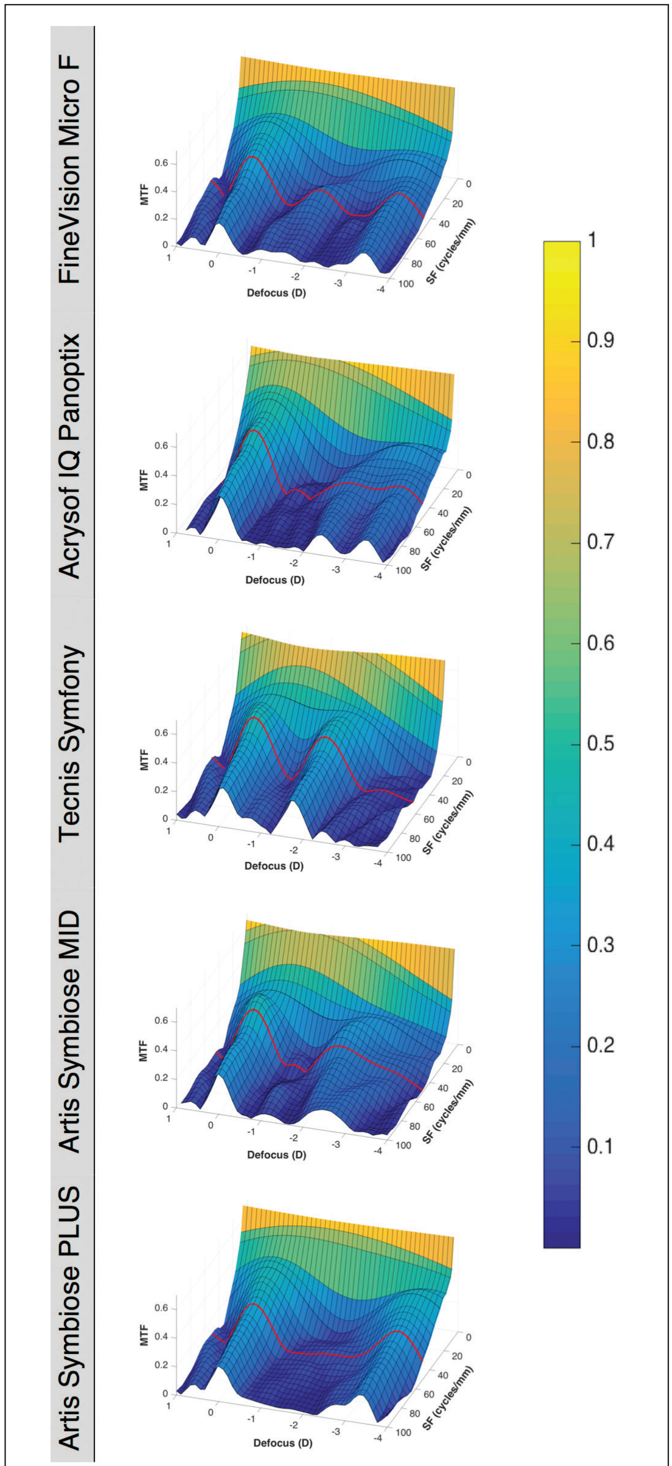

Figure A. Through-focus modulation transfer function (TFMTF) from 0 to 100 cycles/mm of the five multifocal intraocular lenses (IOLs) recorded for a 546-nm wavelength and a 3-mm pupil. The red line represents the TFMTF at 50 cycles/mm of each lens. SF = spatial frequency; D = diopters. The FineVision is manufactured by PhysIOL; the Acrysof IQ PanOptix is manufactured by Novartis; the Tecnis Symfony is manufactured by Johnson & Johnson; and the Artis Symbiose Mid and Artis Symbiose Plus are manufactured by Cristalens Industrie.

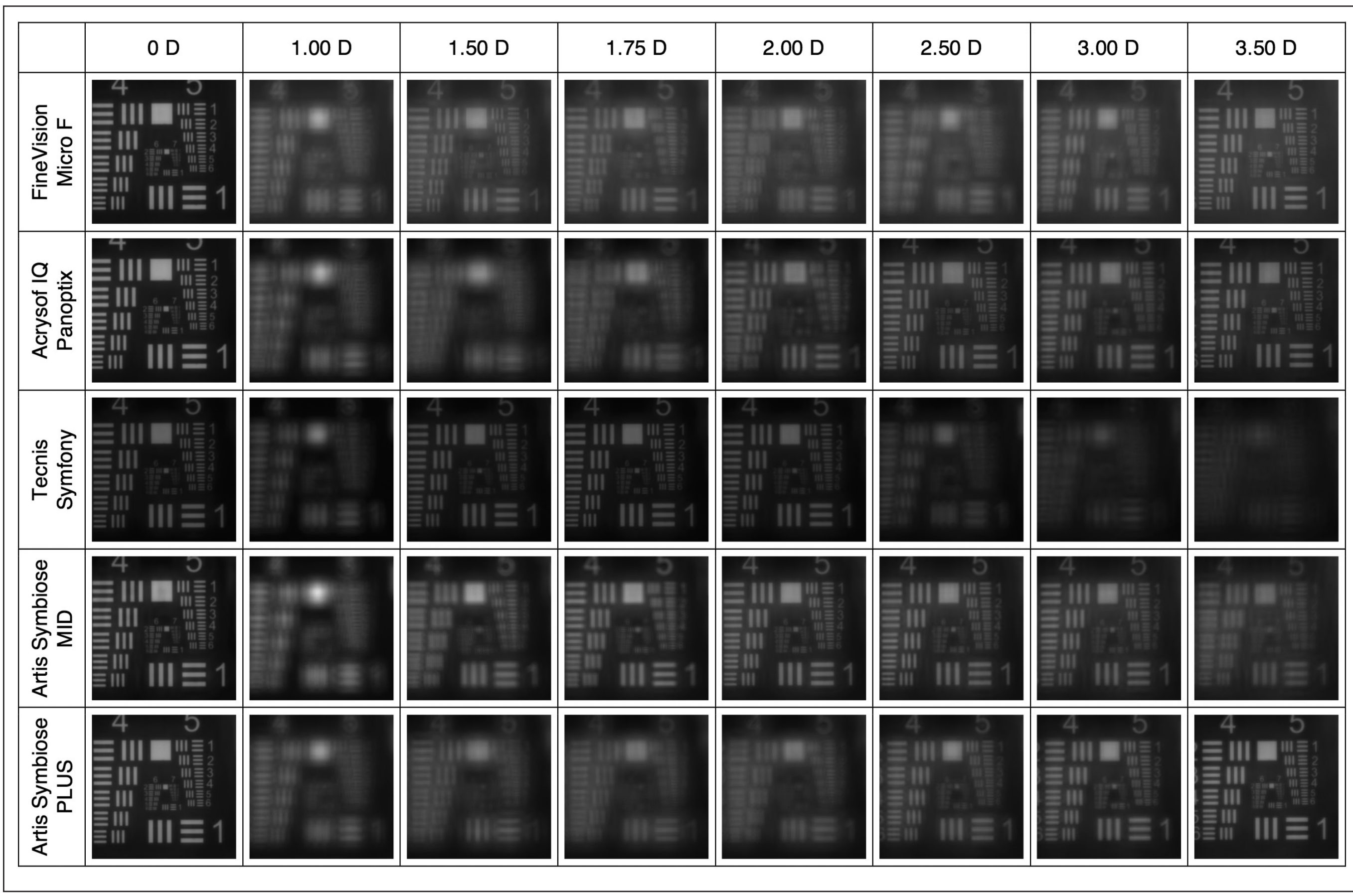

Figure B. Through-focus United States Air Force imaging. Upper row shows the defocus steps at which the images were recorded. D = diopters. The FineVision is manufactured by PhysIOL; the Acrysof IQ PanOptix is manufactured by Novartis; the Tecnis Symfony is manufactured by Johnson & Johnson; and the Artis Symbiose Mid and Artis Symbiose Plus are manufactured by Cristalens Industrie.