Comparison of bifocal and trifocal diffractive and refractive intraocular lenses using an optical bench

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PURPOSE: To assess the differences in optical performance of 9 multifocal IOLs using the same optical bench and to propose a possible comparison for surgeons.

SETTING: Rothschild Foundation, Paris, France.

DESIGN: Experimental study.

METHODS: Nine IOLs (Acrysof Restor +3.0 diopter [D] SN6AD1, Acrysof Restor +4.0 D SN60D3, Acrysof aspheric monofocal SN60WF, Acri.Lisa 366D, Finevision Micro F, Tecnis ZM900, and Rezoom, Diffractiva Diff-s, and Lentis Mplus +3.0 D) were tested using the same optical bench that complies with International Organization for Standardization standard 11979 requirements. The through-focus modulation transfer functions (MTFs) were compared, and the image of the United States Air Force (USAF) target was taken while each IOL was at far, intermediate, and near focal points.

RESULTS: The through-focus MTF of the trifocal IOL showed a peak in the intermediate range that was not present with monofocal and bifocal IOLs. The USAF target images showed similar resolution with all IOLs for far focal points. Diffractive IOLs showed better resolution for near focal points, and the only sharp image in the intermediate range was obtained using the trifocal IOL.

CONCLUSION: There was a significant difference in the degree of near, intermediate, and distance quality of the image with the various types of multifocal IOLs in vitro. Intermediate vision was more prominent with the trifocal IOL.

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Multifocal intraocular lenses (IOLs) are designed to increase the depth of the field of vision and to enhance near vision for cataract patients. The International Organization for Standardization (ISO) standard 11979-2[1] has been used to define how the optical quality of multifocal IOLs or any IOL should be assessed. Measurement of the modulation transfer function (MTF) is now recognized as a routine test for measuring the optical quality of IOLs.[2] The MTF of an optical system describes the amount of contrast that is passed through the system for a given spatial frequency or object size; it is defined as the amplitude of the image contrast divided by the amplitude of the object contrast and is a function of spatial frequency. The contrast decreases more rapidly at higher spatial frequencies (ie, the number of line pairs per millimeter) or with object size. Pupil size also affects the relative power distributions of the light generated by various multifocal designs. Optical bench evaluations, such as MTF testing, provide valuable information on the optical quality of IOLs.[3–5]

In addition to MTF testing, the visualization of targets via multifocal IOLs may help surgeons evaluate the optical performances of various multifocal IOLs. Terwee et al.,[6] Maxwell et al.,[2] and Kim et al.[7] were the first to provide images of targets via multifocal IOLs. These images were more representative of the patient's vision than the MTF or cross-correlation curves. Since 2010, 2 innovative IOLs have been introduced to the market. One is fully diffractive and

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trifocal (Finevision Micro F, PhysIOL S.A.) and the other is refractive with rotational asymmetry (Lentis Mplus, Oculentis GmbH). These IOLs were compared with those already available on the market.

This research was performed to aid surgeons in comparing the optical performances of different multifocal IOL designs to better match the performances with the patient's expectations and ocular characteristics, such as pupil diameter. Outcomes of the tests performed on 9 IOL models, including 1 monofocal, 2 refractive, 2 bifocal diffractive, 1 diffractive trifocal, and 3 bifocal diffractive with diffractive optic reduced to the central part, are presented here. It is important to note that every diffractive IOL is a refractive–diffractive IOL because the far focus is always produced via refraction.

MATERIALS AND METHODS

Intraocular Lenses

The following multifocal IOLs were tested: the aspheric monofocal Acrysof SN60WF, the Acrysof Restor +4.0 diopter (D) SN60D3, and the aspheric Acrysof Restor +3.0 D SN6AD1 (all Alcon Laboratories, Inc.); the Acri.Lisa 366D (Carl Zeiss Meditec AG); the Finevision Micro F; the Tecnis ZM900 and the Rezoom (both Abbott Medical Optics, Inc.); the Diffractiva Diff-s (Human Optics AG); and the Lentis Mplus +3.0 D. The Diffractiva Diff-s and Acrysof Restor +3.0 D SN6AD1 have an add power of +3.00 D; the Finevision Micro F, +3.50 D; the Acri.Lisa 366D, +3.75 D; and the Tecnis ZM900 and the Acrysof Restor +4.00 D SN60D3, +4.00 D. The Lentis Mplus LS-312 MF30 provides an add of +2.75 D and the Rezoom, of +3.50 D.

Table 1 shows the differences between the diffractive IOLs. The Finevision Micro F IOL (Figure 1, *top*) is a combination of 2 bifocal diffractive patterns, of which 1 is for far and near vision and the other for far and intermediate vision. This design has been described comprehensively by Gatinel et al.[8]

The Lentis Mplus LS-312 MF30 is a refractive IOL (Figure 1, *bottom*) and contains an aspheric distance-vision zone combined with a 3.00 D posterior sector-shaped near-vision zone. Theoretically, light hitting the transition area of the embedded sector is reflected away from the optical axis to prevent the superposition of interference or diffraction. The ultraviolet-filtering hydrophilic copolymer acrylic IOL has a hydrophobic surface, a biconvex design, a 6.0 mm optical zone, an overall length of 12.0 mm, and a 360-degree continuous square optic and haptic edge.

Optical Bench

The PMTF optical bench was developed by Lambda-X to measure the image quality (MTF) of diffractive multifocal IOLs. This equipment complies with the requirements of ISO standards 11979-2[1] and 11979-9[9] and was designed to measure multifocal IOLs accurately. Figure 2 shows a schematic of this equipment. It measures lenses using a patented quantitative deflectometry technique based on phase-shifting principles, which enable precise measurements based on the deviation of light beams. The source wavelength is 545 nm. The image obtained via the IOL is collected by a microscope and is analyzed by the software. After image processing, an MTF curve is obtained.

To measure the optical quality of an IOL, ISO 11979-2[1] specifies the use of a model eye, including an aberration-free model cornea, and measuring at different apertures so that any aberration observed or the effect of any aberration on image quality will result from the IOL itself. In the literature, other types of model eyes have been proposed to take into account the positive spherical aberration of the human cornea.[4] To approximate the actual aberration of the average human cornea, the original ISO model has been modified tentatively to provide different levels of spherical aberration. However, there is no consensus on the exact value of aberration that must be used. Aberration values are often chosen depending on the IOL that the authors would like to highlight rather than using objective criteria. For example, Maxwell et al.[2] used a model eye with an aberration of 0.2 μm, and Pieh et al.[4] used an aberration of 0.26 μm. In this study, an aberration-free model eye was used to emphasize the effect of the IOL itself.

The IOL is placed in an 11.0 mm diameter holder before being inserted into the interferometrically tested wet cell, which is filled with deionized water, with the anterior side of the IOL facing the incident light. The holder guarantees tilt-free orientation of the IOL while being inspected. The device detects the optical axis of the IOL automatically, which ensures 0.2 mm of precision when positioning the IOL. The collimated light (546 nm) passed through the artificial cornea singlet is focused on the IOL, thereby simulating the vergence of a human eye. The software automatically locates the best focus at 50 line pairs/mm for the distance lens power because the charge-coupled device camera can be moved using a rail, thus providing the peak signal intensity for each position using a through-focus algorithm.

Measurements can be made at various apertures (2.00 mm, 3.00 mm, 3.75 mm, and 4.50 mm) without removing the IOL from the holder so that all measurements are performed using the same IOL alignment. The MTF measurements at various spatial frequencies and at different (de)focused planes are performed to achieve through-frequency and through-focus curves for different pupil apertures. The peak of the MTF, which is measured at all distances between the far point and the near point, is transposed into a curve that is called the through-frequency MTF, where the x-axis is the defocus expressed as diopters (D) and the y-axis is the maximum MTF value.

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Table 1. Comparative characteristics of common diffractive bifocal multifocal IOLs and Physiol trifocal multifocal IOL.

IOL	Diffractive Optic	Additional Power for Near Vision (D)	Pupil Dependent	Diffractive Steps (n)
Tecnis ZM900	Fully	+4.00	No	32
Acri.Lisa 366D	Fully	+3.75	No	28
Acrysof Restor +3.0 D SN6AD1	Diffractive from 0.0 to 3.6 mm diameter and then monofocal	+3.00	Yes	9
Acrysof Restor +4.0 D SN60D3	Diffractive from 0.0 to 3.6 mm diameter	+4.00	Yes	12
Finevision Micro F	Fully	+3.50	Yes	26
Diffractiva Diff-s	Diffractive from 0.0 to 3.4 mm diameter and then monofocal	+3.50	Yes	9

IOL = intraocular lens

The United States Air Force (USAF) 1951 Resolution Target test can be performed in the PMTF system. The setup is identical to the MTF test except that the slit object is replaced with the Air Force target. This feature enables estimation of IOL performance at far distance and, if applicable, near and intermediate distances. The equipment and the analysis software were validated using calibration glass lenses that were simulated theoretically.

Tests

The through-focus MTFs are measured using 3.0 mm, 3.75 mm, and 4.5 mm apertures at 50 cycles/mm in the ISO-standardized model eye; that is, as the focus is shifted gradually from a far object (at infinity) to increasingly closer object distances. This spatial frequency corresponds to the fundamental frequency of the 20/40 line on the Snellen eye chart.

The USAF test (Figure 3) provides horizontal and vertical paired 3-bar targets of different spatial frequencies to assess resolution efficiency qualitatively, which is determined by comparing the finest pattern for which both horizontal and vertical bars can be distinguished clearly.[2] Three photographs (at far, intermediate, and near focal distances) of the 1951 USAF target (Figure 3) are shot, using the peak of the through-focus MTF to determine the camera position that results in the most resolved image. If it was not possible to determine an intermediate focal position due to the absence of a peak in the through-focus MTF between the far peak and near peak, the median position between the far peak and near peak was chosen.

RESULTS

Figure 4 shows the through-focus MTF values measured for the 9 IOLs (the diffractive IOLs, the refractive bifocal IOLs, and the monofocal IOL) for each different pupil aperture (3.0 mm, 3.75 mm, and 4.5 mm).

eFigure 5 to eFigure 13 (available at http://jcrsjournal.org) show an image of the USAF target for far, intermediate, and near vision for each IOL at a 3.0 mm pupil aperture. For each image, the camera was positioned at the distance corresponding to a peak of the through-focus MTF.

The percentage light distribution can be approximated from the MTF area beneath the peaks of different foci. Figure 4 shows that all diffractive multifocal IOLs measured in this study were primarily designed for distance viewing at any aperture. Indeed, the amount of energy directed to far-vision focus was superior to that directed for near-vision focus for all apertures of 3.0 to 4.5 mm, which is also the case for the refractive multifocal IOL. For the Acri.Lisa 366D and the Tecnis ZM900 IOLs, a similar amount of energy was allocated to both far vision and near vision, regardless of the pupil aperture. This finding was in contrast to the Acrysof Restor +3.0 D, Acrysof Restor +4.0 D, Diffractiva Diff-s, and Finevision Micro F diffractive multifocal IOLs, which increased the percentage of light energy allocated to the far vision with increasing apertures at the expense of the percentage of light energy allocated to the near vision. These IOLs showed a gradual decrease in the height of diffractive steps from the center to the periphery. Thus, these IOLs became more refractive for larger pupils to benefit distance vision. Surprisingly, the Lentis Mplus segmented refractive multifocal IOL displayed the opposite trend; this IOL allocated increasing energy to the near vision when the pupil enlarged.

For comparison, the monofocal Acrysof IOL, which was measured using the same protocol, displayed a single MTF peak assigned to far vision. This peak amplitude decreased significantly with aperture to the point that it became inferior to the far MTF of the Acrysof Restor +3.0 D IOL at a 4.5 mm aperture. Notably, the spherical aberrations of these 2 IOLs were −0.1 μm for the Acrysof Restor +3.0 D IOL and −0.2 μm for the monofocal Acrysof IOL. This difference, observed when using an aberration-free cornea on the optical bench, explains this apparent discrepancy, which showed a better MTF for a diffractive multifocal IOL than for a monofocal IOL.

Figure 1. *Top*: Finevision Micro F IOL. *Bottom*: Lentis Mplus IOL.

Addition Power

The position of the highest point of the second peak on the through-focus MTF curve fixed the addition (add) power assigned to the multifocal IOLs for near vision (Figure 4). No second peak was observed for the Acrysof monofocal IOL.

Intermediate Vision

A third peak appeared in the Finevision Micro F IOL through-frequency at +1.75 D, which corresponded to the foci allocated for intermediate vision.

The diffractive bifocal multifocal IOLs showed a small MTF peak in the intermediate vision range; however, the signal intensity (MTF <0.1) was too low to constitute a true intermediate focus. This finding underscores the importance of integrating the area below the MTF curve. The Rezoom was the only bifocal IOL providing some intermediate vision.

Image Quality

eFigure 5 shows the measured MTFs were consistent with the image quality of the USAF target. The defocused images provided a limited amount of glare. The difference in the amount of energy allocated for far vision, the effect of which is quantifiable on the through-focus MTF curves, is difficult to appreciate when comparing the images of the IOLs studied. The decentration of the near optical zone with respect to the paraxial rays affected the image resolution of both refractive multifocal IOLs, although the MTF curves were superior due to the absence of the higher harmonic images of diffractive optical designs.

DISCUSSION

Since the introduction of different diffractive multifocal IOLs, several publications have sought to assess their optical behavior. In an artificial eye model, Inoue et al.[10] evaluated the ability to observe and treat the retina using a multifocal IOL. Other studies have assessed the quality of vision when looking through a multifocal IOL.

Tognetto et al.[11] compared 24 IOLs on an optical bench by assessing the MTF. The evaluation was performed with the bandwidth of the MTF set at 70%. Gobbi et al.[12] determined the visual acuity when a multifocal IOL was inserted in an artificial eye. Artigas et al.[13] compared the Acrysof Restor SN60D3, the Tecnis ZM900, the refractive Rezoom NGX (Abbott Medical Optics), and the Acrysof SN60WF monofocal IOLs. Their method was based on the image of cross lines converted to point-spread function by image processing. Maxwell et al.[2] assessed the Crystalens AT-50SE (Bausch & Lomb), Acrysof Restor SA60D3 and

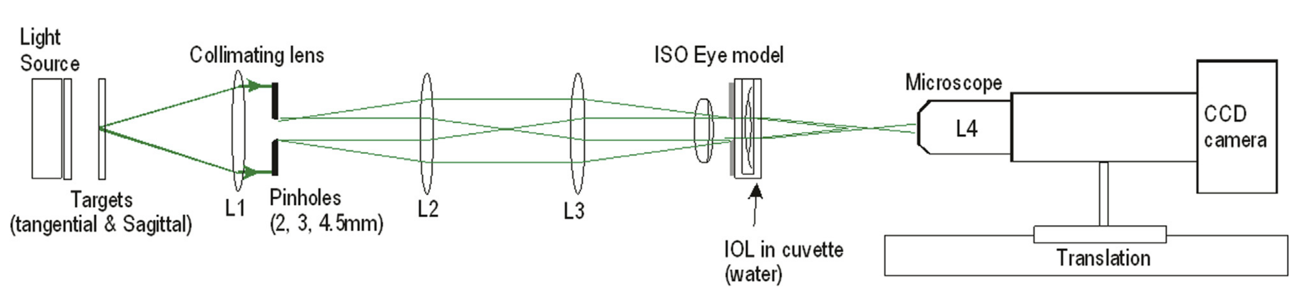

Figure 2. Optical test bench schematic (CCD = charge-coupled device; IOL = intraocular lens; L = lens; OIS = International Organization for Standardization).

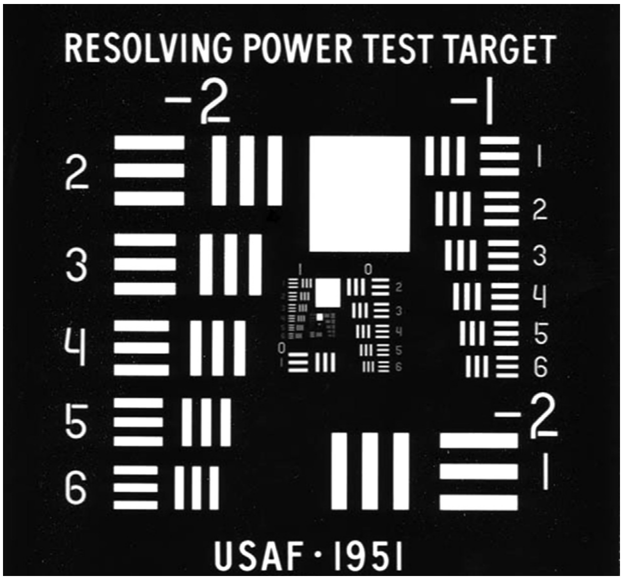

Figure 3. Original 1951 USAF target (USAF = United States Air Force).

SNAD3 (Alcon Laboratories, Inc.), Rezoom NXG1, Acri.Lisa 366D, and Tecnis 900 (Abbott Medical Optics) IOLs. They used the MTF at different apertures and the Air Force test.

Vega et al.[14] used an artificial eye model to show that the energy efficiency was strongly dependent on pupil size and the spherical aberrations achieved. Kim et al.[7] used an optical bench to study the focus MTFs of the Acrysof Restor +4.0 D SN6AD3 (Alcon Laboratories, Inc.), the Acrysof Restor +3.0 D SN6AD1, the Rezoom NGX1, the Tecnis monofocal ZM900, and the Crystalens HD500 (Bausch & Lomb). They also visualized a resolution target (Sloan letter Es) through those IOLs and found that multifocality was effective and that bifocal IOLs provided effective far and near vision with a related decrease in the contrast of far vision. They also concluded that there was a loss in image quality when viewing targets at an intermediate distance with the bifocal IOLs.

Our study had similar outcomes. To our knowledge, this is the first study to compare a trifocal IOL with bifocal IOLs using through-frequency MTF curves. We observed a lack of intermediate vision with bifocal IOLs, whereas a distinct peak at the intermediate distance was obvious for the trifocal diffractive IOL. Tognetto et al.[11] showed that no significant variability was found when the measurements using each IOL model were repeated. He showed that any variability within measurements of different types of IOLs can consequently be accepted with certainty. All IOLs used were 20.0 D in power; hence, our results do not indicate how the IOL designs assessed may differ with the base power of the IOL.

With respect to resolution, the 2 refractive IOLs provided poorer outcomes than any diffractive IOL except for far vision via a 3.0 mm aperture. This finding has been reported by Maxwell et al.[2] in patients using

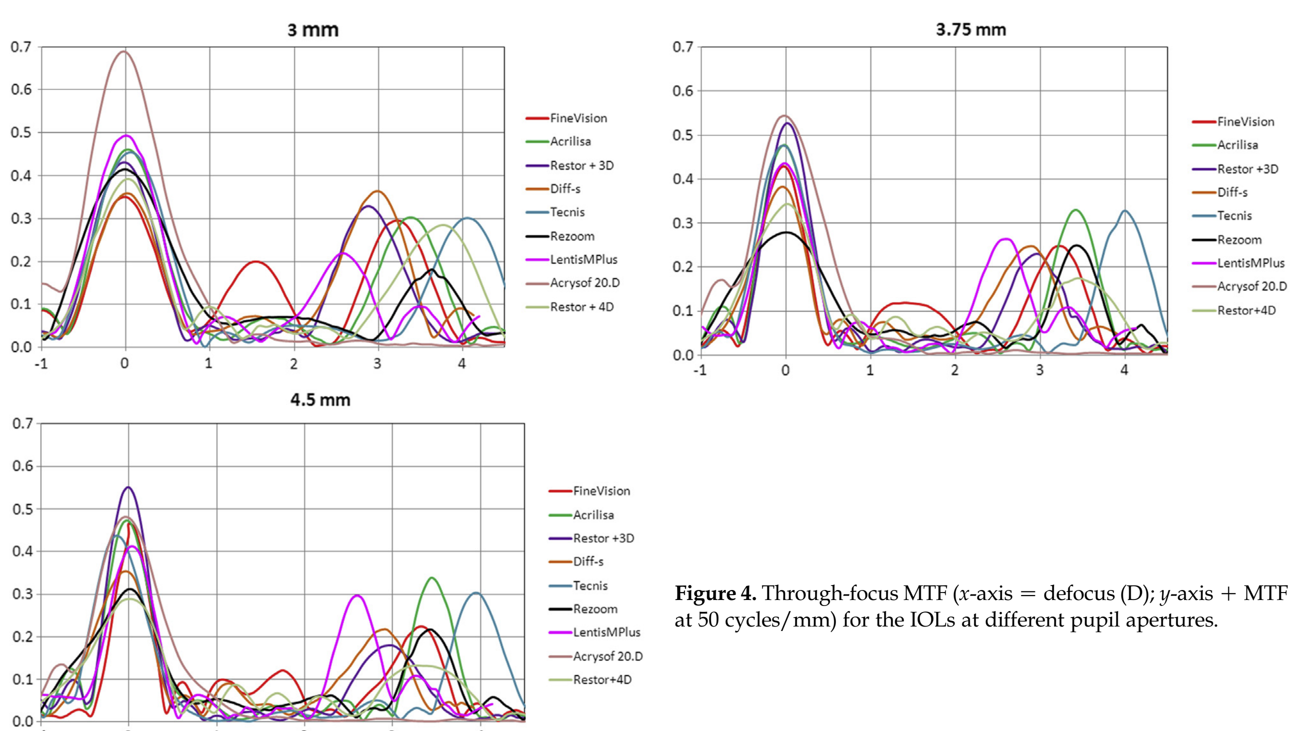

Figure 4. Through-focus MTF (x-axis = defocus (D); y-axis + MTF at 50 cycles/mm) for the IOLs at different pupil apertures.

5.0 mm apertures. This is easily explained by the fact that the harmonics of a diffractive IOL create defocused images that reduce the contrast sensitivity but not the resolution because these defocused images are too blurred. In refractive IOLs, where there is only 1 defocused image (for bifocal IOLs), the paraxial rays do not contribute to the near image. Thus, the near image provided by the annular refractive zones is corrupted by the higher-order aberrations, which degrade the resolution very quickly. In the case of the nonrotationally symmetrical IOL design (Lentis Mplus), coma-like aberrations were introduced because this IOL has a sector-shaped segment for near vision. Alió et al.[15] measured an elevated coma aberration in vivo after implantation of the Lentis Mplus IOL. The rotational symmetry of the Rezoom IOL minimizes the induction of coma-like aberrations and may be less detrimental to resolution.

The measurements of the IOL through-focus MTFs were generated using a single wavelength in the center of the visible spectrum, which does not provide information on the comparative performances of the IOLs at the spectrum extremities (ie, on the chromatic aberrations of these multifocal IOLs). Although the chromatic aberrations of an IOL of a given power are determined by the Abbe number (or V-number) of its material, the chromatic aberrations of IOLs performed using the same material are comparable.[16] In this paper, the Acrysof monofocal, Restor +3.0 D, and Restor +4.0 D IOLs are manufactured using the same aromatic acrylic. The Rezoom and Tecnis IOLs are made from aliphatic acrylic. The Diff-s is a silicone IOL. The Acri.Lisa, the Lentis Mplus, and the FineVision Micro F IOLs are 25% hydrophilic acrylic.

One must consider the spherical aberration amplitude of the IOL at a larger aperture (>3.0 mm) to generate an accurate interpretation of the MTF through-focus curves. The advantage of an aberration-free cornea on the optical bench is that it does not affect the IOL measurement because each IOL model has its own spherical aberrations.

These results parallel the clinical outcomes observed after bifocal IOL implantation: The light energy allocated to the near focus point underlies the second peak of the MTF through-focus curve of our artificial eye model and explains the induction of uncorrected near vision in implanted eyes. The MTF in the intermediate range with the Restor +3.0 D IOL was better (higher) than with the Acrysof Restor +4.0 D IOL, and this reduced added power has been shown to improve intermediate vision in the clinic.[17,18] The introduction of a third focal point for intermediate vision with the Finevision Micro F trifocal IOL has been shown clinically to provide intermediate distance vision[19] without significantly degrading the far and near performance compared with preexisting diffractive bifocal designs. The intermediate vision provided by bifocal IOLs is indeed most closely related to the depth of field. Intermediate visual acuity can be improved only with the existence of a third focal point.

WHAT WAS KNOWN

- The optical quality and the USAF images viewed through bifocal diffractive IOLs has been studied.

WHAT THIS PAPER ADDS

- The optical quality and the USAF images viewed through a bifocal rotationally asymmetric refractive bifocal IOL and a fully diffractive trifocal IOL were studied experimentally and showed differences between existing bifocal IOLs.

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