It has been demonstrated that higher order aberrations (HOAs) increase after laser refractive surgery.\textsuperscript{1-4} The most commonly affected aberration is the spherical aberration, which increases positively after myopic laser surgery and negatively after laser correction for hyperopia.\textsuperscript{1-4} It is crucial to know the type of aberrations induced by currently available presbyopia-correcting IOLs for evaluating whether their implantation is recommendable in eyes with previous laser refractive surgery that are already aberrated. From a clinical perspective, the outcomes of the implantation of presbyopia-correcting IOLs, including different types of multifocal IOLs, in eyes with previous refractive surgery have been evaluated.\textsuperscript{5-7} However, as far as we know, studies of the effect of these IOLs on the aberrations of an eye with previous refractive surgery has not been performed, either clinically or in vitro. The possibility of knowing the aberrometric induction of any presbyopia-correcting IOL before its implantation is a valuable tool to predict the consequences on the patients’ visual quality of such implantation and to define and optimize selection of the IOL to implant.

In a previous study, the “in vitro” aberrometric pattern of a refractive IOL and two extended depth of focus IOLs were analyzed.\textsuperscript{8} Three multifocal IOLs were analyzed in virgin eyes: Lentis Mplus X LS-313 MF30 (Oculentis GmbH, Berlin, Germany), TECNIS Symfony ZXR00 (Johnson & Johnson Vision, Santa Ana, CA), and Mini Well (SIFI S.p.A., Lavinaio, Italy). Three different pupil sizes were used for the comparison (3, 4, and 4.7 mm). In that study, it was concluded that the Mini Well IOL induced negative primary and positive secondary
spherical aberrations for all pupil sizes. The Symfony IOL aberrations seemed to be pupil dependent, not producing negative primary spherical aberration for 3 mm but increasing for larger pupils. Meanwhile, the HOAs for the Mini Well and Symfony IOLs were not significant for all sizes. The Mplus IOL showed in all cases the highest HOAs and became clinically relevant for pupils larger than 4 mm.

The aim of the current investigation was to propose a technique to simulate the optical performance of three presbyopia-correcting IOLs implanted in eyes with previous myopic or hyperopic laser refractive surgery. This methodology combines in vitro IOL wavefront aberration measurement, the use of real corneal topographic data, and ray-tracing simulation.

PATIENTS AND METHODS

DESCRIPTION OF IOLS MEASURED

The Mini Well IOL is a progressive extended depth-of-focus (EDOF) IOL, with an equivalent addition of +3.00 diopters (D). It has a patented optical design based on the application of positive and negative spherical aberration in the central part of the IOL to increase the depth of focus. The optic is divided into three different annular zones: the inner and middle zones have different spherical aberrations with opposite signs, whereas the outer zone is monofocal aspheric. The IOL overall diameter is 10.75 mm, its optical surface diameter is 6 mm, and it includes an ultraviolet light-absorbing filter. Furthermore, the dioptric spectrum that is commercially available ranges from 0.00 to +30.00 D. In our in vitro study, we used an IOL with 20.00 D of optical power.

The Symfony IOL is a biconvex and pupil-independent diffractive IOL, which combines an achromat diffractive surface with an echelette design. Its overall diameter is 13 mm and its optical zone diameter is 6 mm. The power spectrum available ranges from +50.00 to +34.00 D, and incorporates an ultraviolet light-absorbing filter. We used an IOL of 20.00 D with an addition of +4.00 D for the current study.

The Mplus IOL is a refractive bifocal IOL composed of an aspheric distance vision zone combined with a posterior sector-shaped near vision zone allowing seamless varifocal transition between the zones. The IOL overall diameter is 11 mm and its optical zone diameter is 6 mm. The power spectrum available ranges from -10.00 to +36.00 D. In our study, we used an IOL with a power of 20.00 D and an addition of 3.00 D.

MEASUREMENT SIMULATION SET-UP

Following the guidelines established by the ISO11979-9, the in vitro optical quality of an IOL can be evaluated by measuring the through-focus modulation transfer function (MTF) for a spatial frequency of 50 cycles/mm (MTF values for different levels of vergence) using an aberration-free eye model, where the studied IOL is inserted. The curves obtained for a spatial frequency of 50 cycles/mm approximates the visual function assessment with an optotype for 0.50 decimal visual acuity (20/40 Snellen).

In the current study, the theoretical through-focus MTF of each specific IOL was evaluated in eyes with previous laser refractive surgery. Specifically, simulations were conducted in two eyes, one with previous myopic LASIK and another with previous hyperopic LASIK. The simulations were made according to the following steps:

1. The wavefront profile of each IOL was characterized using a Hartmann–Shack wavefront sensor while the IOL was placed in a liquid medium contained between two flat windows. Once characterized, the phase transformation introduced by each IOL was calculated.

2. An eye model was built using the OpTaliX software (Optenson Optical Engineering Software, Heerbrugg, Switzerland). The topographic data of the two eyes used for the simulations was uploaded and exported in .csv format from the Sirius system (CSO, Firenze, Italy),11 whose repeatability in patients with previous refractive surgery has already been demonstrated.12

3. The IOL was introduced as a phase element in the eye model and the through-focus MTF for each IOL was simulated by ray tracing.

It has been suggested that Hartmann–Shack type wavefront sensors may bias some aberrometric measurements obtained with some diffractive IOLs due to a split of lenslet spots produced by more than one diffractive zone within the same lenslet.13,14 In our study, the only diffractive IOL evaluated was the Symfony, which had diffractive zones that were large enough (only 10 diffractive zones) to be resolved by our Hartmann–Shack configuration based on the use of a lenslet pitch of 150 µm and a low wavelength of 532 nm.13,14 In our measurements with the diffractive IOL mentioned, only some isolated spots were not well defined due to the registration of the wavefront using information coming from a diffractive transition zone.

Ray tracing has been employed to determine the optimal IOL power after laser surgery. The main drawback of these studies is that real IOL data (radius of curvature of its surfaces, thickness, and refractive...
index) are required. In most cases, this type of data is not accessible or even patent protected. As we mentioned above, we have circumvented this situation by measuring the phase transformation that the IOL induces and implementing it in our simulated eye model that uses real topographic data. All measurements were performed for three exit pupil sizes (3-, 4-, and 4.7-mm diameter).

**CLINICAL DATA**

The topographic data of two eyes were used for the ray-tracing simulations conducted in the current study (Figure A, available in the online version of this article). The first case of myopic LASIK was a 37-year-old man with a manifest refraction of -8.00 -0.25 × 115°, corrected distance visual acuity (CDVA) of 0.00 logMAR (20/20 Snellen), and a scotopic pupil diameter of 5 mm. The second case of hyperopic LASIK was a 38-year-old man with a manifest refraction of +3.75 -0.50 × 95°, CDVA of 0.00 logMAR (20/20 Snellen), and a scotopic pupil diameter of 5 mm. Both eyes were treated with LASIK using the Pulzar Z1 solid-state laser platform (CustomVis Laser Pty Ltd, Osborne Park, Australia, currently CV Laser Pty Ltd) and an automated mechanical microkeratome (M2; Moria, Antony, France), creating a 110-µm thickness flap with superior hinge and 9- to 9.5-mm diameter at the Department of Ophthalmology (Oftalmar) of Vithas Medimar International Hospital (Alicante, Spain).

**RESULTS**

The through-focus MTFs for all IOLs and the three pupil sizes are shown in Figures 1-2. These figures are presented with the same scale for direct comparison. Furthermore, in this section, we used tables showing the level of spherical aberration for each pupil size before and after IOL implantation.

**SIMULATIONS IN THE EYE WITH PREVIOUS MYOPIC LASIK**

As can be seen in Figure 1A, the Mini Well IOL showed a well-defined peak for far vision and a smooth transition between the intermediate (-1.50 D)
and near (-2.50 D) focus that was higher than for the rest of the IOLs for a pupil size of 3 mm. The Symfony IOL showed a wider far zone, but the MTF values for near (-2.50 D) and intermediate (-1.50 D) zones were narrower. The Mplus IOL showed the worst through-focus curve, including a peak for far vision and a lower peak for near vision (-3.50 D). For the 4-mm pupil size (Figure 1B), the Mini Well IOL improved the MTF for far vision and maintained two foci for near (-2.50 D) and intermediate (-1.50 D), with a smooth transition. However, for near vision, any focus was obtained. The Mplus IOL showed a peak for near vision (-5.00 D) and another two lower peaks for -2.50 and -0.75 D defocus levels. For the 4-mm pupil size (Figure 2B), the Mini Well IOL displayed a similar behavior similar to the 3-mm pupil size but with decreased far vision MTF. With the Symfony IOL, the far focus diminished drastically and showed a wider area of focus for intermediate and near vision, between -1.50 and -3.00 D defocus levels. The best focus with the Mplus IOL was obtained for near (-3.00 D), with some focal increase of the MTF for intermediate and far vision. For the 4.7-mm pupil size (Figure 2C), the Mini Well IOL maintained the peak for far focus and displayed an extended depth of focus centered at the -2.50 D defocus level. The Symfony IOL only showed a wider focus for intermediate vision centered at the -2.50 D defocus level. The Mplus IOL did not show any focus for these pupil sizes (Figure 2).

The spherical aberration of the eye with previous myopic LASIK changed from +0.087 µm for the 3-mm pupil to +0.57 µm for the 4.7-mm pupil without an IOL (Table 1).

### DISCUSSION

Our simulations have shown that the optical quality of the system eye and IOL is worsened in eyes with previous laser refractive surgery when the pupil size increases. This is consistent with the scientific evidence reported to date supporting the fact that laser refractive surgery leads to some level of aberrometric induction, even when aspheric profiles are used.\(^1\)\(^-\)\(^4\)

**TABLE 1**

<table>
<thead>
<tr>
<th>Case</th>
<th>3-mm Pupil</th>
<th>4-mm Pupil</th>
<th>4.7-mm Pupil</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MW SYM MP</td>
<td>MW SYM MP</td>
<td>MW SYM MP</td>
</tr>
<tr>
<td><strong>Myopic refractive surgery</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eye</td>
<td>-0.128</td>
<td>+0.087</td>
<td>-0.121</td>
</tr>
<tr>
<td>IOL</td>
<td>-0.038</td>
<td>0.085</td>
<td>0.181</td>
</tr>
<tr>
<td>Eye+IOL</td>
<td>-0.096</td>
<td>-0.007</td>
<td>-0.017</td>
</tr>
<tr>
<td><strong>Hyperopic refractive surgery</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eye</td>
<td>-0.128</td>
<td>-0.007</td>
<td>-0.121</td>
</tr>
<tr>
<td>IOL</td>
<td>-0.199</td>
<td>-0.092</td>
<td>-0.065</td>
</tr>
<tr>
<td>Eye+IOL</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

IOL = intraocular lens; MW = Mini Well, SIFI S.p.A., Lavinaio, Italy; SYM = Symfony, Johnson & Johnson Vision, Santa Ana, CA; MP = Mplus, Oculentis GmbH, Berlin, Germany

**SIMULATIONS IN THE EYE WITH PREVIOUS HYPEROPIC REFRACTIVE SURGERY**

In general, the best through-focus MTF values were obtained for the 3-mm pupil size because the three IOLs provided higher peaks (Figure 2A). The Mini Well IOL showed two peaks for far and intermediate distance (-1.50 D defocus). For near distance, a depth of focus between 3.50 and 5.50 D was observed. For the 3-mm pupil size, the Symfony IOL showed a wider area for far and intermediate vision (-1.00 D), with a smooth transition. However, for near vision, any focus was obtained. The Mplus IOL showed a peak for near vision (-5.00 D) and another two lower peaks for -2.50 and -0.75 D defocus levels. For the 4-mm pupil size (Figure 2B), the Mini Well IOL displayed a similar behavior similar to the 3-mm pupil size but with decreased far vision MTF. With the Symfony IOL, the far focus diminished drastically and showed a wider area of focus for intermediate and near vision, between -1.50 and -3.00 D defocus levels. The best focus with the Mplus IOL was obtained for near (-3.00 D), with some focal increase of the MTF for intermediate and far vision. For the 4.7-mm pupil size (Figure 2C), the Mini Well IOL maintained the peak for far focus and displayed an extended depth of focus centered at the -2.50 D defocus level. The Symfony IOL only showed a wider focus for intermediate vision centered at the -2.50 D defocus level. The Mplus IOL did not show any focus for these pupil sizes (Figure 2).

The spherical aberration of the eye with previous hyperopic LASIK changed from -0.096 µm for the 3-mm pupil to -0.560 µm for the 4.7-mm pupil without an IOL (Table 1).
cal IOLs in eyes with previous laser refractive surgery to control the potential aberrometric change induced by the IOL.

The analysis of the results in the eye with previous myopic LASIK shows a better ocular optical quality with the Mini Well and Symfony IOLs rather than with the Mplus IOL because the through-focus MTF achieves higher values. The Mini Well and Symfony IOLs maintained the far focus independently of the pupil size, with the Mini Well IOL showing the highest MTF values as the pupil size increased. In general, the three IOLs evaluated lost some level of optical quality at near and intermediate distances for the 4- and 4.7-mm pupil sizes. For the 3-mm pupil size, the Mini Well IOL showed the best intermediate and near ocular optical quality outcome. This is consistent with results of previous simulations performed in an optical bench evaluating the same IOLs in the ISO model eye with no previous refractive surgery.17-19 Domínguez-Vicent et al.18 showed that the Mini Well IOL provided two main focus areas in the ISO eye model: one corresponding to distance vision focus and the other including both intermediate and near vision foci. Similar behavior was observed in our simulations, although the change induced in spherical aberration introduced some minimal modifications. The positive spherical aberration of the eye with previous myopic refractive LASIK was always compensated for with the IOLs evaluated and was maintained within acceptable clinical values for all pupil sizes. This compensation was higher for the Symfony and Mplus IOLs as the pupil size increased because the spherical aberration remained constant with the Mini Well IOL regardless of whether the pupil size increased.

In the eye with previous hyperopic refractive LASIK, the Mini Well IOL showed two peaks for intermediate and far distance and a wider area for near vision of approximately -4.00 D of defocus for all pupil sizes. Despite the Symfony IOL showing a wider focus area for near and intermediate distance for 3-mm pupil size, this area disappeared as the pupil size increased, with the presence of only a near focus (-2.50 D defocus level). The Mplus IOL only showed a near focus for the 3- and 4-mm pupil size for defocus levels of -4.50 and -3.00 D, respectively. All IOLs increased the level of negative spherical aberration of the eye, leading to ocular values higher than -0.5 µm for 4.7-mm pupil size. This may be the reason for the worsening of the ocular optical quality with the three IOLs for the highest pupil size evaluated. This suggests that this combination of previous hyperopic LASIK and presbyopic-correcting IOL should be only used in eyes with small pupil sizes to avoid a potentially significant deterioration of the visual quality.

Our simulations suggest that the Mini Well and Symfony IOLs work better than the Mplus IOL in eyes with previous myopic LASIK. In general, there was a loss of near and intermediate optical quality for the three IOLs analyzed as the pupil size increased, with the Mini Well IOL showing the best intermediate and near optical quality performance for the 3-mm pupil size. For far distance, both the Mini Well and Symfony IOLs provided a good focus, showing that the Mini Well IOL had the highest MTF values. In eyes with previous hyperopic LASIK, our simulations indicated that the Mini Well IOL showed acceptable near, intermediate, and far foci for all pupil sizes. Both the Symfony and Mplus IOLs gradually lost the far focus, only showing a near or intermediate focus, as the pupil size increased.

A new method that combines in vitro IOL wavefront aberration measurement, real topographies, and ray-tracing simulation is able to simulate the ocular optical performance after presbyopia-correcting IOL implantation in eyes with previous laser refractive surgery. Although this new method is proposed, there is little validation of it; therefore, the results shown in this study are not generalizable because more patients should be analyzed. In future studies, larger sample sizes will be studied to confirm our results and determine whether they are consistent with those obtained in clinical practice. It should be remembered that there are differences between experimental and clinical conditions because the eye is not a perfectly centered optical system. Therefore, differences between IOLs might change in other conditions. Furthermore, this methodology may be applied to other IOLs whose aberrometric pattern may be reproducible with Hartmann–Shack sensors.

**AUTHOR CONTRIBUTIONS**

Study concept and design (VJC, JJM, CG, AT, DPP); data collection (VJC, JJM, CG, AT, DPP); analysis and interpretation of data (VJC, JJM, CG, AT, DPP); writing the manuscript (VJC, JJM, DPP); critical revision of the manuscript (VJC, JJM, CG, AT, DPP); statistical expertise (VJC, DPP); administrative, technical, or material support (VJC, CG); supervision (VJC, JJM, DPP, CG)

**REFERENCES**


Figure A. Corneal topographic data of the two eyes used for the simulations: post-myopic LASIK (top) and post-hyperopic LASIK (bottom).