Through-Focus Response of Extended Depth of Focus Intraocular Lenses

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ABSTRACT

PURPOSE: To investigate extended depth of focus intraocular lenses (EDOF IOLs), intended to extend the depth of field after cataract surgery in a comparative study at the optical bench.

METHODS: An optical bench with either green or white light was used for this study. The artificial cornea used exhibited a spherical aberration of 0.2 µm. Examinations of the following lenses with a pupil opening of 3 and 4.5 mm were carried out: AcrySof IQ Vivity (Alcon Laboratories, Inc), Isopure (PhysIOL), Tecnis Eyhance (Johnson & Johnson), Vivinex Impress (Hoya Surgical Optics), and xact (Santen).

RESULTS: Using green light and a pupil aperture of 3 mm, the AcrySof IQ Vivity showed the highest light energy for the intermediate area, whereas the Isopure and Vivinex Impress provided the highest energy for distance vision. Under the same examination conditions with a pupil opening of 4.5 mm, all lenses showed a low light distribution for the intermediate range. Regarding light distribution for distance, the Tecnis Eyhance had the highest light intensity. Using white light, the curves became much wider and more similar to each other.

CONCLUSIONS: The five EDOF lenses investigated differ mainly by their different weighting of energy between the far and intermediate ranges.

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Intraocular lenses (IOLs) that deliberately elongate the focal point are grouped under the term extended depth of focus (EDOF) IOLs. The predetermined goal of these lenses is good visual acuity at distance and a certain visual acuity in the intermediate field. The easiest way to construct such a lens is to increase the spherical aberration, as is the case with purely spherical IOLs.[1] These spherical aberrations cause a symmetrical widening of the focal point and therefore also a reduction in image quality.[2] Modern EDOF lenses go beyond the concept of spherical monofocal lenses and are intended to provide targeted light energies for the intermediate range.

This is achieved technically by a central steepening of front lens geometry[3] and using small apertures.[4,5] To enlarge the depth of field, two narrow focal points can be merged into one broad focal point, as is the case in some diffractive concepts.[6]

The purpose of this study was to compare the light distribution along the optical axis of the latest generation of EDOF IOLs.

MATERIALS AND METHODS

Description of the Lenses Tested

The AcrySof IQ Vivity (Alcon Laboratories, Inc) has a circular change in the lens geometry within the central 2.2 mm on the anterior surface. The manufacturer terms this wavefront shaping technology (X-WAVE technology). This IOL exhibits negative spherical aberrations to compensate for the positive spherical aberration of the cornea. The one-piece IOL, made of hydrophobic acrylic, has an overall length of 13 mm, whereas the diameter of the optic is 6 mm. Furthermore, this lens has a blue light filter with a continuous cut-off from 400 to 475 nm.

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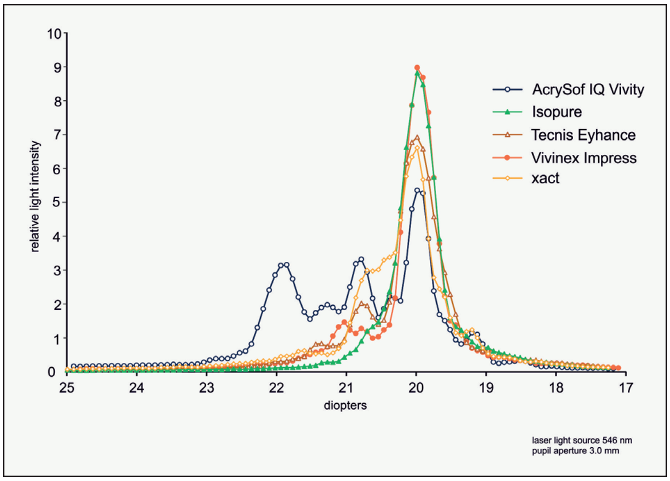

Figure 1. Through-focus response curves of five extended depth-of-focus (EDOF) lenses (AcrySof IQ Vivity [Alcon Laboratories, Inc], Isopure [PhysIOL], Tecnis Eyhance [Johnson & Johnson], Vivinex Impress [Hoya Surgical Optics], and xact [Santen]) at 546 nm using an artificial cornea with a 0.2-µm spherical aberration and a pupil opening of 3 mm. Normalization of the curves is based on the area under the curves.

The Isopure (PhysIOL) is made of hydrophobic acrylic with a 360-degree sharp edge. The lens has smooth anterior and posterior surfaces steepening in the center. Furthermore, the lens exhibits a blue light filter.

The Tecnis Eyhance ICB00 (Johnson & Johnson) has a central steepening on the anterior surface[3] and uses the ZCB00 platform. The overall diameter of this lens is 13 mm and the optic diameter is 6 mm. It is made of a hydrophobic acrylate and has a circular sharp edge.

The Vivinex Impress (Hoya Surgical Optics) is based on the Vivinex platform.[7] The anterior surface is a combination of aspherical surfaces. The central part of the lens is intended to allocate the incident light primarily to the intermediate range, whereas the lens periphery is intended to primarily serve the distance range. The lens is made of a hydrophobic acrylic IOL material, with a 13-mm overall diameter and an optic diameter of 6 mm.

The xact (Santen) is made of hydrophobic acrylic and has an overall diameter of 12.5 mm with an optic size of 6 mm. This lens has four diffractive rings on the lens surface to extend the focal point toward the intermediate vision range.

Experimental Set-up

The experimental set-up consisted of an optical bench with a laser light source. In this series of examinations, a wavelength of 546 nm, which corresponds to the green light and white light, was used by means of different filters. This was followed by a collimator system, followed by an artificial cornea in air corresponding to a human cornea with a spherical aberration of 0.2 µm. In this study, an artificial pupil with an opening of 3 mm for the first test run and 4.5 mm for the second was placed in a wet cell. Behind it within the wet room, the lenses were fixed in a special holder using the lens haptics. The wet cell was filled with isotonic saline and closed with a glass plate. Behind it was an imaging system able to record light intensity curves along the optical axis by means of a charge coupled device array. All lenses used had a power of 20.00 diopters (D). Light intensity was evaluated at a range of 18.00 to 25.00 D and the results were superimposed as through-focus response curves of all of the lenses examined. To ensure comparability, all through-focus response curves were standardized on the basis of the same area below the curve.

RESULTS

Measurements on the optical bench are sensitive to decentration. To ensure comparability, lens centration was optimized at the beginning of each through-focus response determination using the modulation transfer function and the resulting Strehl ratio for the main focal point under monitor control.

Subsequently, the best centration was confirmed by measurements of the Strehl ratio in best centration and deviations in 20-µm steps on the x- and y-axis.

The through-focus response curves for the 3-mm test run are shown in **Figure 1**. The course of the AcrySof IQ Vivity, which at 22.00 D provides significantly more light energy than all of the other lenses, is notable. The Isopure and the Vivinex Impress show the most light energy for distance. Between 20.00 and 21.00 D, all lenses show a light energy outside the actual focal point, even if in part this is only slight. The Isopure shows the lowest light energy for the intermediate area under these test conditions.

Figure 2 shows the results with green light and a pupil aperture of 4.5 mm. Here the Tecnis Eyhance shows the highest peak for distance, but only low light intensities between 20.00 and 21.00 D. The AcrySof IQ Vivity shows the second highest peak for distance and a small almost separated peak at 22.00 D. The Vivinex Impress shows the third highest peak and a small separable peak at 21.50 D. The light intensity for the xact in distance is below that of the Vivinex Impress and shows two clearly separate peaks at approximately 20.50 and 21.20 D in its course. These are apparently diffractive diffraction maxima that merge at the base. The Isopure has a relatively small peak and surprise with light intensities in the hyperopic area.

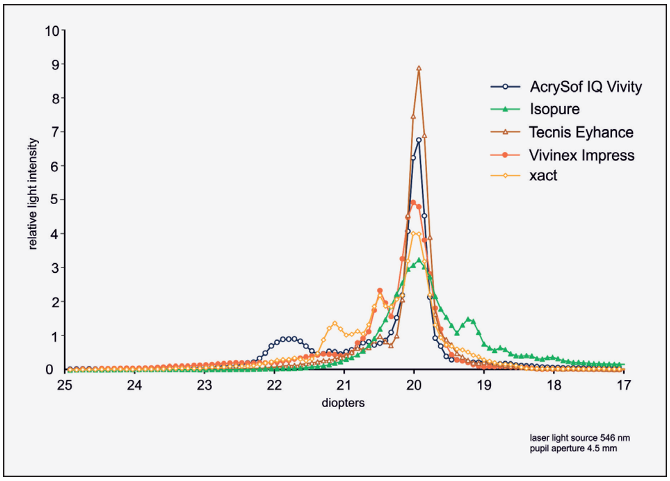

Figure 2. Though-focus response curves of five extended depth-of-focus lenses (AcrySof IQ Vivity [Alcon Laboratories, Inc], Isopure [PhysIOL], Tecnis Eyhance [Johnson & Johnson], Vivinex Impress [Hoya Surgical Optics], and xact [Santen]) at a pupil opening of 4.5 mm. Green laser light with 546 nm was used and the spherical aberration of the artificial cornea was 0.2 µm. Normalization was performed on the basis of the area under the curves.

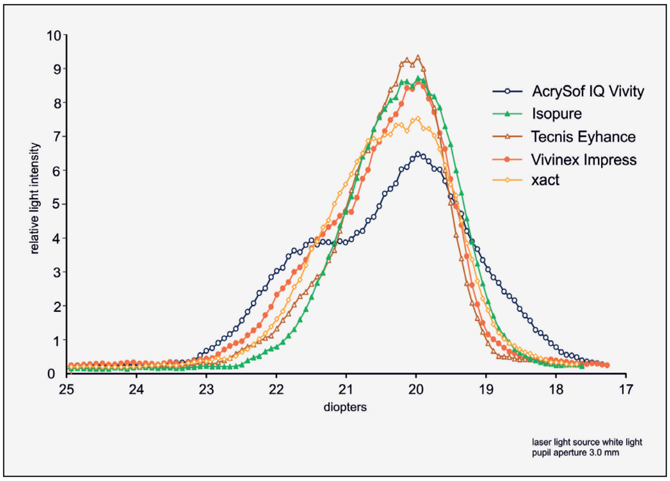

Figure 3. Through-focus response curves of the five extended depth-of-focus lenses investigated (AcrySof IQ Vivity [Alcon Laboratories, Inc], Isopure [PhysIOL], Tecnis Eyhance [Johnson & Johnson], Vivinex Impress [Hoya Surgical Optics], and xact [Santen]) using white light and an artificial cornea with a 0.2-µm spherical aberration. The pupil opening was 3 mm and the curves were normalized on the basis of the area underneath the curves.

The test run with a 3-mm pupil opening with white light is shown in **Figure 3**. Using white light, the curves change significantly compared with **Figure 1**; in particular, the curves become much more similar and wider. Although the AcrySof IQ Vivity course shows a short plateau between 21.00 and 22.00 D, the Isopure, Tecnis Eyhance, Vivinex Impress, and xact courses are uniform, showing by contrast a steady increase and decrease.

When using white light, with a pupil width of 4.5 mm, again the curves become more similar and wider (**Figure 4**). The Tecnis Eyhance shows the highest peak, whereas the xact at 21.50 D provides the most light energy for the intermediate range. It is remarkable that the two peaks that were still visible for the intermediate range with green light (**Figure 2**) now defacto merge into an almost constantly falling curve. As with the use of green light, the Isopure also shows light intensities in the hyperopic range.

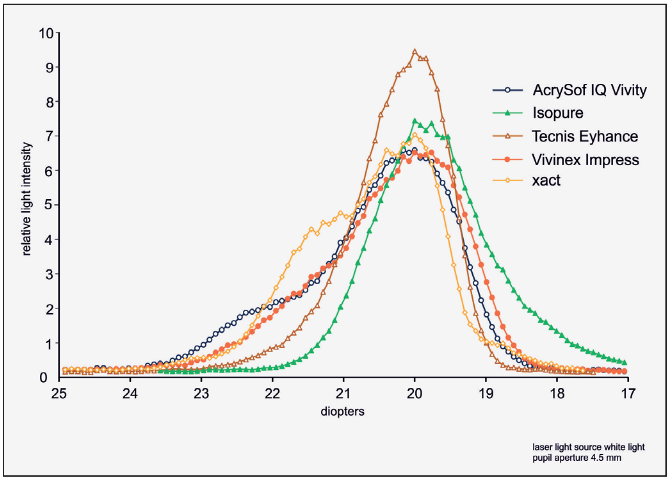

Figure 4. Comparative presentation of through-focus response curves of five extended depth-of-focus lenses (AcrySof IQ Vivity [Alcon Laboratories, Inc], Isopure [PhysIOL], Tecnis Eyhance [Johnson & Johnson], Vivinex Impress [Hoya Surgical Optics], and xact [Santen]) using white light at a pupil aperture of 4.5 mm. The artificial cornea had a spherical aberration of 0.2 µm. The curves are normalized to the surface under the curves.

DISCUSSION

Modern EDOF lenses widen the focal point toward the myopic area. In addition, they usually change the light distribution with the pupil width, according to the near point reaction. Thus, a narrow pupil favors reading distance, whereas a wide pupil favors distance vision. This is usually because the central parts of the IOL direct incident light more to the intermediate range, whereas the periphery serves for distance. The central parts of an EDOF lens can be designed by central steepening or circular steepening, or the light distribution in the center is modified by diffractive structures.

The introduction of EDOF lenses broke with the traditional aim of designing IOLs that make light distribution in the focal point as high and narrow as possible. The EDOF concept enables the transmission of low and medium spatial frequencies via a higher depth of field, but at the expense of the transmission of high spatial frequencies. Even if these high spatial frequencies are less important in our daily lives, there is, in theory, a loss of resolution, not only for high spatial frequencies but also for fine contrasts. The youthful lens, which also partially compensates for the positive spherical aberrations of the cornea,[7] is the standard set by nature and is recreated by classic monofocal aspheric lenses. In this context, the EDOF lens can only be understood as a compromise compared with a classic monofocal lens at the expense of imaging quality.

The lenses examined extend the focal point by changing the lens geometry, with the exception of the xact, which uses central diffractive structures. The AcrySof IQ Vivity with its circular paracentral changes and the central division of the Tecnis Eyhance are reminiscent of the early days of refractive multifocal lenses, although the calculation method has probably improved with modern computer simulation programs, especially with regard to the phase shift due to the deviation from the optimal lens thickness curve. The Vivinex Impress has not yet been launched on the market. Santen's xact is likely to create two focal points close to each other with the central diffractive rings.

A cornea with 0.2 µm was chosen for the experimental set-up because this corresponds to an average spherical aberration of the human cornea.[8] The pupil widths of 3 and 4.5 mm were chosen primarily to show the different light distribution in these two pupil widths and thus to question the light distribution as a function of the pupil width. In addition, these diameters correspond to the pupil width in daylight and that under mesopic conditions.[9] Green and white light was used to better understand how the lenses work, in particular to question whether separate focal points arise with green light, which then merge into a broad focal point using white light.

Through-focus responses with green light should be used for clinical interpretation of how the extended focal point of the lenses function at different object distances, as we adapt our subjective refraction to the wavelength of the green light. The in vitro through-focus response deviates somewhat from the light distribution in vivo. This is because optics with the charge coupled device array, which evaluates the focal point, are shifted in in vitro measurement, whereas in vivo the object distance changes. This results in a different incidence of light on the lens in vitro than is actually the case in vivo, which affects the refraction to a certain extent.[10]

Looking at the measurement results in **Figure 1**, the AcrySof IQ Vivity offers the highest light intensities for intermediate distance at 22.00 D. Conversion of the lens plane of 22.00 D to the spectacles plane would result in a near addition of 1.30 D. Taking the frequently chosen target refraction of -0.50 D for lens biometry into account, a near addition of 1.80 D can be assumed. This corresponds approximately to the usual computer distance. However, this provision of light energy in the intermediate range leads to a lower height of the distance peak than those of the other lenses studied.

With the same set-up as in **Figure 1** but a pupil opening of 4.5 mm (**Figure 2**), the Tecnis Eyhance shows the highest peak for distance, followed by the AcrySof IQ Vivity. The progression of the AcrySof IQ Vivity reveals that the increase in pupil width leads to a clear shift of light distribution toward distance focus. This appears to be advantageous, considering the near point reaction with pupil narrowing. For the 4.5-mm pupil, the xact showed the highest light intensities for the intermediate range. This could be explained by the fact that the peripheral zone of this lens, which is supposed to serve distance, begins more peripheral relative to the other lenses. The Isopure surprises with light energies in the hyperopic range between 19.20 and 19.70 D. To use this, a strategic choice of a higher myopic target refraction could harness these parts for sharp distance vision.

The results with white light in **Figures 3-4** are remarkable, because the curves are much more similar than those with green light. This is mainly because the distance peak is no longer clearly separated, turning to a broad peak that shows an asymmetric progression toward the myopic area. At 3 mm, the light intensity curves of all lenses, except for the AcrySof IQ Vivity, are similar. Regarding the AcrySof IQ Vivity, an energy peak is recognizable due to a plateau in the myopic area. Regarding **Figure 4**, the highest light energy for the Tecnis Eyhance in the distance and still relatively high light energies in the intermediate range for the diffractive xact are noticeable. All of the other lenses show a comparable course of light intensity.

Looking at the light distribution at 3 mm with green light in **Figure 1**, the lenses, except the Isopure, provide light energies of varying degrees for the intermediate range. Clearly, the AcrySof IQ Vivity provides the most energy for the intermediate range in this comparison. With a wide pupil, most of the lenses tend to shift the light distribution toward distance focus.

Modern EDOF lens design usually aims to extend the focal point mainly toward the myopic area of the focal point, and not to the hyperopic area, because these light energies are not usable for a sharp image. This deviation from a classic aspherical monofocal lens design leads to an extension of the depth of field at the expense of imaging quality at high spatial frequencies and fine contrasts.[11,12] The five EDOF lenses examined differed mainly in terms of light distribution between the far and intermediate ranges.

AUTHOR CONTRIBUTIONS

Study concept and design (SP, KK); data collection (CA, VP); analysis and interpretation of data (SP, DS, KK); writing the manuscript (SP, CA, VP); critical revision of the manuscript (DS, KK); administrative, technical, or material support (KK); supervision (SP)

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