

# Through-Focus Energy Efficiency and Longitudinal Chromatic Aberration of Three Presbyopia-Correcting Intraocular Lenses

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**Purpose:** To compare the chromatic performance of the Bausch & Lomb Versario 3F trifocal intraocular lens (IOL) with the PhysiOL FineVision MicroF trifocal IOL and the Johnson & Johnson Vision TECNIS Symphony ZXR00 extended range of vision (ERV) IOL.

**Methods:** The through-focus energy efficiency (TF-EE) was measured in vitro with red (R), green (G), and blue (B) wavelengths and was used to obtain the focus powers and longitudinal chromatic aberrations (LCAs) for each IOL. Other metrics, derived from the RGB TF-EE curves, were assessed for a more complete description of the chromatic performance of the IOLs.

**Results:** Both of the trifocal IOLs, although not specifically designed to tackle chromatic aberrations, showed acceptable LCA ( $\leq 0.50$  D) in all foci with more balanced R and B efficiencies of their foci. Despite having the lowest TF-EE value at all foci, the Versario 3F demonstrated the most balanced chromatic performance with the smoothest energy transition among all foci and the smallest chromatic span. The Symphony lens effectively reduced LCA at distance and intermediate foci ( $\leq 0.36$  D), despite the unbalanced and asymmetric R and B efficiencies at its foci.

**Conclusions:** To fully describe the chromatic performance of an IOL it is necessary to take into account not only the LCA but also the RGB TF-EE and chromatic span. This comprehensive analysis suggests that, in comparison with the other IOLs under study, the Versario 3F lens might contribute to further mitigating the impact of chromatic aberration.

**Translational Relevance:** The in vitro bench testing of the optical properties of modern presbyopia-correcting intraocular lenses (more specifically in this work, the polychromatic through-focus energy efficiency and longitudinal chromatic aberration) provides objective and complementary information that helps to interpret the visual quality outcomes of pseudophakic patients obtained in clinics.

## Introduction

Increasing patient demand for restoration of functional distance, intermediate, and near vision and not having to rely on any additional refractive correction after cataract surgery has been an extraordinary incentive for the development of presbyopia-correcting intraocular lenses (IOLs). The first diffractive multifocal IOLs (MIOLs) were bifocal lenses<sup>1</sup> that provided good far and near visual acuities<sup>2,3</sup> but insufficient

intermediate vision.<sup>4,5</sup> The newest commercially available presbyopia-correcting IOLs extend the range of vision by means of an additional focus (trifocal) and/or an extended depth of focus (EDOF).<sup>6</sup> Trifocal IOLs incorporate a third focal point to help improve intermediate vision while maintaining performance for distance and near vision.<sup>7,8</sup> In these lenses, every focused image is overlaid by two out-of-focus images originated by the other foci; this effect has an impact on the image contrast and is among the causes of dysphotopsia (such as halo and glare), as happens

with bifocal IOLs.<sup>9,10</sup> EDOF IOLs produce a focal segment that allows the implanted eye to benefit from intermediate vision. The definition of EDOF, unlike a physics definition, is based on a consensus statement by a task force of the American Academy of Ophthalmology. They based the EDOF concept on the clinical property of focus extension achieved by the average postoperative patient: at least 0.5 diopter (D) wider than for a monofocal patient at 0.2 logMAR visual acuity.<sup>11</sup> MIOLs and EDOF IOLs are not mutually exclusive classes. The EDOF lenses were developed to address photic phenomena and discontinuous visual transition for varying object distance; however, clinical testing proved that they might not provide the same level of near vision as trifocal IOLs do, and objective dysphotopsia might not be reduced compared to trifocal IOLs.<sup>9,10,12–14</sup>

Recently, a new trifocal IOL has been introduced in the market: the Versario 3F (Bausch & Lomb Surgical, Bridgewater, NJ). Clinical tests indicate that the new lens might be classified as a “trifocal extended depth of focus IOL because of the performance between extended depth of focus IOLs and medium-high addition trifocal IOLs.”<sup>15</sup>

The optical quality of an IOL can be assessed using optical and clinical methods; optical bench testing is complementary to clinical assessments because it is objective and independent of the patient. Therefore, in this study, we aim to assess the *in vitro* optical properties of this new lens, focusing on the spectral performance and, in particular, on the chromatic aberrations. These aberrations have drawn increasing attention in visual optics research<sup>16–19</sup> and, more recently, in IOL design,<sup>20–23</sup> as they may have a negative impact on vision quality<sup>16,18,19,24</sup> and depend on the material and design features.<sup>19,25,26</sup>

Bench evaluations of MIOLs are generally performed by measuring through-focus image quality from the light distribution and efficiency of the different foci. Most bench studies are performed in monochromatic light<sup>27–30</sup> using the design wavelength according to the International Organization for Standardization standard recommendation (ISO 11979-2:2014).<sup>31</sup> Polychromatic image quality is a further step in IOL characterization because human visual function is generally performed under polychromatic light.

The longitudinal chromatic aberration (LCA) is a common metric used to describe chromatic image performance in lenses. Although modern IOL designs try to reduce LCA as much as possible to improve lens performance, they may overlook the RGB energy efficiency, which should be balanced to not severely alter the color content of images. Therefore, when an

IOL shows large differences in red (R), green (G), and blue (B) energy efficiencies, the LCA evaluation on its own might not comprehensively describe its chromatic performance. To this end, the RGB through-focus energy efficiency (TF-EE) curves are particularly well suited to determining LCAs at the IOL foci and the individual R, G, and B energy efficiencies at all foci, allowing the chromatic energy efficiency span of the IOL to be assessed.

In this experimental study, we employed an optical setup similar to that used in related works<sup>21,22</sup> to measure the RGB TF-EE of the trifocal Versario 3F IOL. In addition, we compared the experimental results for this lens with those obtained for two other commercially available IOLs: the FineVision MicroF trifocal lens (PhysIOL, Liège, Belgium) and the TECNIS Symphony ZXR00 EDOF lens (Johnson & Johnson Vision, Jacksonville, FL), maintaining the same experimental conditions, procedures, and metrics.

## Methods




### Intraocular Lenses

The Versario 3F is a one-piece, non-angulated, plate-haptic IOL made of hydrophilic/acrylic material with a hydrophobic surface. It has an aspheric diffractive full optic trifocal structure with an innovative smooth-step design. Per the manufacturer, the energy percentages delivered by the optic system are 41% far, 22% intermediate, and 26% near, with 11% unavailable for vision.<sup>32</sup>

The FineVision MicroF is an aspheric diffractive trifocal IOL. Its design combines two bifocal diffractive profiles with two different additions: one for near, one for intermediate. A combination of the two profiles for far vision optimizes the quality of vision without increasing the fraction of useless light energy compared to bifocal diffractive IOLs. The energy percentages delivered by the apodized optic system are 43% far, 15% intermediate, and 28% near, with 14% of unused light.<sup>7</sup>

The TECNIS Symphony ZXR00 is an extended range of vision IOL, often referred to as an EDOF lens. It was the first EDOF-labeled IOL approved by the U.S. Food and Drug Administration, in 2016. Its design is based on a combination of refractive and diffractive technologies for providing extended range of vision with combined correction of spherical and chromatic aberrations.<sup>33</sup> Several papers<sup>28,34</sup> have shown that this lens performed as a low-addition bifocal IOL under monochromatic illumination ( $\lambda = 550$  nm). A mathe-

**Table 1.** Main Specifications of the Three Intraocular Lenses

	Versario 3F 	TECNIS Symphony ZXR00 	FineVision MicroF 
Characteristic			
Material	Hydrophilic acrylic, hydrophobic surface	Hydrophobic acrylic	Hydrophilic acrylic
Refractive index	1.46	1.47	1.46
Optical diameter (mm)	6.0	6.0	6.15
Overall diameter (mm)	11.0	13.00	10.75
Spherical aberration <sup>a</sup> (μm)	-0.165	-0.27	-0.11
Abbe number	58	55	58
Base power (D)	+30	+30	+30
Intermediate/near power addition at the IOL plane (D)	+1.50 and +3.00	+1.75	+1.75 and +3.50
Power (D), 0.5-D steps	+0 to +32	+5 to +34	+10 to +35

<sup>a</sup>Spherical aberration values are expressed in terms of the  $C_4^0$  Zernike coefficient for a 6-mm pupil diameter.

mathematical model based on a first- and second-order diffractive profile, supported by experimental through-focus measurements of the energy efficiency under RGB illumination,<sup>22</sup> fully confirmed those results. These and additional technical specifications of the IOLs examined in this study are listed in Table 1.

All of the studied lenses had base power of +30 D. We chose these IOLs for several reasons:

1. We could compare them with seven more IOLs of various designs (monofocal, bifocal, and extended range of vision), studies of which have been reported in References 21 and 22.
2. We were able to minimize changes in the experimental setups reported in related works.<sup>21,22</sup> Because an IOL was introduced in a wet cell without an artificial cornea lens (the latter typically having a dioptric power of about 25 D, according to the ISO 11979-2:2014 standard<sup>31</sup>), all of the refractive and diffractive power was exclusively due to the IOL. IOLs with power in the most common range of implanted lenses (20–24 D) would have produced variations in the image magnification and image axial distances that, in practice, would have required further modification of the setup. The results obtained for 30-D IOLs can be translated to IOLs of a different power (for example, in the range of 20–24 D) using equations provided elsewhere.<sup>22</sup>

### Experimental Setup and Metrics

Optical bench testing of IOLs has already been described in earlier works<sup>21,22</sup> and is summarized here for the sake of conciseness. The setup is shown in Figure 1, where the inset illustrates the LCA affecting the distance and near foci of an exemplary diffractive bifocal lens<sup>1</sup> that uses the base lens curvature and zeroth and first diffraction orders to achieve simultaneous distance and near foci, respectively. The intermediate focus existing in the case of a trifocal IOL has been omitted for the sake of simplicity.

Three R, G, and B light-emitting diodes (LEDs; Thorlabs, Inc., Newton, NJ) with nominal wavelengths of 455 nm (B), 530 nm (G), and 625 nm (R) and full width at half maximum of 18 nm for the B and R LEDs and 33 nm for the G LED were sequentially used to illuminate the setup. A 200-μm pinhole test object was placed at the front focal plane of a collimating lens. The collimated beam illuminated the wet cell where the IOL was inserted. The IOL imaged the pinhole either on separate image planes (as corresponds to multifocal lenses) or on a focal segment (as corresponds to EDOF lenses). A diaphragm placed in front of the wet cell and used as the entrance pupil limited the IOL aperture to a diameter of 3.5 mm throughout the test. Even with such an intermediate pupil (3.5 mm), the impact of the negative spherical aberrations of all tested IOLs on their images was still relatively low. This fact helped us to compute the energy efficiency metric. Additionally, we kept the same pupil size as used in former papers of

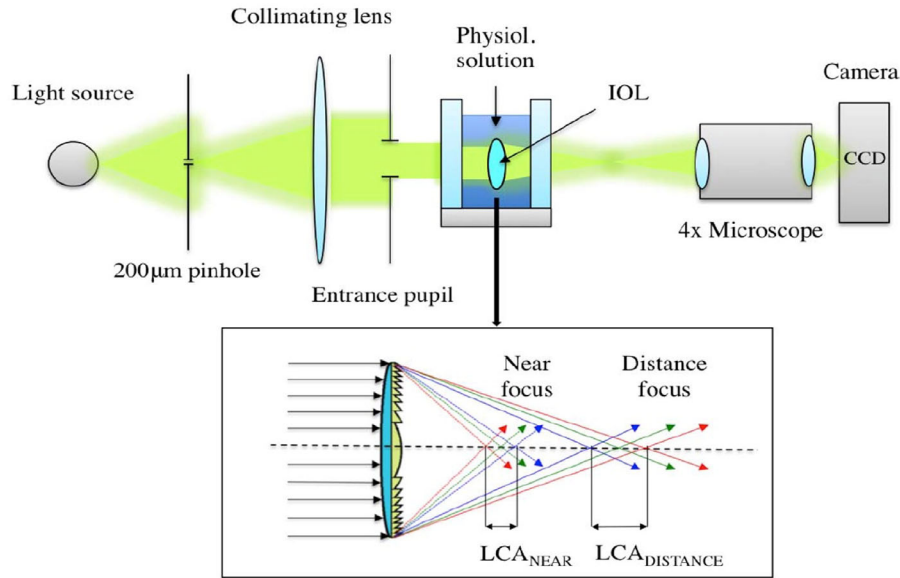


Figure 1. Experimental setup.

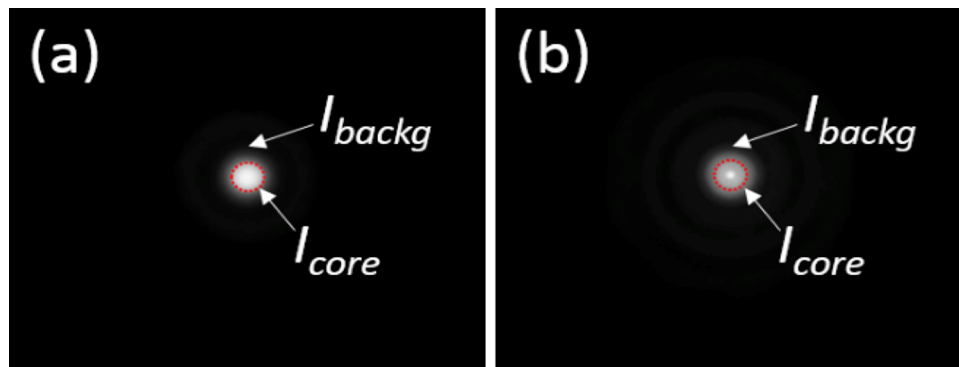


Figure 2. Images of the pinhole object obtained under G illumination with the Versario 3F IOL with its distance focus set at 0.0 D (a) and +2.5 D (b) defocus positions. The red dotted circle delimits the core region of the images from which the intensity  $I_{core}$  was obtained. The intensity outside this region is labeled  $I_{backg}$ .

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ours (Refs. 21 and 22) so that further comparisons with lenses of various designs could be done.

Behind the wet cell an infinite corrected microscope mounted on a translation holder focused the aerial image of the pinhole and magnified it onto a monochrome 8-bit charge-coupled device camera (Wells Research and Development, Inc., Lincoln, MA) used for digital image acquisition. The microscope objective (4× Olympus Plan Achromat; Olympus Corp., Tokyo, Japan), suited for high-quality imaging applications, had diffraction-limited performance through the visible spectrum. The microscope and camera moved together along the bench axis to precisely locate the positions of the focal planes for each IOL with a spatial resolution of 1 µm. Axial scanning was stretched to smoothly cover the

focal segment of interest—from distance to intermediate and near images—in trifocal and EDOF IOLs. More precisely, through-focus measurements covered an image vergence range of about 7 D (range, +2.0 to −5.0 D) in 0.1-D steps with 0.05-D resolution. To improve the signal-to-noise ratio, each image was eventually the result of averaging eight image frames.

The RGB TF-EE of each IOL was measured. Figure 2 illustrates the procedure used to calculate the energy efficiency (EE) that was measured in the image space. An edge detection algorithm, Canny edge detector, as implemented by MATLAB (MathWorks, Natick, MA) was first applied to segment the central core from the image of the pinhole at a given image focus plane. In every focus (distance, intermediate, and near), a local maximum EE value (which

also involved a peak in the area under the modulation transfer function curve) determined the position of the best focus plane. Figure 2A shows the pinhole image under G light at the distance focus plane of a lens, which corresponds to an image vergence of 0.0 D. Then, the intensity in the image as a whole was calculated ( $I_{total} = I_{core} + I_{background}$ ) to obtain the EE metric from the  $I_{core}/I_{total}$  ratio:  $EE (\%) = (I_{core}/I_{total}) \times 100$ . The EE metric was easy to compute for the three R, G, and B wavelengths and under experimental conditions approached the so-called light-in-the-bucket metric.<sup>20,35</sup> By definition, the light-in-the-bucket metric represents the diffraction EE of an IOL, as well as the image blur caused by aberrations and scattering, because it quantifies the amount of light in the central core of the point spread function (PSF) relative to that of a monofocal diffraction-limited PSF for the same wavelength and pupil size.<sup>20,35</sup> The implementation of this metric in experimental practice, where the ideal point source is replaced by a pinhole of certain size, has been described and justified in a former work.<sup>21</sup>

The procedure was then repeated step by step to axial scan the region of interest (from +2.0 to -5.0 D, in 0.1-D steps with 0.05-D resolution) in trifocal and EDOF IOLs.

The focus powers and their corresponding LCAs were experimentally obtained in all lenses from the maxima of the RGB TF-EE curves. LCA values were computed from the power difference between the B and R EE peaks at each focus plane. For an achromatized lens, for which the B - R power difference is ideally reduced to zero, we also computed the residual chromatic aberration from the maximum power difference between the G EE peak and the R and B ones. The distance power was measured with respect to the distance focus at G illumination (closest to the design wavelength according to the ISO 11979-2:2014). At such a G distance focus plane, the image vergence was set to 0.0 D. Further details can be found elsewhere.<sup>21,22</sup>

The following additional metrics are defined here and were included in the analysis for a more complete characterization of the chromatic performance of the lenses:

- The energy efficiency difference ratio (EEDR) at each  $i$ -focus:

$$EEDR^i (\%) = \left[ \max \Delta (EE_{R,G,B}^i) / EE_G^i \right] \times 100,$$

with  $i = \{\text{distance, intermediate, near}\}$

is the ratio expressed in percentage between the maximum EE absolute difference, measured from the R, G, B peak values— $\max \Delta (EE_{R,G,B}^i) = \max\{|EE_R - EE_B|, |EE_R - EE_G|, |EE_B - EE_G|\}$ —

and the green EE peak value ( $EE_G$ ). A positive or negative sign is arbitrarily assigned to EEDR depending on the R, G, B peak order. Thus, a negative EEDR indicates  $EE_B < EE_R$ , which generally occurs for distance focus; the opposite, a positive EEDR, indicates  $EE_B > EE_R$ , which generally occurs for near focus.  $EE_G$  is typically between  $EE_B$  and  $EE_R$ . An ideally balanced energy distribution (in terms of the R, G, B components) would require similar amounts of EE for the R, G, B peaks and, therefore, EEDR values close to 0% for all foci. Otherwise, chromatic deviations might appear when comparing color visual performances among near, intermediate, and distance vision. The lower the EEDR value at a given focus, the more balanced the spectral distribution of energy at that vision distance and the better.

- The peak-to-valley energy efficiency difference (EED<sub>PV</sub>) is the EE absolute difference in percentage units between the maximum peak and valley, measured in the G TF-EE curve of each IOL. This metric accounts for the smoothness of the overall TF-EE curve at the design wavelength. As such, the lower the EED<sub>PV</sub> value, the better and smoother the transitions between the foci in the trough-focus curve and the more equalized the transition from distance to near vision.
- The area of the chromatic energy efficiency span (EES) between the RGB TF-EE curves integrates the absolute maximum difference between the RGB TF-EE curves in the whole focal range of interest in  $j$  steps,

$$EES = \sum_j \max \Delta (EE_{R,G,B}^j)$$

The smaller this area, the more compact the energy distribution with respect to both the foci of the lens and the spectral RGB content. A low EES value would contribute to reducing the impact of chromatic aberration.

## Results

### RGB Through-Focus Energy Efficiency (TF-EE and EEDR)

Figure 3 shows the TF-EE curves obtained with the Versario 3F, FineVision, and Symphony IOLs. The relative displacement of RGB plots for every focus and IOL accounts for the existing LCAs, which is discussed further below. Table 2 summarizes all RGB TF-EE, LCA (including residual chromatic aberration

**Table 2.** Experimental RGB EE Peak Values, LCA, and EEDR at Each Focus (Distance, Intermediate, and Near) for the Studied IOLs

	Near Focus		Intermediate Focus		Distance Focus	
	Vergence (D)	EE (%)	Vergence (D)	EE (%)	Vergence (D)	EE (%)
<b>Versario 3F</b>						
Red	3.23	15.6	1.47	19.6	-0.29	50.7
Green	3.04	18.0	1.59	22.0	0.00	35.6
Blue	2.76	22.5	1.53	23.9	0.21	29.9
LCA <sup>a</sup> (D)	-0.47	—	0.06 [0.12]	—	0.50	—
EEDR (%)	—	38.2	—	19.4	—	-58.6
<b>FineVision MicroF</b>						
Red	3.87	24.3	1.75	14.0	-0.20	66.5
Green	3.45	28.8	1.68	17.4	0.00	46.4
Blue	3.27	33.0	1.82	19.3	0.21	37.6
LCA <sup>a</sup> (D)	-0.60	—	0.06 [0.14]	—	0.41	—
EEDR (%)	—	30.2	—	30.4	—	-62.2
<b>TECNIS Symphony</b>						
Red	—	—	2.12	20.9	0.07	63.1
Green	—	—	1.71	48.6	0.00	32.4
Blue	—	—	1.75	68.5	0.13	14.2
LCA <sup>a</sup> (D)	—	—	-0.36 [-0.40]	—	0.06 [0.13]	—
EEDR (%)	—	—	—	98.0	—	-151.0

<sup>a</sup>Bracketed value is the residual chromatic aberration.

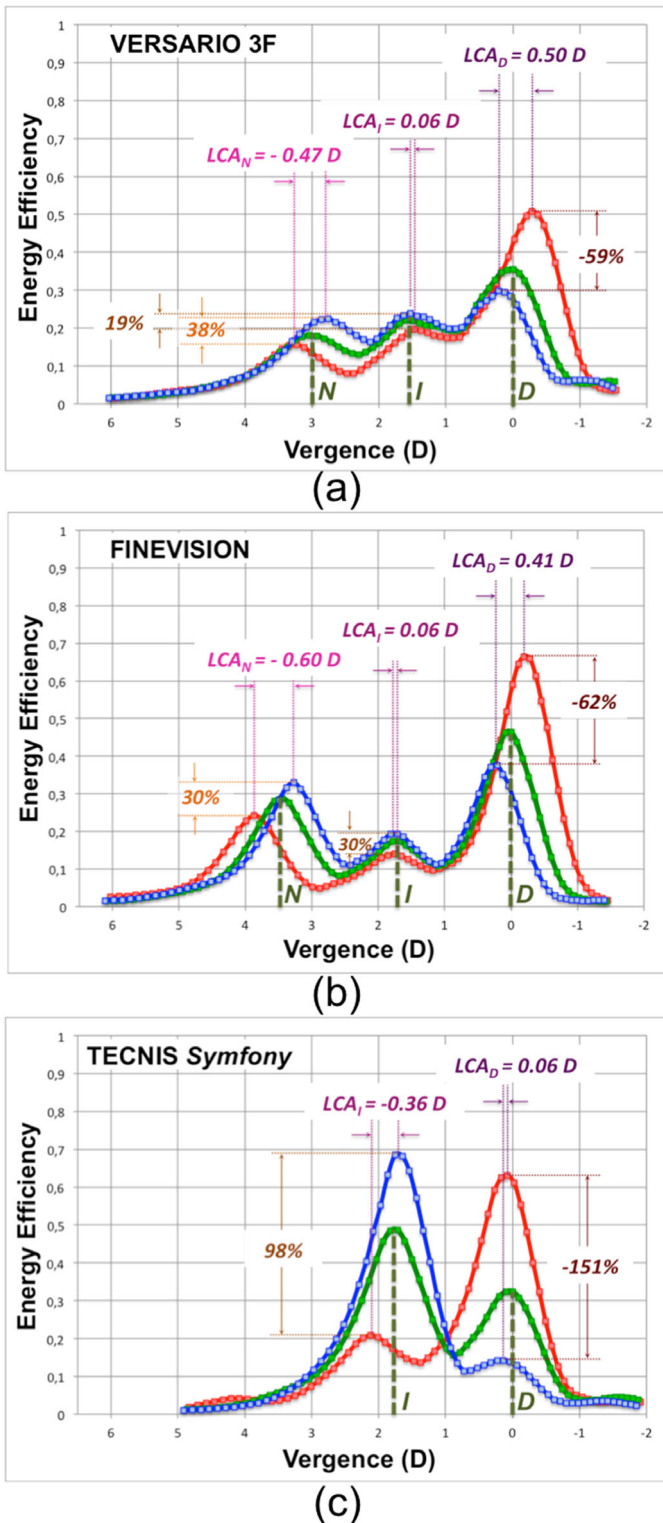
of achromatized focus in brackets), and EEDR values obtained with these three IOLs; some of these values are also included in Figure 3 to help with interpretation of the results.

The TF-EE curves obtained with the Versario 3F showed a triple set of RGB TF-EE peaks that corresponded to the distance, intermediate, and near foci of the lens (Fig. 3A). The energy was split and focused on the foci, with the higher efficiency corresponding to the distance focus no matter the R, G, or B illumination considered; thus, this lens showed a relative energy predominance of distance focus over intermediate and near foci, which had relatively balanced EE. For distance focus, the highest and lowest EE values corresponded to the R (50.7%) and B (29.9%) lights, respectively; the opposite situation occurred for near focus, for which the B component had the highest EE (22.5%) and the R component had the lowest EE (15.6%) (Table 2). Under green light illumination, the maximum EE reached 35.6% at the distance focus, which was slightly higher than the value reached by the Symphony lens (32.4%) but lower than the value reached by the FineVision (46.4%) for its distance focus (Table 2); for intermediate focus, the RGB EE values were very close (Table 2). The EEDR was rather low in the intermediate (19%) and near (38%) foci, whereas

it increased in magnitude and became negative (-59%) for the distance focus (Fig. 3A, Table 2).

The results obtained with the Versario 3F lens were quite similar to those obtained with the trifocal FineVision IOL; however, the latter showed higher RGB EE values at the distance and near foci and lower values at the intermediate focus (Fig. 3B, Table 2). The EEDR at the near and intermediate foci of the FineVision IOL were very similar (30.2% and 30.4%, respectively) and rather low. The EEDR for the distance focus for the FineVision IOL remarkably increased in magnitude while becoming negative (-62.2%) (Table 2).

The TF-EE curves obtained with the Symphony lens were markedly different from those obtained with the two trifocal IOLs, as they showed clearly visible distance and intermediate foci and a lack of near focus (Fig. 3C). In particular, the TF-EE curves for the R and B components appeared to be asymmetric, as the R component had the highest EE value (63.1%) for distance focus and the lowest value for intermediate focus (20.9%); the B component had a very high EE value for intermediate focus (68.5%) and a very low value for distance focus (14.2%) (Table 2). The EEDR values obtained at the intermediate and distance foci with this lens were much greater than those obtained with the two trifocal IOLs (98% and -151%, respec-



**Figure 3.** Through-focus energy efficiency versus defocus for the studied 30-D IOLs with a 3.5-mm pupil: (a) Versario 3F, (b) FineVision, and (c) TECNIS Symphony. Results were obtained with R (■-□-■), G (■-□-■), and B (■-□-■) illumination. The vergence of the distance (D), intermediate (I), and near (N) foci of each IOL under G illumination is indicated by vertical thick dashed lines. Values for LCA (D) and EEDR (%) at the foci of the IOLs (Table 2) are shown.

tively) (Table 2). Note that the results obtained with the Symphony lens, shown in Figure 3C, are consistent with those reported in figure 3b of Reference 22, which were obtained in similar experimental conditions.

### Peak-to-Valley Energy Efficiency Difference (EED<sub>PV</sub>)

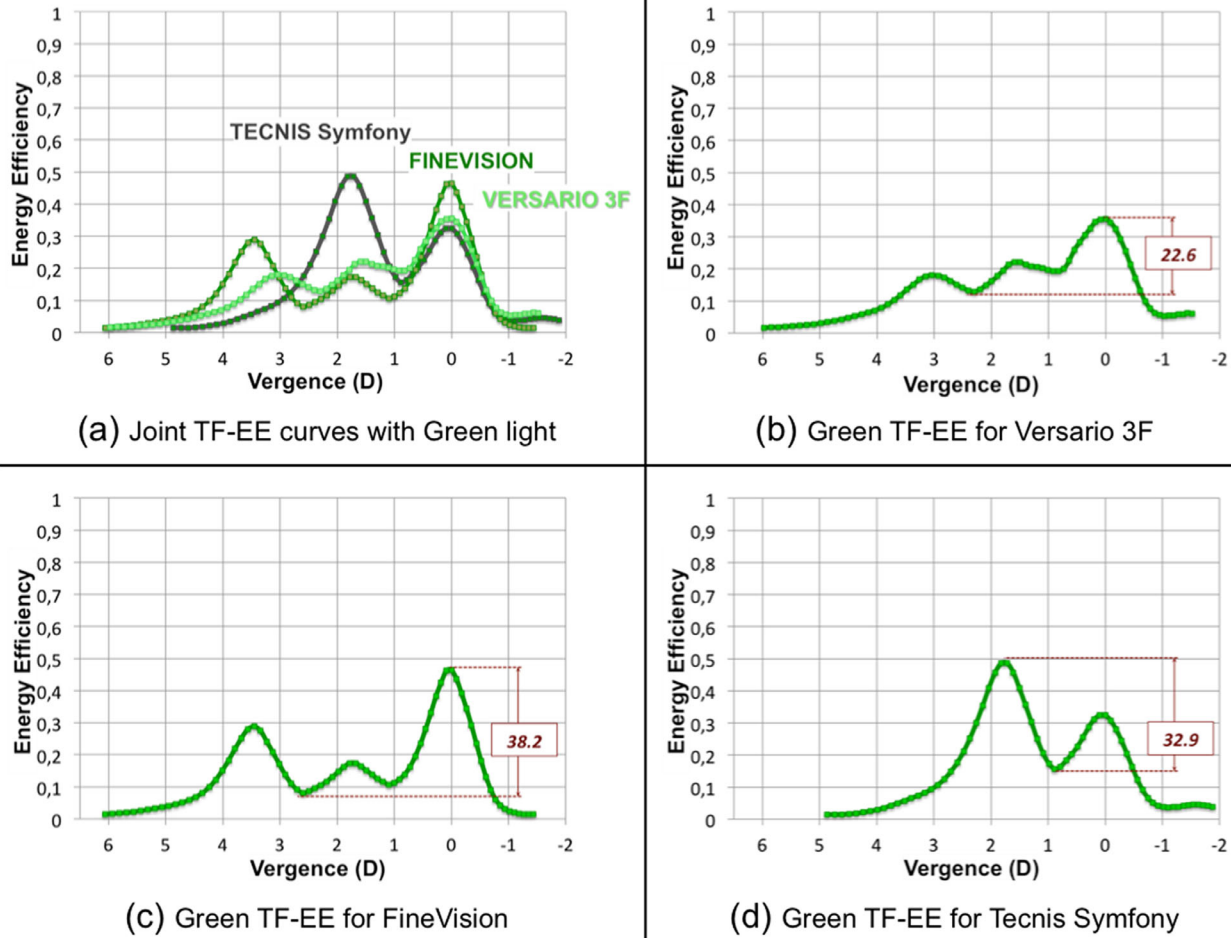
Figure 4 illustrates the distribution of the energy among the foci of the studied IOLs for the G light. The designs of IOLs are optimized in model eyes that include a cornea lens. In our study, the IOLs were optically tested without a cornea, so the energy distributions and EED<sub>PV</sub> values shown in Figure 4 must be treated as first-approach figures and not fully representative of what happens in a model eye.

Although the Versario 3F lens never reached the highest EE value at any of the three foci (distance, intermediate, or near) compared to the other tested IOLs (Fig. 4A), it showed the smoothest G EE distribution with the lowest EED<sub>PV</sub> value (22.6 percentage points) (Fig. 4B). This fact does not mean that the Versario 3F lens has better image quality (e.g., it was worse than the FineVision lens at distance focus), but the energy focused at the image core showed less variation in a through-focus analysis between the focal planes. The other IOLs had more marked peaks in their respective G TF-EE profiles, which resulted in larger EED<sub>PV</sub> values: 38.2 percentage points for the FineVision lens (Fig. 4C) and 32.9 percentage points for the Symphony lens (Fig. 4D).

### LCAs and Area of the Chromatic EE Span Between the RGB TF-EE Curves

Table 2 and Figure 3 show the LCA values in the distance (LCA<sub>D</sub>), intermediate (LCA<sub>I</sub>), and near (LCA<sub>N</sub>) foci of the three IOLs. The LCA values presented in Table 2 do not fully represent the clinical situation because they account only for aberrations of the IOLs. However, other sources of LCA are also present in the eye.

The Versario 3F and FineVision IOLs showed, at least to some extent, a rather similar performance with regard to LCAs. With both lenses, positive values were obtained for LCA<sub>D</sub> (0.50 D for the Versario 3F lens and 0.41 D for the FineVision lens) and negative values for LCA<sub>N</sub> (-0.47 D for the Versario 3F lens and -0.60 D for the FineVision lens). Finally, LCA<sub>I</sub> was negligible (0.06 D) for both lenses, with little residual chromatic aberration (0.12 D for the Versario 3F lens and 0.14 D for the FineVision lens). For the Symphony IOL, LCA<sub>D</sub> was negligibly positive (LCA<sub>D</sub> = 0.06 D, with little residual



**Figure 4.** Green TF-EE curves for the Versario 3F, FineVision, and Symphony IOLs shown (a) jointly and (b, c, d) separately, respectively. EED<sub>pv</sub> values are shown in percentage points for the three lenses.

aberration of 0.13 D), and LCA<sub>I</sub> was still rather small but negative (LCA<sub>I</sub> = -0.36 D, very close to the residual -0.40 D aberration).

Figure 5 shows the chromatic EES measured from the area limited by the RGB TF-EE curves in each IOL (and expressed in arbitrary units, a.u.). The Versario 3F lens had the best result with the smallest area (EES = 46 a.u.) compared to the other two IOLs, with the EES values for the FineVision and Symphony lenses being 73.5 a.u. and 103.2 a.u., respectively.

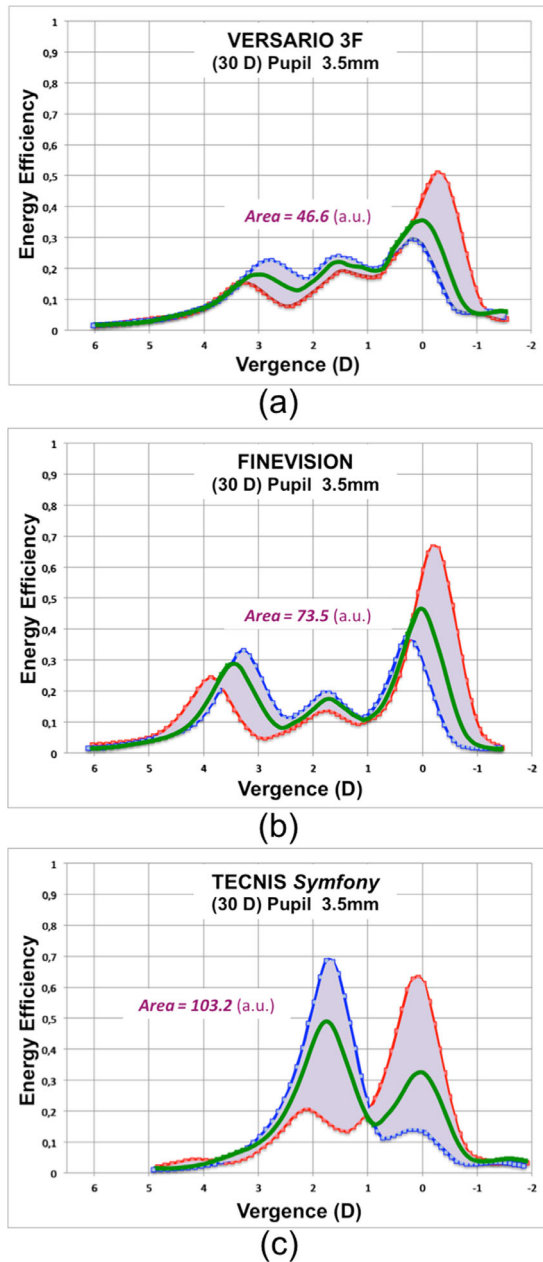
## Discussion

LCA is a commonly used metric to describe chromatic image performance in lenses. Modern IOL designs try to reduce it as much as possible to improve lens performance. Quite frequently, however, the RGB energy efficiency, which should be balanced at the foci

of the lens in order to not severely alter the color content of images, is overlooked.

To our knowledge, this is the first study to assess the chromatic performance of the Versario 3F IOL at the foci. In addition, for the sake of comparison, the results obtained for this new IOL are compared with other trifocal lenses, such as the FineVision MicroF, and with the TECNIS Symphony EDOF lens using the same experimental setup and metrics. This comparative analysis was performed because, depending on their particular design, diffractive-based IOLs may alter the chromatic performance of pseudophakic eyes in comparison to phakic ones. Moreover, it is necessary to evaluate chromatic performance differences between the foci of the IOLs and, at each focus, the balance of the chromatic components. In vitro chromatic characterization of diffractive IOLs through optical bench testing can provide useful information for determining the possible existence of spectral dependence in the visual performance of pseudophakic patients tested at





**Figure 5.** Chromatic span (EES) measured from the area limited by the TF-EE curves in each IOL (in arbitrary units): (a) Versario 3F, (b) FineVision, and (c) TECNIS Symphony.

different distances. For example, Łabuz et al.<sup>36</sup> used the wavelength-dependent optical quality of a diffractive IOL tested in vitro to explain the effects of red light on the visual performance of pseudophakic patients tested at various observation distances in the clinics. In addition, with the aim of achieving an exhaustive analysis of the optical properties of the tested IOLs, new metrics—EEDR, EED<sub>PV</sub>, and EES—have been utilized along with the standard LCA and RGB TF-EE curves. These new metrics were used to assess and compare the three lenses.

The LCA measurements of each IOL could have been introduced in a model eye, with the crystalline lens replaced by the IOL and the LCA of such a pseudophakic model eye recalculated (as done in Ref. 21 assuming a LeGrand eye model). However, there is no general consensus about the effects that can be predicted on the visual performance from the calculated LCA in a pseudophakic eye model. In addition to this, we do not consider such a calculation to be essential for the proposed comparison. In our study, we have met the basic requirement of comparing the chromatic performance of the three lenses under the same and simple conditions given by the wet cell.

The RGB TF-EE curves obtained with the Versario 3F lens were qualitatively similar to those of the FineVision trifocal IOL. Both lenses showed a triple set of RGB TF-EE peaks that corresponded to the distance, intermediate, and near foci. This behavior is in line with results reported on the optical quality of trifocal IOLs based on measurements of the modulation transfer function.<sup>27,37,38</sup> At near and intermediate foci, we found that the EEDR values were rather low for both lenses, thus indicating a good balance in terms of the energy distribution of chromatic components, whereas the spectral distribution for distance focus appeared to be less balanced, as the EEDR values sensibly increased for both the Versario 3F and FineVision IOLs.

The energy split clearly showed that these lenses had a relative energy predominance of distance focus over intermediate and near foci. For distance focus, the highest and lowest EE values corresponded to the R and B lights, respectively, whereas for near focus the B component had the highest EE values and the R component the lowest. Other studies have reported similar wavelength dependence of the EE<sup>21</sup> and the modulation transfer function<sup>23,38</sup> for the distance and near foci of bifocal diffractive IOLs. This was explained for those bifocals on the basis of the wavelength dependence exhibited by the EE of the zeroth and first diffraction orders, which are the orders that primarily contributed to the distance and near foci of the FineVision trifocal IOL in our study.

For the Versario 3F and FineVision lenses, the LCA values for intermediate focus were very low, whereas those for distance and near foci increased in magnitude and had an opposite sign, but never exceeded  $\pm 0.6$  D; these results indicate that, although not being specifically designed to address chromatic aberrations, both lenses have low LCA values for distance and intermediate foci and moderate LCA values for near focus in comparison with other multifocal diffractive lenses reported in the literature (see, for example, Refs. 20, 21, 23, and 38). Despite the similarities in the RGB

TF-EE curves between these two lenses, some quantitative differences were found. The slightly larger addition powers of the FineVision lens in comparison with the Versario 3F led to less smooth transitions from the distance to the intermediate peaks and from the intermediate to the near peaks. The EE distribution of the Versario 3F lens showed less variation through the focal planes, as can be seen from the EE under G illumination, which showed a lower  $EED_{PV}$  for this lens (22.6% vs. 38.2% for the FineVision lens).

The TF-EE curves obtained with the Symphony lens were markedly different from those obtained for the two trifocal IOLs. They showed the existence of distance and intermediate foci and the absence of near focus. These results are in agreement with the findings reported in our earlier study.<sup>22</sup> In the present study, we found a negligible  $LCA_D$  and a very low  $LCA_I$ , with values quite comparable to those already reported,<sup>22</sup> thus confirming that this lens was specifically designed to compensate for LCA in distance and intermediate foci. Moreover, as in our earlier study,<sup>22</sup> the TF-EE curves showed an evident asymmetry between the R and B components, with the peak for the R TF-EE curve occurring in the opposite direction of that shown for the B TF-EE curve. This fact led us to state that “this increase in both the R and B TF-EE asymmetry could have an impact on the color image quality that deserves further evaluation in future work.”<sup>22</sup> Recently, Łabuz et al.<sup>36</sup> showed in a clinical evaluation of patients implanted with Symphony that the spectral dependence of the lens had an adverse effect on visual acuity and contrast sensitivity at intermediate distance and even greater at near.

The low LCA values of the Symphony IOL appeared to be in contrast with the large energy efficiency differences between its B and R TF-EE curves. Such differences were larger than those found in the two tested trifocal IOLs. Therefore, we computed the EES based on the area span between the TF-EE curves; indeed, the EES value for the Symphony lens was the highest among all three tested IOLs. In contrast, the Versario 3F lens had the smallest area, a result that again pointed out a more balanced distribution of light, not only for distance, intermediate, and near foci but also for the spectral RGB content. This property might predict a reduced impact of chromatic aberration. In addition, the results in our study on the  $EED_{PV}$  and EES values suggest that, for a given IOL, the mere evaluation of the LCA provides only partial information on its chromatic properties, whereas taking into account the entire spectral RGB TF-EE provides a more detailed description of its chromatic performance.

At the moment, the new metrics introduced in this study are useful for describing IOL performance

on the optical bench, but further and more intensive studies are necessary to confirm their usefulness beyond the *in vitro* approach. When the IOL has been implanted, many factors (optical, physiological, and neurological) influence the pseudophakic patient’s visual quality as tested in clinics. It is worth noting that studies have established a mathematical relationship between modulation transfer function (MTF)-based metrics and the high-contrast visual acuity (VA) tested in clinical practice. They show that *in vitro* MTF-based measurements can be used for a preclinical estimation of average through-focus VA (see, for example, Refs. 39–41). This methodological approach has been recommended in the ANSI\_Z80.35-2018 standard.<sup>42</sup> Further correlations between the polychromatic EE and clinical average VA of pseudophakic patients have been reported recently.<sup>43</sup> Suchkov et al.<sup>44</sup> showed the influence of modifying LCA on VA, both experimentally and by simulation using a chromatic eye model. Although VA exhibits a robust response under modified chromatic conditions, the authors reported impairment in the predictability of the results with an LCA modified from natural conditions, as the experimental VA values were lower than the predicted. Marcos et al.<sup>45</sup> reported in a recent paper that psychophysical LCA was consistently larger than objective LCA in a group of patients implanted with a monofocal IOL. Such reports indicate that clinical applications of *in vitro* measurements and simulations using eye models are of great interest, and studies are currently proceeding at a rapid pace, although much additional research is required.

## Conclusions

In terms of energy, the Versario 3F trifocal IOL was not the most efficient lens at distance, intermediate, and near foci compared to the other two lenses tested; however, the Versario 3F lens demonstrated good properties with respect to chromatic performance. LCAs were low ( $\leq 0.50$  D) for all three foci; in particular, LCA was negligible at intermediate focus. In this respect, the quality of the Versario 3F lens was very similar and no worse than the FineVision trifocal lens.

The span between the RGB TF-EE curves of the Versario 3F lens was markedly smaller throughout the vergence range of interest in comparison with the two other IOLs, revealing a more balanced distribution of light with respect to not only the distance, intermediate, and near foci but also the spectral RGB content. It might be expected that this property could contribute, in terms of chromatic performance, to a balanced in

vivo vision quality transition through near, intermediate, and far focusing distances. However, to prove this assumption, further analyses of LCAs measured in vivo after implantation during cataract surgery are necessary.

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