

Topography and longitudinal chromatic aberration characterizations of refractive–diffractive multifocal intraocular lenses



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Purpose: Most optical systems present chromatic aberration quantified along the optical axis by the longitudinal chromatic aberration (LCA). LCA is controlled by the biomaterial Abbe number combined with diffractive effects, driven by the intraocular lens (IOL) topography. This study experimentally aimed at describing the effect in vitro of LCA in diffractive multifocal IOLs, with the help of dedicated optical benches and topographic characterization.

Setting: Centre Spatial de Liège, Belgium.

Design: Optical and topology analysis of various multifocal diffractive IOLs.

Methods: Seven diffractive multifocal IOLs, available on the market and exhibiting different diffractive profiles, made from various biomaterials, were characterized under different wavelengths.

Results: Through-focus modulation transfer function (MTF) curves and IOL diffraction efficiency depends on the incident light wavelength. In this study, the topology properties of various multifocal IOLs were investigated and their characteristics were correlated to their optical behavior for various wavelengths. Chromatic properties and their origins were then compared. As expected, diffractive and refractive effects were found to act in opposite ways, and could be partially or completely compensated.

Conclusions: The LCA of each of the IOLs was evaluated in vitro. In most of the multifocal IOLs studied, some of the foci were found to be refractive, whereas others were diffractive. Although the results were not extrapolated to clinical relevance, it was shown, in some of the cases, that LCA could be fully compensated.

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Multifocal intraocular lenses (IOLs) are now recognized as a powerful solution that can be proposed to patients who need cataract surgery and wish to become spectacle independent.^{1–9} A number of these advanced IOLs have been introduced onto the market, each with their own advantages and disadvantages, depending on the proposed solutions and the physiology of the intended patient. The diversity of available IOLs makes them complex to analyze. In this study, we focused on multifocal IOLs based on diffractive technology. The profile of the diffractive grating and some optical metrics, such as the longitudinal chromatic aberration (LCA) generated by IOLs, is discussed. Each IOL is made of a specific biomaterial, characterized by its Abbe number, with specific refractive shape and diffractive profiles. In most of the diffractive multifocal IOLs, a hybrid refractive–diffractive design is presented. Light energy is split between a number of foci, typically dedicated to far, intermediate, and near vision for trifocal IOLs. In most

designs, the far foci receive light that appears to be purely refracted (0 order of diffraction), whereas the other foci (intermediate and near) are obtained through a combination of diffracted light (first and second order of diffraction). Bifocal IOLs exhibit only two foci, with various addition powers. As an example, the Tecnis ZMB00 (Johnson & Johnson Vision Care, Inc.) is a bifocal diffractive IOL. Its far vision is provided by refraction, whereas its near vision is driven by a combination of refraction and diffraction. Another example is the Tecnis Symphony (Johnson & Johnson Vision Care, Inc.). This is a bifocal IOL,⁷ which is a fully refractive–diffractive IOL without any purely refractive focus. Because the far and intermediate foci are close enough together in the Tecnis Symphony, an overlapping is observed in modulation transfer function (MTF) through-focus curves for small pupils. This gives a continuous vision from far to intermediate. At larger pupil diameters, this IOL presents distinct peaks. This type of IOL is referred to as an extended depth-of-focus (EDOF)

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IOL.⁷ In addition, trifocal IOLs have been developed to offer good visual performance over a broader range of vision through the definition of three foci. This is the case for the FineVision (PhysIOL, S.A.), AT LISA tri (Carl Zeiss Meditec AG) or PanOptix (Alcon Laboratories, Inc.) IOLs,⁹ for instance.

In the IOL literature, most of the in vitro optical characterizations have been performed in monochromatic green light, which corresponds to the most sensitive domain of light for the human eye. However, the natural visual environments of the human eye are polychromatic. White light comprises the different colors and wavelengths of visible light, ranging from red (650 nm) to violet (400 nm). The way the different wavelengths are handled by optical components leads to LCA, causing an additional aberration to all higher-order geometrical aberrations. However, the exact consequences on visual acuity are not demonstrated in this paper and remain to be explored in further studies.

Refractive or diffractive focalization leads to opposite signs of LCA. The combination of both of these principles offers an opportunity to reduce or compensate the LCA generated by the multifocal IOL. Diffraction theory predicts that addition powers and the amount of light distributed to foci are dependent on the wavelength of the incident light.

In this study, we investigated the basic structure of the diffractive patterns of various multifocal IOLs and explored, on an optical bench, the behavior of these IOLs in relation to various light wavelengths.

MATERIALS AND METHODS

Multifocal Intraocular Lens Descriptions

Seven IOLs were studied and compared. For comparison with purely refractive components, two monofocal IOL with two characteristic biomaterials and Abbe numbers were also included in the study. The study was limited to a base power labeled to 20.0 diopters (D). This corresponds to the far focus power of a multifocal IOL used to achieve emmetropia in an “average” pseudophakic eye.

1. **Pupil-Independent Fully Diffractive Bifocal Multifocal Intraocular Lens** The Tecnis ZMB00 is a pupil-independent, fully diffractive bifocal multifocal IOL, with a +4.00 D addition power. It is a single-piece C-loop IOL, made of hydrophobic material with ultraviolet (UV) filtration. The optic body diameter is 6.0 mm and the overall diameter is 13.0 mm.
2. **Extended Depth-of-Focus Multifocal Intraocular Lens** The Tecnis Symfony ZXR00 is a bifocal multifocal IOL made of a diffractive step-like optical profile, intended to extend the range of vision while being combined with a proprietary technology to correct chromatic aberrations. It is a single-piece C-loop IOL, made of hydrophobic material with UV filtration. The optic body diameter is 6.0 mm and the overall diameter is 13.0 mm.
3. **Apodized Hydrophobic Fully Diffractive Intraocular Lens** The FineVision^{HP} POD F GF is a double C-loop multifocal IOL with 5 degrees of angulation, made of PhysIOL proprietary hydrophobic G-free material,¹⁰ with UV filtration and a blue-light blocker. The optic body diameter is 6.0 mm and the overall diameter is 11.4 mm. In addition to its far refractive power, FineVision^{HP} provides two foci for intermediate and near distance vision, with addition powers of +1.75 D and +3.50 D, respectively.

4. Apodized Hydrophilic Fully Diffractive Intraocular Lens

The FineVision POD F is a double C-loop multifocal IOL with 5 degrees of angulation, made of hydrophilic (meth)acrylic material, with UV filtration and a blue-light blocker. The optic body diameter is 6.0 mm and the overall diameter is 11.4 mm. In addition to its far refractive power, the FineVision POD F provides two foci for intermediate and near distance vision, with addition powers of +1.75 D and +3.50 D, respectively.

5. Hydrophobic Fully Diffractive Trifocal Longitudinal Chromatic Aberration-Corrected Intraocular Lens

The LCA-corrected FineVision multifocal IOL (PODLGF) is a double C-loop lens with 5 degrees of angulation, made of PhysIOL proprietary hydrophobic G-free material, with UV filtration and a blue-light blocker. The optic body diameter is 6.0 mm and the overall diameter is 11.4 mm. In addition to its far refractive power, the LCA-corrected FineVision provides two foci for intermediate and near distance vision, with addition powers of +1.75 D and +3.50 D, respectively. This IOL has been specially designed to minimize chromatic aberration for far and intermediate vision.

6. Hydrophobic Partially Diffractive Trifocal Intraocular Lens

The trifocal Acrysof IQ PanOptix TFNT00 is a UV-filtering and blue light-filtering foldable diffractive multifocal IOL. It is a hydrophobic acrylic single-piece IOL, with a 6.0 mm optic, two open-loop haptics, and an overall diameter of 13.0 mm. The diffractive structure is located within the central 4.5 mm of the anterior surface and distributes the incoming light into +2.17 D intermediate and +3.25 D near addition powers.

7. Hydrophilic Partially Diffractive Trifocal Intraocular Lens

The AT LISA tri 839MP is a trifocal diffractive IOL, with +3.33 D for near addition and +1.66 D for intermediate addition at the IOL plane. This multifocal IOL has an aspheric design, with an overall diameter of 11.0 mm and an optic diameter of 6.0 mm. The IOL presents an asymmetric light distribution: light is distributed between distance and near foci within the whole optical zone. On the other hand, in the central 4.34 mm zone, light is divided among distance, intermediate, and near foci.

8. Hydrophilic Monofocal Intraocular Lens

The MicroPlus (PhysIOL, S.A.) is an aspheric monofocal IOL with 2 degrees of haptic angulation, made of hydrophilic (meth)acrylic material, with UV filtration and a blue-light blocker. The IOL has 4 closed haptics.

9. Hydrophobic Monofocal Intraocular Lens

The MicroPure (PhysIOL, S.A.) is an aspheric monofocal IOL with 2 degrees of haptic angulation, made of PhysIOL proprietary hydrophobic G-free material with UV filtration and a blue-light blocker. The IOL has 4 closed haptics.

Surface Topography

Because the diffractive profile has a strong impact on the optical properties of a given IOL, the topology of each diffractive IOL was measured. Topography measurements were acquired using an optical profilometer (Bruker Contour GTI). The IOLs were measured in the Interferometry VXi mode, with a 20× magnification objective and a 0.55× zoom lens and total magnification of 11×. The field of view of a simple image was 0.6 × 0.4 mm². To cover the whole radius of the lens, image stitching was applied. Equidistant images were taken along the IOL radius. An image composite was generated automatically by the calibrated instrument software. Relative positions of the images were recorded by the motorized stage encoder of the optical profilometer. The recording process was performed without changing the view angle. From the completely reconstructed profile, the main IOL curva-

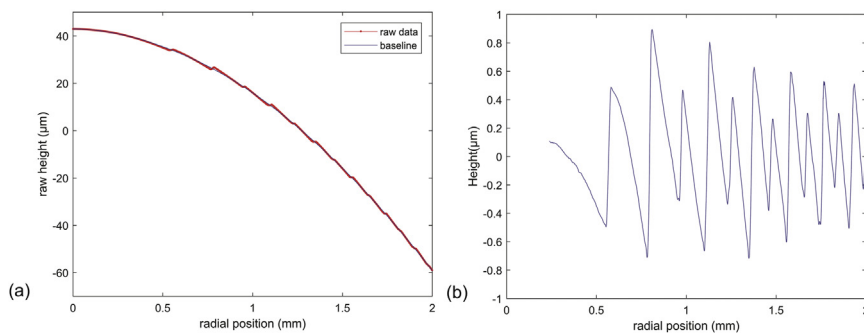


Figure 1. Diffraction intraocular lens cross section (FineVision^{HP} POD F GF, PhysIOL, S.A.), which (a) corresponds to the raw data measured by the Bruker profilometer and its calculated baseline, whereas the curve (b) shows the extracted diffractive profile.

ture was evaluated and removed to extract the experimental diffractive profile. The height and position of each diffractive step were evaluated and made in correspondence with the diffractive Fresnel IOL add-focus and phase relationship.^{11,12} Figure 1 shows this process. Height correction has been applied to take into consideration the view angle associated with the IOL curvature along the radius.

Index of Refraction and Abbe Number

All the IOLs studied in this paper are made of different biomaterials, presenting advantages and disadvantages in terms of biocompatibility, transparency, UV filtering, and so forth. From the imaging point of view, materials have different refractive indices and Abbe numbers. Both parameters are complementary because they act on the chromatic properties of an IOL and on the phase shift of light traveling through it. The higher the Abbe number, the lower the chromatic aberration. Table 1 shows some parameters of the IOLs studied.

Optical Bench

The optical bench used for this series of measurements was the PMTF (Power and Modulation Transfer Function bench, developed by Lambda-X) to measure image quality—MTF of diffractive multifocal IOLs.¹ The PMTF optical bench is equipped with three monochromatic light sources, at three different wavelengths (480 nm, 546 nm, and 650 nm \pm 2 [SD]). The apparatus complies with International Organization for Standardization (ISO) number 11979-2¹³ and ISO number 11979-9¹⁴ requirements. Measurements were performed with a model cornea, displaying zero spherical aberration (0 μm of longitudinal spherical aberration), to assess the optical performance of the IOLs themselves, excluding the potential influence of the cornea lens. Residual chromatic aberration generated by the optical bench was calibrated and was removed from the through-focus curves.

The PMTF enables MTF measurement at different apertures (2.0 mm, 3.0 mm, 3.75 mm, and 4.5 mm), focal planes (through-focus curve) and spatial frequencies.

Table 1. Summary of the properties of the studied IOLs.

IOL Name	Biomaterial	Index of Refraction (Hydrated, 550 nm)	Abbe Number	Base Power (D)	Active Diffractive Orders	Reference Numbers
FineVision POD F*	Hydrophilic	1.46	58	19.5	FAR: 0 order, INTER: 1st order 1st profile, NEAR: 1st order 2nd profile	3,6,10
AT LISA tri†	Hydrophilic	1.46	58	22	FAR: 0 order, INTER: 1st order 1st profile, NEAR: 1st order 2nd profile	4,5
Tecnis ZMB00‡	Hydrophobic Aliphatic	1.47	55	20	FAR: 0 order, NEAR: 1st order	6,7
Tecnis Symphony‡	Hydrophobic Aliphatic	1.47	55	20	FAR: 1st order, INTER: 2nd order	6,7
FineVision ^{HP} POD F GF*	Hydrophobic Aliphatic-aromatic	1.52	42	20	FAR: 0 order, INTER: 1st order 1st profile, NEAR: 1st order 2nd profile	6
LCA-corrected FineVision*	Hydrophobic Aliphatic-Aromatic	1.52	42	21	FAR: 1st order, INTER: 2nd order 1st profile, NEAR: 2nd order 2nd profile	6
Acrysof IQ PanOptix§	Hydrophobic-Aromatic	1.55	37	20.5	FAR: 0 order, INTER: 2nd order, NEAR: 3rd order	9
Monofocal MicroPlus*	Hydrophilic	1.46	58	20	FAR: refractive focus only	10
Monofocal MicroPure*	Hydrophobic Aliphatic-Aromatic	1.52	42	20	FAR: refractive focus only	10

INTER = intermediate; IOL = intraocular lens; LCA = longitudinal chromatic aberration

*PhysIOL, S.A.

†Carl Zeiss Meditec AG

‡Johnson & Johnson Vision Care, Inc.

§Alcon Laboratories, Inc.

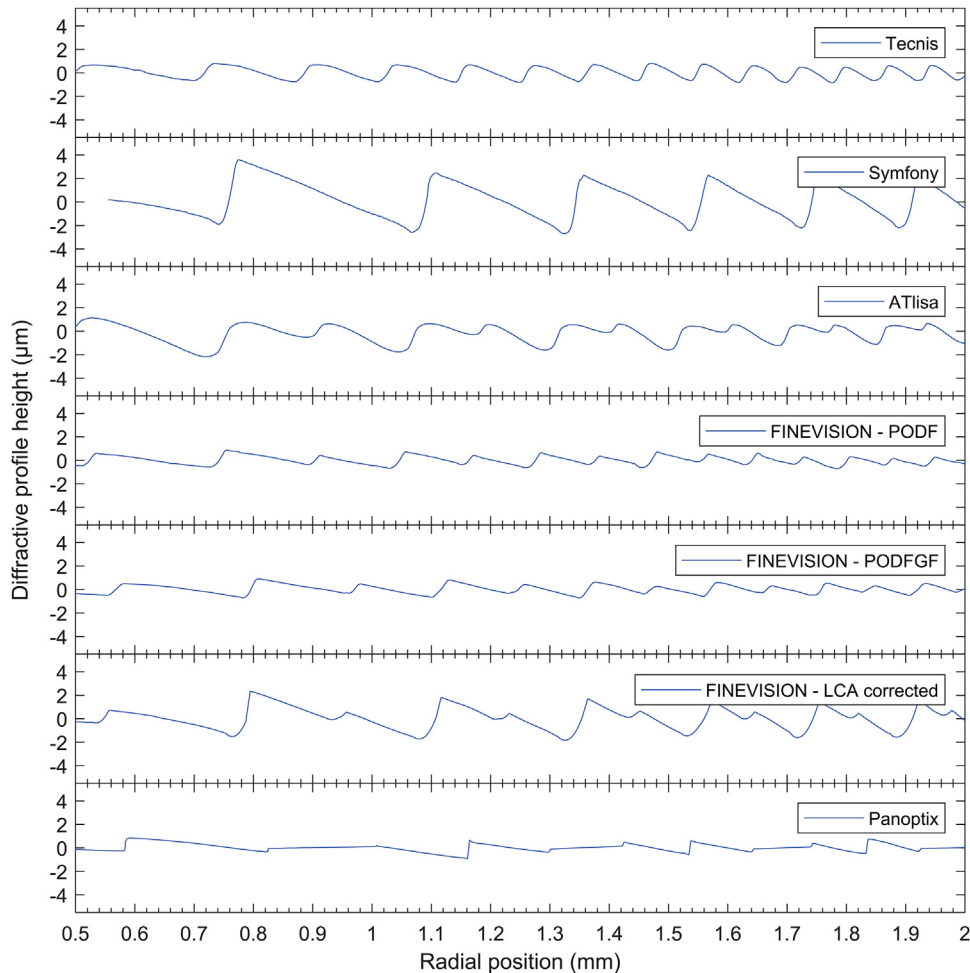


Figure 2. Diffractive topologies of the IOLs studied in this paper. The graphs represent the diffraction profiles extracted from the general topology of the IOLs, as described in Figure 1. In the two first subplots, bifocal IOL topologies are represented, respectively, for the Tecnis ZMB00 (a) and the Tecnis Symphony (b) (both Carl Zeiss Meditec AG). In both cases, a single diffraction profile is present, giving rise to a single added power. The 5 following curves for the AT LISA tri (Carl Zeiss Meditec AG); FineVision POD F, FineVision^{HP} POD F GF, and LCA-corrected (PhysIOL, S.A.); and PanOptix (Alcon Laboratories, Inc.) present more complex shapes, with alternating step heights. They correspond to the combination of at least two diffraction profiles, giving rise to trifocal IOLs (IOL = intraocular lens; LCA = longitudinal chromatic aberration).

In the experimental setup, the tested multifocal IOL was placed in an 11.0 mm diameter lens holder before being inserted into a quartz cell filled with aqueous sodium chloride 0.9%. The anterior side of the IOL was placed facing the incident light. The lens holder guaranteed a tilt-free orientation of the IOL under inspection. The device automatically detects the optical axis of the IOL with 0.2 mm of lateral precision.

The through-focus MTF curves were recorded at 50 cycles/mm at a 3.0 mm aperture in accordance with ISO standard recommendations.

RESULTS

Intraocular Lens Surface Topography

Diffraction topographies were obtained once the main IOL curvature had been extracted. Figure 2 shows these topographies. All the multifocal IOLs studied in this paper were

found to present diffraction profiles, and a number of these exhibited alternating step height variation.

In diffraction multifocal IOLs, the main curvature provides the main power of the lens. It is often associated with far vision, which is mainly driven by the refractive elements of the IOL. There are, however, a few exceptions, which can be found in the case of the Symphony and LCA-corrected FineVision IOLs. These cases will be discussed in more detail later in the paper. The diffraction profiles were superposed on the main curvature of the lens to give rise to the addition power for intermediate and/or near vision. It is worth noting that one or more diffraction profiles can be combined to give one or more additional foci, respectively.

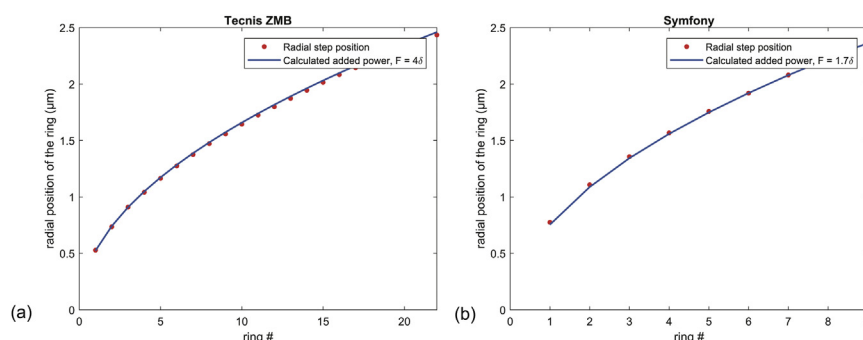


Figure 3. Radial positions of the steps relative to both diffraction bifocal IOLs: Tecnis ZMB00 (a) and Tecnis Symphony (b) (both Carl Zeiss Meditec AG). Radial step positions are plotted as a function of their ring number. Theoretical dependency following (Equation 1) is shown as a solid line. This curve is fully dependent on the focal length or the added power of the diffractive lenses. The Symphony IOL presents fewer steps than the Tecnis ZMB00 IOL, which corresponds to a lower addition power (IOL = intraocular lens).

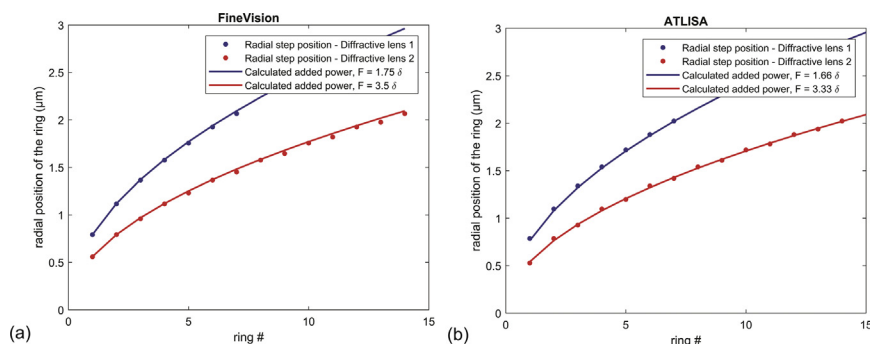


Figure 4. Radial positions of the steps relative to both diffractive trifocal IOLs made of hydrophilic material: FineVision (a) (PhysIOL, S.A.) and AT LISA (b) (Carl Zeiss Meditec AG). The radial step positions are plotted as a function of their ring number. In the specific case of trifocal IOLs, both diffractive gratings are imbricated with a ratio of two, between grating 1 and grating 2. Hence, one step over two is used for a lower power grating, whereas all steps are used for a higher addition diffraction add power. Theoretical dependency following Equation 1 is shown as a solid line (IOL = intraocular lens).

As mentioned previously, all the multifocal IOLs studied in this paper exhibit diffractive profiles, even the EDOF Symphony IOL. The Symphony clearly behaves like a diffractive bifocal IOL. The extension of range of vision, claimed by the manufacturers to be provided by this IOL, derives from the close position of the far and intermediate foci along the optical axis. The EDOF effect is amplified when the pupil is small.

Bifocal Diffractive Intraocular Lenses

Both Tecnis IOLs (ZMB00 and EDOF Symphony) exhibit a bifocal diffractive design; however, the Symphony presents a shorter grating frequency compared with the ZMB00. This reflects the lower add power of the Symphony IOL. This property was confirmed by measurement of the MTF through-focus curves. On these diffractive bifocal Tecnis IOLs (ZMB00 and EDOF Symphony), a simple structure is observed. This structure is typical of a simple diffractive IOL added to the main refractive lens. As described earlier, the refractive lens provides the main IOL power. Step positions define annular zones within the diffractive

lens. Each of these zones have an equal effect on the focus, hence the fact that the pitch distance between two steps is inversely proportional to the square root of the added power and is proportional to the square root of the step number. It is for this reason that the added power is higher (roughly double) in the case of the ZMB00 compared with the Symphony IOL.

Trifocal Diffractive Intraocular Lenses

Trifocal diffractive IOLs present a double diffractive structure, which corresponds to a combination of two diffractive patterns. The AT LISA tri 839MP, FineVision POD F, FineVision^{HP} POD F GF, and LCA-corrected FineVision all have two addition powers with a ratio of two (eg, 1.75 D, +3.50 D). This harmonic relationship translates into a steady geometric variation of high and low step heights.

Step Position

The position of diffractive steps along the IOL radius depends on the square root of the step number, as shown in the following relationship:

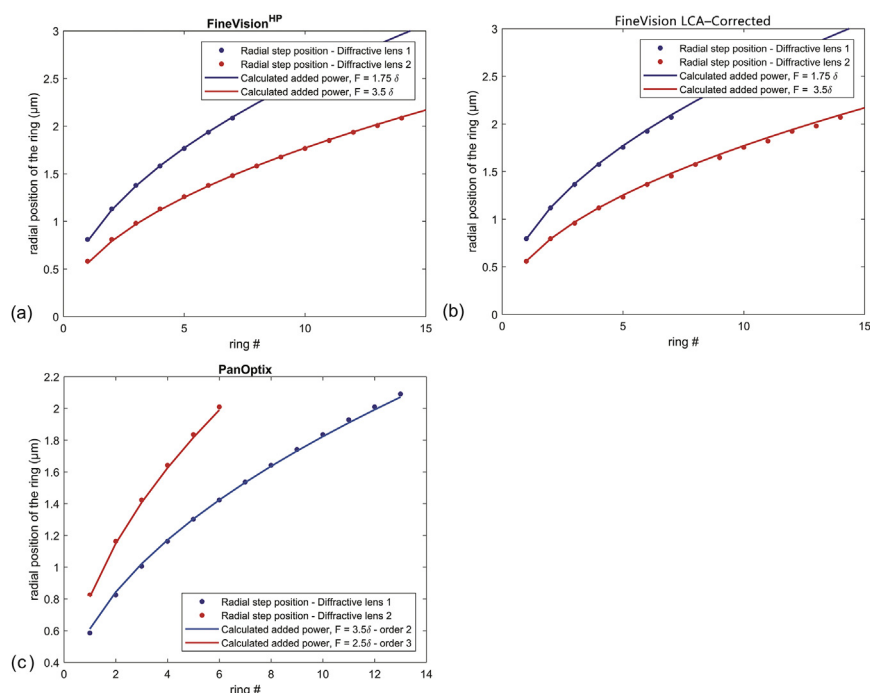


Figure 5. The radial step positions of the three trifocal IOLs made of hydrophobic material: FineVision^{HP} (a) (PhysIOL, S.A.) FineVision LCA-corrected (b) (PhysIOL, S.A.), and PanOptix (c) (Alcon Laboratories, Inc.). The radial step positions are plotted as a function of their ring numbers. In the specific case of trifocal IOLs, both diffractive gratings are also imbricated. In the case of the FineVision^{HP} and FineVision LCA-corrected, the focal ratio between grating 1 and grating 2 is applied. Theoretical dependency following Equation 1 is shown as a solid line for these IOLs. In the case of the PanOptix, although the IOL is trifocal, the ratio between both diffractive gratings is not a natural number. In PanOptix, the use of a higher diffraction order associated with a low add power grating gives rise to values of 2.5δ and 3.5δ .⁹ Theoretical dependencies are presented for both PanOptix gratings (IOL = intraocular lens; LCA = longitudinal chromatic aberration).

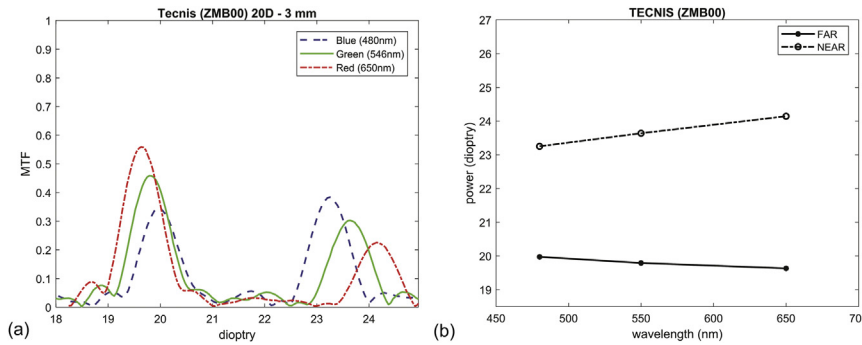


Figure 6. Tecnis ZMB00 (Carl Zeiss Meditec AG): Experimental chromatic through-focus curves for the intraocular lens at a 3.0 mm aperture (a) and chromatic dispersion curves based on the experimental power (b) measured for each focus (MTF local maximum from 6, a, at different wavelengths). Far focus presents a negative slope, expressing a refractive process, whereas near focus exhibits a positive slope, corresponding to a diffractive dominant process (MTF = modulation transfer function).

$$\rho_q = \sqrt{2q\lambda_0 F} \quad (\text{Equation 1})$$

where ρ_q is the step position on the radial axis, q is an integer associated with the step number, λ_0 is the design wavelength, and F the diffractive focal length in meters.

Figures 3 to 5 show the step positions of the investigated diffractive IOLs as a function of their number order and associated added power. Dots represent the experimental data, whereas the solid lines correspond to the theoretical curves, based on the above formula.

Chromatic Properties of Diffractive Intraocular Lenses

As the following mathematical relationship shows, the diffractive added power is wavelength-dependent:

$$F(\lambda) = \frac{p \lambda_0 F_0}{m \lambda}, \quad (\text{Equation 2})$$

where p is an integer that represents the maximum phase modulation as a multiple of 2π , λ_0 is the design wavelength, F_0 is the focal length (in meters) at the design wavelength, m is the considered order of diffraction, and λ is the wavelength of interest.

The refractive focus is wavelength-dependent because of its refractive index dependency, as seen in Equation 2. However, it can be seen that the diffractive foci are also wavelength-dependent but in the opposite way: the focus position is inversely proportional to the considered wavelength. In the case of a refractive-diffractive IOL, the chromatic aberration appears as a combination of both effects, and it can be theoretically balanced.

Step Height

The amount of light energy distributed on each focus is fully dependent on the diffractive structure of the IOL and its height, the wavelength of use, and the variation of the refractive index between the IOL and its surrounding medium. The energy associated with a particular focus is linked to the diffraction efficiency of the IOL. This efficiency is directly connected to the phase modulation undergone by the light when it passes through a periodic structure, as in the case of a sawtooth grating, for instance. The phase modulation is given by the following relationship:

$$\phi(\lambda) = \frac{2\pi}{\lambda} \Delta n(\lambda) h_0 \quad (\text{Equation 3})$$

where λ is the wavelength, Δn is the refractive index difference between the inner and outer media, and h_0 is the local thickness crossed by the light.

For a specific wavelength, a 2π phase modulation will give the maximum diffraction efficiency. This implies that in most the cases, the step will have a height given by:

$$h_0(\lambda_0^{\max}) = \frac{\lambda_0}{\Delta n(\lambda)} \quad (\text{Equation 4})$$

In the case of a low diffraction order value, an approximation of the diffraction efficiency can be given by the well-known diffraction efficiency law of the sawtooth grating:

$$\eta = \text{sinc}^2(ap - m) \quad (\text{Equation 5})$$

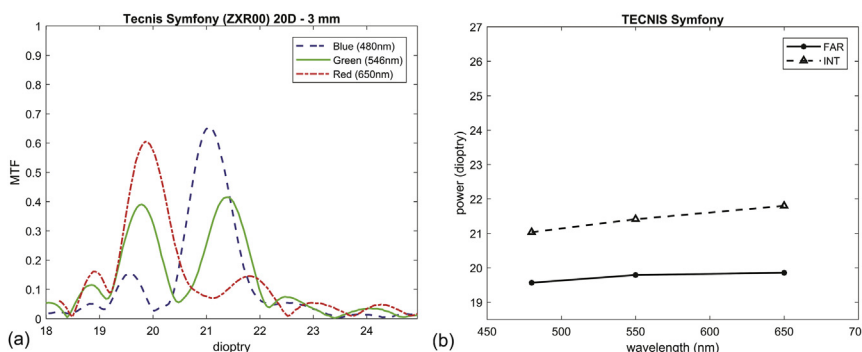


Figure 7. Tecnis Symphony (Carl Zeiss Meditec AG): Experimental chromatic through-focus curves for the intraocular lens at a 3.0 mm aperture (a) and chromatic dispersion curves based on the experimental power (b) measured for each focus (MTF local maximum from 7, a, at different wavelengths). Far and intermediate curves present positive slopes, expressing a diffractive dominant process in both cases (INT = intermediate; MTF = modulation transfer function).

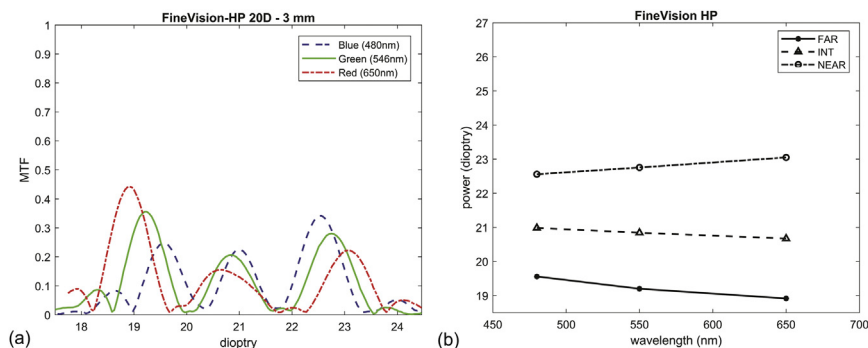


Figure 8. FineVision^{HP} (PhysIOL, S.A.): Experimental chromatic through-focus curves for the IOL at a 3.0 mm aperture (a) and chromatic dispersion curves based on the experimental power (b) measured for each focus (MTF local maximum from 8, a, at different wavelengths). The far curve presents a negative slope, expressing a refractive process, whereas the near focus exhibits a positive slope, corresponding to a diffractive dominant process. The intermediate focus presents a slightly negative slope, which means that the chromatic aberration is almost compensated by both effects (refractive and diffractive) (INT = intermediate; MTF = modulation transfer function).

where $\alpha \approx \lambda/\lambda_0$, m is the diffraction order, and $p = \Delta n h/\lambda_0$, which produces an optical phase difference of $p\lambda_0$ or a maximum equivalent phase shift of $p2\pi$.

In practice, none of the diffractive IOLs has the maximum grating amplitude at the design wavelength, because, for the IOLs to be effective, the different foci must be present together. The phase modulation given by the surface profile therefore then determines how the incident energy is distributed through the various diffraction orders. In most of the IOLs studied, the step height is lower than h_0 to distribute light onto the zero order (often associated with far focus) and the first orders (intermediate or near).

Through-Focus Modulation Transfer Function Curves

Figures 6 to 12 show MTF through-focus curves recorded at a pupillary aperture of 3.0 mm, a spatial frequency of 50 LP/mm and three wavelengths: 480 nm, 546 nm, and 650 nm under an ISO 1 cornea. The green curve is taken as the reference. As can be seen in most of the graphs, the MTF peaks in three wavelengths (red, green, blue) and over the different foci, exhibiting, in most cases, an offset compared with the behavior in green light. These shifts are attributable to chromatic aberration. The order in which the peaks are displayed is associated with the dominant process (refractive or diffractive) occurring for the creation of a specific

focus. As an example, in most of the multifocal IOLs, far foci (except for the Symphony IOL), red-maximum appears for lower power values and blue-maximum for higher values. This red–green–blue distribution is the signature of a refractive dominant process. Inversely, in most of the near foci, blue appears first, whereas red has the highest power (blue–green–red). In that case, the dominant process is diffractive. Peak positions (power) are driven by a Bragg-like law or the kinoform law (Equation 1), whereas the efficiency of the diffractive profiles is mainly driven by the step height and its relative value compared with wavelength. This is especially visible in the case of the Symphony IOL, which becomes monofocal for far focus in red light and monofocal for intermediate focus in blue light. This IOL is bifocal in green light and is fully driven by a diffractive chromaticity. Because of a large step height in the case of the Symphony IOL, the energy balance is more sensitive than for the other multifocal IOLs.

For each IOL and each associated focus, the measured power is reported in relation to the wavelength used (the *B* graphs in Figures 6, B, to 12, B). The slope of the lines is directly associated with the magnitude of the longitudinal chromatic aberration, and its sign depends on the dominant process: refractive or diffractive. A negative slope relates to a refractive process, whereas a positive slope is directly associated with a diffractive one.

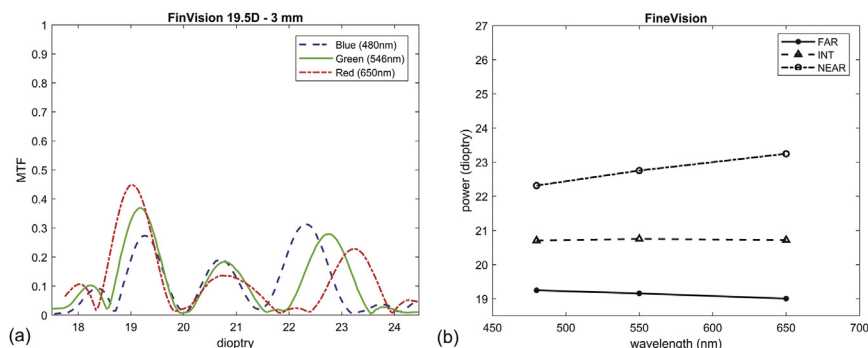


Figure 9. FineVision (PhysIOL, S.A.): Experimental chromatic through-focus curves for the intraocular lens at a 3.0 mm aperture (a) and chromatic dispersion curves based on the experimental power (b) measured for each focus (MTF local maximum from 9, a, at different wavelengths). The far curve presents a negative slope, expressing a refractive process, whereas the near focus exhibits a positive slope, corresponding to a diffractive dominant process. The intermediate curve is almost horizontal, which means that the chromatic aberration is compensated (INT = intermediate; MTF = modulation transfer function).

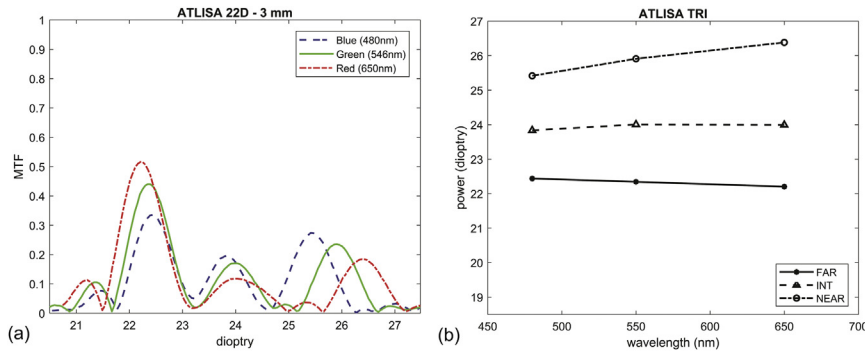


Figure 10. AT LISA tri (Carl Zeiss Meditec AG): Experimental chromatic through-focus curves for the intraocular lens at a 3.0 mm aperture (a) and chromatic dispersion curves based on the experimental power (b) measured for each focus (MTF local maximum from 10, a, at different wavelengths). The far curve presents a negative slope, expressing a refractive process, whereas the near focus exhibits a positive slope, corresponding to a diffractive dominant process. The intermediate focus is slightly positive, but with a very low value, which means that the chromatic aberration is almost compensated (INT = intermediate; MTF = modulation transfer function).

Some foci present a slope very close to zero, which corresponds to a compensation of the refractive and the diffractive LCA. Hence, these foci are said to be chromatically corrected.

DISCUSSION

The chromatic properties of the different IOLs characterized in this study are summarized in Figure 13. For each focus, chromatic effects were computed as a variation of power shift according to the wavelength. Therefore, histogram bars in the positive range of the graph correspond to foci that exhibited less power in blue light than in red light, and vice versa for the bars in the negative range.

As expected, Figure 13 shows that in most cases, the longitudinal chromatic aberration related to the far foci (*blue bars*) was found to be negative and directly linked to the Abbe number of the IOL biomaterial. In the vast majority of the multifocal IOLs studied, we found that far vision was controlled by the intrinsic refractive behavior of the biomaterial (zero order of diffraction). Hence, the magnitude of the LCA in refractive cases was shown to be proportional to the Abbe number (Figure 13). The only exception in this study related to the Symphony IOL, which was found to exhibit a modified, positive LCA for both foci. This

reflects the fact that in this specific case, the IOL was found to be totally diffractive. All the other IOLs exhibiting a zero order far focal point showed a negative LCA directly correlated with the Abbe number of the IOL biomaterial. For the sake of comparison, LCA was also measured on two refractive monofocal IOLs (MicroPlus and MicroPure). These IOLs are made from the same materials as the FineVision and FineVision IOLs, respectively. As expected, the LCA associated with these IOLs was found to be fully refractive and to have the exact same value as the refractive far focus of the related trifocal IOLs (FineVision and FineVision^{HP}).

Four of the IOLs studied presented an interesting behavior in their correction of the longitudinal chromatic aberration, for at least one focus. These IOLs (FineVision, LCA-corrected FineVision, PanOptix, and ATLisa) presented a very low slope on the dispersion curve, mostly for intermediate focus. In the specific case of the LCA-corrected FineVision IOL, two foci were found to be LCA-corrected. Although the results were not extrapolated to clinical relevance, this LCA study complements other studies of the effect of energy distribution on diffractive IOLs between the different foci, especially in the case of spherical aberration and the effect of the apodization.¹⁵ More than the position of the peaks along the optical axis, the chromatic effect

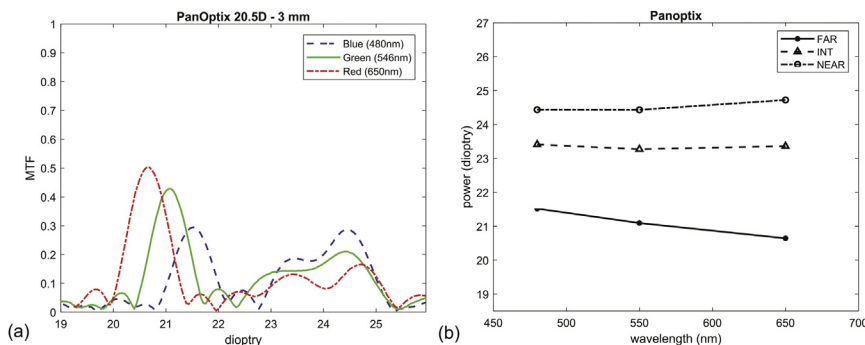


Figure 11. PanOptix (Alcon Laboratories, Inc.): Experimental chromatic through-focus curves for the intraocular lens at a 3.0 mm aperture (a) and chromatic dispersion curves based on the experimental power (b) measured for each focus (MTF local maximum from 11, a, at different wavelengths). The far curve presents a negative slope, expressing a refractive process, whereas the near focus exhibits a positive slope, corresponding to a diffractive dominant process. The intermediate focus is slightly positive, but with a very low value, which means that the chromatic aberration is almost compensated (INT = intermediate; MTF = modulation transfer function).

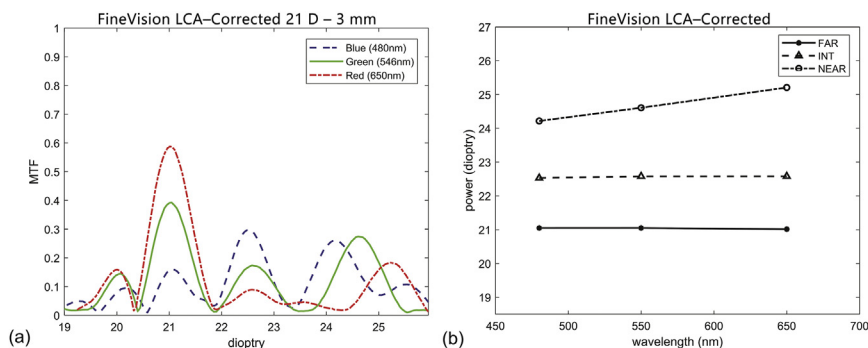


Figure 12. LCA-corrected FineVision (PhysIOL, S.A.): Experimental chromatic through-focus curves for the intraocular lens at a 3.0 mm aperture (a) and chromatic dispersion curves based on the experimental power (b) measured for each focus (MTF local maximum from 12, a, at different wavelengths). The far and intermediate curves are horizontal, which means that the chromatic aberration is compensated for these foci. The near focus slope is positive, typical of a diffractive dominant process (INT = intermediate; LCA = longitudinal chromatic aberration; MTF = modulation transfer function).

changes the MTF distribution in accordance to the wavelength.

In conclusion, in this study, we compared 7 different multifocal IOLs under three different wavelengths. Two monofocal IOLs were added as purely refractive IOLs for the sake of comparison.

First, the surface topography of the diffractive profiles was measured and interpreted in terms of step position and step height. Diffractive step position gives information on the focalization properties of an IOL, whereas step height provides insights into the energy balance between the different foci. MTF through-focus curves were then measured on an optical bench for three different wavelengths. Based on these results, the longitudinal chromatic aberration was assessed for each IOL and its associated foci.

From these measurements, it was shown that LCA is driven by two major processes: refraction and diffraction. The position of the specific wavelength MTF peaks and resulting dispersion curve revealed the dominant process. It was also observed that it was possible for the MTF balance

between the different foci of a given IOL to be strongly modified while changing from green to blue or red light.

In most of the multifocal IOLs studied, some of the foci were found to be refractive (in general, this was true for the far focus) and others were diffractive (intermediate and near foci). However, the Symphony IOL appeared to be an exception; in that case, all the foci were shown to be driven by a diffractive process. It is interesting to note that in some cases, it was possible for the LCA to be fully compensated. This was the case for the intermediate focus of the FineVision, PanOptix, and ATLisa IOLs, whereas the LCA-corrected FineVision IOL was found to be LCA-corrected for both far and intermediate foci.

Finally, it is well understood that chromatic aberration reduction can improve the image quality of any optical system under polychromatic light. However, in the specific case of the eye and its monochromatic aberration, the improvement of vision quality by LCA reduction has not yet been demonstrated. Hence, although the results were not extrapolated to clinical relevance,

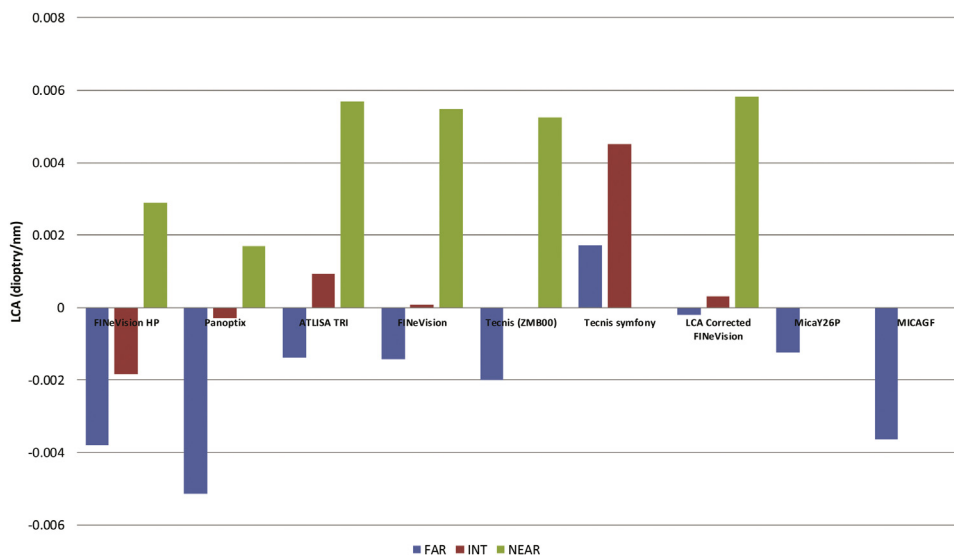


Figure 13. Summary graph presenting the magnitude of the dispersion curve slope in dioptre/nm for the FineVision^{HP} (PhysIOL, S.A.), FineVision (PhysIOL, S.A.), PanOptix (Alcon Laboratories, Inc.), AT LISA tri (Carl Zeiss Meditec AG), Tecnis ZMB00 (Carl Zeiss Meditec AG), Tecnis Symphony (Carl Zeiss Meditec AG), LCA-corrected FineVision (PhysIOL, S.A.), MicroPlus (PhysIOL, S.A.), and MicroPure (PhysIOL, S.A.) intraocular lenses. A negative value indicates a refractive dominant process, whereas a positive value is associated with a diffractive dominant process. A value close to zero indicates a compensation of the longitudinal chromatic aberration (LCA = longitudinal chromatic aberration).

this study still offers the reader a new performance metric to characterize multifocal IOLs and their different foci.

WHAT WAS KNOWN

- Diffractive multifocal intraocular lenses (IOLs) are powerful devices to replace the crystalline lens after cataract surgery. These IOLs reduce the spectacle dependence. Various diffractive multifocal IOLs are present on the market.
- Most of the optical characteristic of IOLs are presented in green light, which is the most sensitive part of the eye. However, the life is polychromatic and most of the optical systems present chromatic aberration because of the intrinsic refractive properties of the optical material or diffractive structure.

WHAT THIS PAPER ADDS

- Longitudinal chromatic aberration (LCA) was driven by two major processes: refraction and diffraction.
- In some cases, and with some focus of the diffractive IOL, LCA can be fully compensated.

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