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Longitudinal chromatic aberration and polychromatic image quality metrics of intraocular lenses.

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Abstract

PURPOSE: To measure longitudinal chromatic aberration (LCA) of various intraocular lenses (IOLs), and to assess LCA effects on polychromatic image quality with a focus on multifocal-IOL designs.

METHODS: The LCA values of four multifocal IOL models (three diffractive models: AT LARA 829MP and AT LISA 809M (both from Carl Zeiss) and Restor SN6AD1 (Alcon); and one refractive model, the Mini-Well Ready (SIFI Medtech) were compared with that of their monofocal counterparts. Optical properties were assessed using an optical-bench device featured with spectral filters. LCA was calculated as a lens-power difference at 480-644nm. The optical quality was evaluated objectively by means of modulation-transfer function metrics.

RESULTS: In all but one IOL, LCA was higher than that of an aphakic model eye (1.04D). At a far focus, LCA of AT Lara, AT Lisa, Restor and Mini-Well was 0.78D, 1.40D, 1.91D, and 1.27D, respectively. AT Lisa and Restor showed comparable results with their monofocal platforms. A near-focus LCA decreased only in the diffractive IOLs. At far, the polychromatic MTF was reduced in all IOLs, however, LCA effects were attenuated at near.

CONCLUSIONS: Multifocal-diffractive IOLs proved effective in reducing LCA, however, the efficiency of the LCA correction differed depending on the optical design. The results indicate that a diffractive lens without an intended dispersion correction manifests LCA of its monofocal platform. LCA adversely affects the polychromatic image quality.

Introduction

Multifocal intraocular lenses (IOLs) have significantly advanced the field of cataract and refractive surgery over the last decades. Until recently, multifocal IOLs have only been available in bifocal and trifocal designs, which provide multiple (two or three) distinct foci. Most recently, however, Extended Depth of Focus (EDoF) IOLs designs have emerged that create an elongated focal point to enhance the range of vision.[1,2]

The optical performance of the pseudophakic eye has been extensively studied. Besides the benefits from the correction of SA, the reduction of chromatic aberration could further enhance the visual performance.[3-6] Chromatic aberration is distinguished in longitudinal chromatic aberration (LCA) and transverse chromatic aberration (TCA).[7,8] LCA characterizes the inability of a lens to focus different wavelengths at the same focal plane, while TCA describes wavelength related changes to the image size of an off-axis object.[7,8] In optical engineering, LCA is typically corrected with an achromatic doublet that consists of two cemented lenses having different dispersion.[7] This approach, however, could not be directly translated into IOLs due to technological limitations, therefore the use of diffractive optics appears as the most suitable way to reduce LCA of IOLs.[3,9,10] Given that refractive and diffractive lenses show opposite LCA behaviors,[9,10] it is essential to understand how refractive and diffractive IOLs affect LCA, and thus the polychromatic image quality.

The aim of this study was to assess the effect of LCA of multifocal IOLs on polychromatic image quality and their potential to correct the LCA of the pseudophakic eye. To this end, we measured in vitro monochromatic and polychromatic MTFs of multifocal IOLs with different designs.

Materials and Methods

Intraocular lenses

Table 1 shows the characteristics of studied multifocal and monofocal IOLs. We included four multifocal models with different optical designs, such as the Mini Well Ready (SIFI MedTech), the Acrysof Restor SN6AD1 (Alcon Laboratories, Inc.), the AT LISA 809MP (Carl Zeiss Meditec AG) and the AT LARA 829MP (Carl Zeiss Meditec AG). The Mini Well is a refractive biconvex EDoF lens, which utilizes SA to increase depth of focus. The Restor is a bifocal refractive-diffractive IOL with an apodized diffractive design that changes the energy split between the two foci with the pupil size. At a 3-mm aperture, the Restor allocates 70% of light to the far focus and 30% to the near focus. The AT Lisa is a bifocal full diffractive IOL, which also shows asymmetric light distribution for far (65%) and near (35%). The AT Lara is an EDoF IOL that has only recently been launched to market. This is a diffractive lens with an aspheric 'aberration neutral' base platform and an optical design to correct chromatic aberration.

LCA of the four multifocal IOLs were compared with that of their monofocal counterparts of their respective manufacturers. The Mini Well was compared with Mini 4 (SIFI MedTech), the Restor IOL with SN60WF (Alcon Laboratories, Inc.), the AT Lisa and AT Lara IOLs with the CT Asphina 409MP (Carl Zeiss Meditec AG).

Optical measurements

The optical performance of the IOLs was assessed using an OptiSpheric IOL PRO 2 optical bench (Trioptics GmbH, Germany). This device measures the nominal power and the MTF of IOLs with an accuracy of 0.1-0.3% and 2%, respectively. The IOLs were submerged in a balanced salt solution in a mechanical holder with two flat windows. A model cornea was a singlet lens with a positive SA of 0.28μm. In this study, however, the IOLs were measured with a 3 mm aperture in order to minimize the effect of SA and pupil dependency of multifocal IOLs.[12] A collimated beam of a LED source was used to illuminate two perpendicular fine slits (a cross reticle) that served as a test target. An image of the cross was projected by the model eye (with the IOL) onto a CCD camera (VA-1MC-M120-A0-C, Vision Systems Technology, USA) through a microscope objective lens. As a result, two-line spread functions were obtained to evaluate sagittal and tangential MTFs. Given the rotational symmetry of the studied lenses, sagittal and tangential MTFs were averaged.

MTF results were presented graphically up to 100lp/mm, as this frequency corresponds approximately to a visual acuity of 20/20. The through focus (TF) MTF was assessed in a defocus range from +2D up to -6D. Moreover, the IOLs were compared by means of calculating the area under the MTF.[13] The MTF area was analyzed at a range of spatial frequencies from 1lp/mm to 100lp/mm (with 1lp/mm sampling) using the following formula:

$$\text{MTFarea} = \frac{1}{100}\sum_{f=1}^{f=100} MTF(f)$$

The MTF performance was assessed at the (best) far and near focus.

The MTF of the IOLs was measured in blue, green and red light and in polychromatic light. To this end, we used three interference filters (10-nm bandwidth) with a central wavelength of 480nm, 546nm and 644nm, and a photopic eye response filter that simulated the photopic luminosity function of the human eye. LCA of the IOL was calculated as the difference between the red and blue foci and expressed in diopters. In our set-up, for an ‘aphakic’ model eye (i.e., without the IOL) LCA was 1.04D. Each individual MTF and LCA measurement per condition was performed with one repetition. The standard deviation (SD) of the MTF assessment was tested for a discrete frequency of 50lp/mm.

Polychromatic image simulation

The 1951 USAF resolution test chart was used to visualize the polychromatic image quality. Three separate photographs of the USAF target were taken with the three monochromatic filters at the position of an optimal polychromatic far and near focus. Given that the optical set-up featured a monochromatic camera, images were processed using a custom-made software (Image Processing Toolbox, Matlab, Mathworks) to add colors that corresponded to wavelengths of the monochromatic filters. These photographs were corrected for camera sensitivity and combined into one RGB image using the same image-processing software.

Results

Chromatic aberration

Table 2 presented the LCA values (± SD) of the IOLs. The lens featured with chromatic aberration correction (AT Lara) demonstrated the lowest LCA. The Restor showed higher chromatic dispersion than the other IOLs at far. All diffractive IOLs demonstrated reduced LCA levels at near as compared to the far focus. The Mini Well showed a slightly higher LCA at near than at far.

An LCA level of the CT Asphina was similar to that of the AT Lisa but higher than that of the AT Lara. LCA was found to be slightly lower in the SN60WF than in the Restor by 0.05D. The Mini 4 lens showed a higher LCA value than that of the Mini Well.

MTF measurements

The IOL Pro 2 devices showed a good repeatability of the MTF assessment with an SD value of 0.001 or less for two consecutive measurements. Figure 1 presents in detail the MTF performance of the four multifocal IOLs. All three diffractive IOLs showed a spectral dependence of the light distribution for far and near demonstrating far dominance in the red light and near dominance in the blue light. The refractive lens showed only small differences in MTF results obtained at the three wavelengths.

In all lenses, the polychromatic MTF was lower than that measured in the green light at the far focus (Figure 1). The percentage of the MTF-area loss at far focus was 14% for the AT Lara, 27% for the AT Lisa, 25% for the Mini Well and 34% for the Restor IOL. At the near focus the AT Lara demonstrated slightly better optical performance in the polychromatic light by 5%. For the AT Lisa, the MTF-area value was lower in the polychromatic light by 1%, for the Restor by 14% and for the Mini Well by 5%.

The TF scan presented in Figure 1 shows the position of monochromatic and polychromatic foci. All but one lens demonstrated a clear separation of the monochromatic (blue, green and red) peaks at the zero defocus level. The AT Lara showed nearly overlapping peaks at far and near indicating a low LCA. The two other diffractive IOLs showed a smaller separation between their monochromatic-near foci as compared to that at far. For the Mini Well, the separation of the monochromatic foci was distinct at far and near.

Polychromatic image simulation

The TF photographs of the USAF resolution chart are presented in Figure 2. Characteristic "fringes" of color appear in all simulated RGB images. The original polychromatic photographs, taken with the monochromatic camera, and the RGB simulations show a close resemblance of their optical quality. Figure 2 confirms the MTF results of the AT Lara showing a better image quality in the red than in the blue light at far, and the reverse relationship at near. At the far focus of the AT Lisa and Restor IOLs, the blue and red photographs appear blurred as compared to the green ones. However, the image blur was reduced at the near focus, particularly for the AT Lisa indicating a lower LCA value. For the Mini Well (Figure 2), the blue and red photographs appeared to be out-of-focus at the far distance, however, it became less apparent at near.

Discussion

We found that a diffractive-optic IOL can be effective in correcting LCA of the pseudophakic eye. Moreover, we showed that uncorrected LCA may reduce the IOL optical quality in the polychromatic light. Although the refractive IOL demonstrated comparable MTF levels in the blue, green and red light, the diffractive lenses showed a varying MTF performance depending on the wavelength.

The diffractive-EDOF IOL demonstrated a clear potential for correcting IOL-material dispersion and to correct LCA of the eye. The model eye with the AT Lara lens showed an LCA of 0.78D at the far focus, which was lower than that of the 'aphakic' model eye (1.04D), indicating the lens ability to compensate chromatic aberration. This finding is in agreement with a study by Millán and Vega, as they also showed an effective LCA correction of a Symfony IOL (Johnson & Johnson Vision).[10] For the other lenses, without an intended chromatic-aberration correction, LCA was consistently higher than that of the mechanical eye model due to a substantial contribution of the IOL material to LCA.

The highest LCA value was found in the Restor IOL (LCA=1.91D). Although in the green light, this lens showed a larger MTF area than the AT Lara, in the polychromatic light, this metric dropped markedly and became lower by 15% than that of the AT Lara (Figure 1). At the best near focus, this difference increased to 23%, as the AT Lara showed an MTF improvement and a low LCA level (0.21D). By contrast, the Restor IOL demonstrated a higher LCA of 1.05D at near focus, and thus a worse MTF performance in the polychromatic light. A larger difference might, however, have been expected given that the dispersion level of the

Restor IOL is more than two fold higher than that of the AT Lara lens. The reason for this relatively small effect is the use of the photopic eye response filter, which simulates the spectral sensitivity of the human eye.[14] In our experimental set-up, the photopic filter performs a spectral weighting that results in a lower intensity of wavelengths at the extreme ends of the spectrum, i.e. 480nm and 644nm, than that of the 546-nm wavelength. As a consequence, the effect of LCA on the optical quality was diminished, but yet the AT Lara showed that the LCA correction can be of real benefit to the polychromatic image quality.

Although the LCA correction at the far focus emerges as a new feature of modern IOL designs, the compensation of the chromatic shift was found in all diffractive IOLs at the near focus, including those that were introduced more than a decade ago, such as the Restor. For the diffractive-apodized IOL, near LCA was lower than that at the far focus by 0.86D. This LCA correction at the near focus results from that chromatic aberration of a diffractive and a refractive element has the opposite signs. LCA of a diffractive-refractive lens can be expressed as:

$$LCA = LCA_{refractive} + LCA_{diffractive}$$

Although the $LCA_{refractive}$ component does not change at the far and near focus, $LCA_{diffractive}$ varies between different diffraction orders (m). For instance, the diffractive element of the Restor lens directs the light energy to the far and near focus by using the zeroth (m_{Far}=0) and first (m_{Near}=1) diffraction orders, respectively.[15] Given that at the zeroth order the diffractive element has no power, $LCA_{diffractive}$ is zero. Therefore, in this case, LCA at the far focus depends only on chromatic aberration of a monofocal-lens platform, which can explain very close (far) LCA levels of the Restor and the SN60WF IOL. At the near focus (m_{Near}=1), the Restor IOL has a 3D power (P_0) at the designed wavelength (λ_0) of 550nm.[15] However, the power (P) of the diffractive element changes at different (than designed) wavelengths (λ)[16] according to this formula:

$$P(\lambda) = m P_0 \lambda / \lambda_0$$

For the wavelengths used in this study, P(λ=480nm)=2.62D and P(λ=644nm)=3.51D can be calculated, which results in an $LCA_{diffractive}$ of -0.89D. So, for the measured $LCA_{refractive}$=1.91D and the estimated $LCA_{diffractive}$=-0.89D, LCA at the near focus would be 1.02D, which is very close to the measured value of 1.05D. This approach can also be applied to predict the LCA level at the near focus of the AT Lisa. Then, the result would be 0.28D as compared to a value of 0.26D found in the current study. Given that the AT Lara provides LCA correction at the two foci indicates that its optical design differs from a standard (m_{Far}=0, m_{Near}=1) diffraction-order approach.[10] In contrast to the other diffractive IOL included in this study, the diffractive element of this EDOF IOL seems to provide an add power to the two foci, as LCA correction at the far focus can only take place for a non-zero $LCA_{diffractive}$ component. A similar novel approach has also been introduced in the Symfony (Johnson & Johnson Vision), as shown by Millán and Vega,[10] indicating that a concept of the IOL correcting the eye's LCA is growing in popularity and becomes a new trend in the IOL market.

In contrast to its diffractive counterparts, the refractive IOL did not show a lower LCA value at the near focus. Although it yielded the highest LCA value at the near focus among all studied multifocal IOLs, interestingly, the polychromatic MTF area was less reduced than that of the Restor (5% vs 14%). The reason for that may be an EDOF character of the Mini Well, which forms an extended near-focus peak (Figure 1). Although the chromatic shift can be seen in TF scan (Figure 1), the peak of each spectral component yet overlap due to the EDOF effect, which appears to attenuate an effect of LCA of the IOL (Figure 2). Intriguingly, the Mini Well showed a different LCA at the far focus than its monofocal counterpart (Mini 4). This might suggest that the material dispersion of the Mini Well differs from that of the Mini 4, however, we could not confirm this explanation as the Abbe numbers of these IOLs have not been disclosed by the manufacturer.

The refractive multifocal IOL revealed very close MTF results that were independent of the wavelength if the chromatic shift was accounted for (Figure 1). By contrast, the optical performance of the diffractive IOLs seems to strongly depend on the wavelength as demonstrated in Figure 1. Although all diffractive-optic IOL showed a similar far-focus dominance in the green light, the MTF metrics differed in the blue and red light. The AT Lara demonstrated a strong distance-vision dominance at 644nm with a 3.8-fold larger MTF area at the far than at the near focus. At 480nm, however, a smaller but reverse effect was found with a 1.9-fold larger area under the MTF at near than at far. This spectral effect can also be noticed in Figure 2 (AT Lara). For the two other diffractive IOLs, the MTF metrics at the far and near focus were comparable in blue and far dominant in red. Given that the photographs of Figure 2 were taken at the best polychromatic focus, these changes to the monochromatic MTF performance of the AT Lisa and the Restor were not clearly seen due to the chromatic shift, except from the near-focus images of the AT Lisa. The found wavelength dependence could be explained by the diffraction efficiency at the m_{Far} and m_{Near} diffraction orders, which have been shown to be wavelength dependent.[17] In a paper of Valdemar Portney, a geometrical model was proposed to assess the light distribution of diffractive lenses in different wavelengths. We applied the proposed model to calculate the energy distribution of the AT Lisa at the three wavelengths used in the current study. This resulted in a fraction of energy split of 0.63/0.37 for far/near at 546nm, but at 480nm and 644nm that proportion changed to 0.51/0.49 and 0.74/0.26, respectively. These values represent an ideal case without a light loss to other diffraction orders. Although the MTF quality metrics do not correspond in a one-to-one fashion with the light distribution, as the MTF can also be influenced by other factors, the MTF area of the AT Lisa measured at the far/near focus (0.42/0.38 at 544nm, 0.49/0.30 at 480nm, and 0.57/0.22 at 644nm) seems to show a similar behavior. This may indicate that the diffraction efficiency is an important factor affecting the optical performance of diffractive

IOLs if they function in other than a designed wavelength. However, it remains to be elucidated if the found spectral-dependency has important functional effects on the patient's vision.

In conclusion, the analyzed monofocal and multifocal IOLs demonstrated a range of LCA levels that mostly depended on intrinsic properties of their biomaterial. Moreover, we showed that the diffractive IOLs can be effective in compensating the dispersion of the IOL and the eye. Although considerable differences in LCA exist between the IOLs, the effect of chromatic aberration on the polychromatic image quality can be diminished by spectral weighting. The MTF performance of the diffractive IOLs showed a clear wavelength dependence, however, a functional implication of this finding yet needs to be assessed in a clinical setting.

References

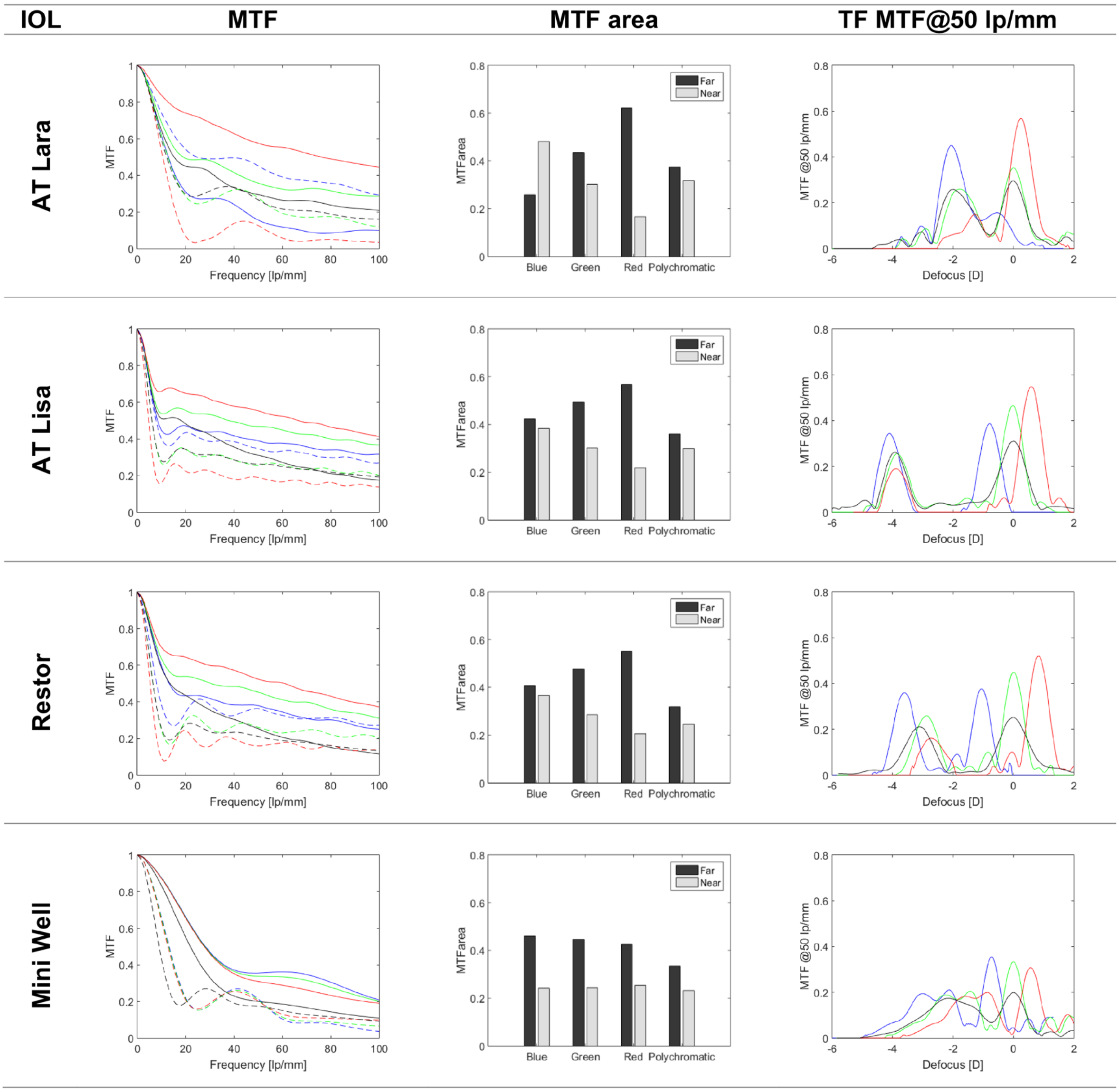
1. Cochener B. Clinical outcomes of a new extended range of vision intraocular lens: International Multicenter Concerto Study. *Journal of Cataract & Refractive Surgery.* 2016;42(9):1268-1275.
2. Weeber HA, Meijer ST, Piers PA. Extending the range of vision using diffractive intraocular lens technology. *Journal of Cataract & Refractive Surgery.* 2015;41(12):2746-2754.
3. Weeber HA, Piers PA. Theoretical performance of intraocular lenses correcting both spherical and chromatic aberration. *Journal of Refractive Surgery.* 2012;28(1):48-52.
4. Artal P, Manzanera S, Piers P, Weeber H. Visual effect of the combined correction of spherical and longitudinal chromatic aberrations. *Optics express.* 2010;18(2):1637-1648.
5. Piers PA, Fernandez EJ, Manzanera S, Norrby S, Artal P. Adaptive optics simulation of intraocular lenses with modified spherical aberration. *Investigative ophthalmology & visual science.* 2004;45(12):4601-4610.
6. Yoon G-Y, Williams DR. Visual performance after correcting the monochromatic and chromatic aberrations of the eye. *JOSA A.* 2002;19(2):266-275.
7. Bass M, DeCusatis C, Enoch J, et al. *Handbook of optics, Volume II: Design, fabrication and testing, sources and detectors, radiometry and photometry.* McGraw-Hill, Inc.; 2009.
8. Thibos L, Bradley A, Still D, Zhang X, Howarth P. Theory and measurement of ocular chromatic aberration. *Vision research.* 1990;30(1):33-49.
9. López-Gil N, Montés-Micó R. New intraocular lens for achromatizing the human eye. *Journal of Cataract & Refractive Surgery.* 2007;33(7):1296-1302.

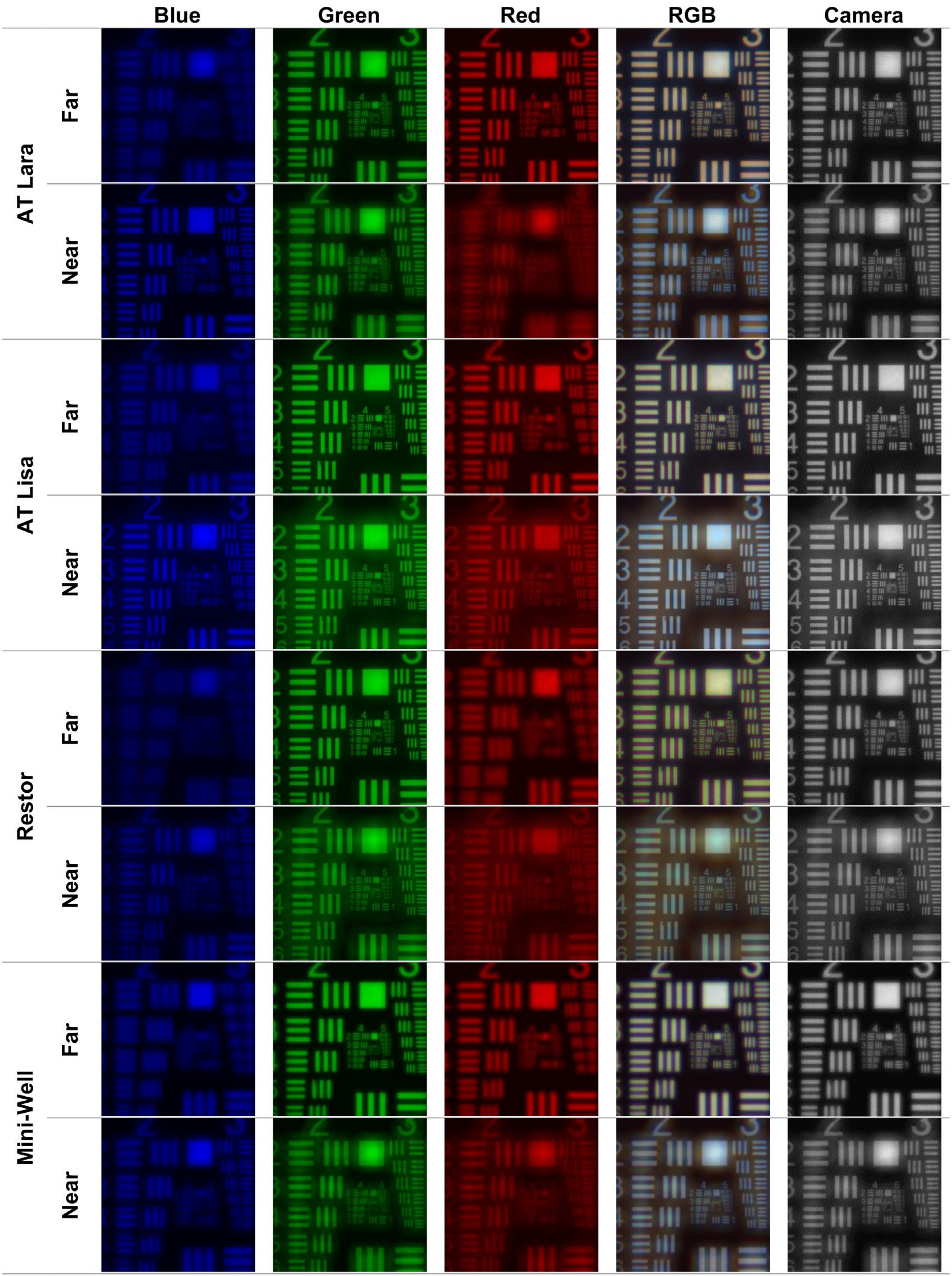
10. Millán MS, Vega F. Extended depth of focus intraocular lens. Chromatic performance. *Biomedical optics express.* 2017;8(9):4294-4309.
11. Carson D, Hill WE, Hong X, Karakelle M. Optical bench performance of AcrySof® IQ ReSTOR®, AT LISA® tri, and FineVision® intraocular lenses. *Clinical ophthalmology (Auckland, NZ).* 2014;8:2105.
12. Davison JA, Simpson MJ. History and development of the apodized diffractive intraocular lens. *Journal of Cataract & Refractive Surgery.* 2006;32(5):849-858.
13. Alarcon A, Canovas C, Rosen R, et al. Preclinical metrics to predict through-focus visual acuity for pseudophakic patients. *Biomed Opt Express.* 2016;7(5):1877-1888.
14. Singer W, Totzeck M, Gross H. *Handbook of optical systems, volume 2: Physical image formation.* John Wiley & Sons; 2006.
15. Vega F, Alba-Bueno F, Millán MS. Energy distribution between distance and near images in apodized diffractive multifocal intraocular lenses. *Investigative ophthalmology & visual science.* 2011;52(8):5695-5701.
16. Faklis D, Morris GM. Spectral properties of multiorder diffractive lenses. *Applied Optics.* 1995;34(14):2462-2468.
17. Portney V. Light distribution in diffractive multifocal optics and its optimization. *Journal of Cataract & Refractive Surgery.* 2011;37(11):2053-2059.

Figure legends

Figure 1. Optical quality metrics of the multifocal IOLs. The figure presents three measure outcomes. (1) The MTF (left) panels show MTF curves measured at the best far and near focus of each lens. (2) The middle panels show MTF-area values assessed at the far (black bars) and near (gray bars) focus. (3) The right panels present the trough focus (TF) MTF evaluated at a single frequency of 50lp/mm and for a +2D to -6D defocus range. The blue, green, red and black lines correspond to MTF values measured with a 480nm, 546nm, 644nm and polychromatic filters, respectively. The solid lines stand for the far-focus MTF; the dashed lines stand for the near-focus MTF.

Figure 2. USAF resolution chart photographs taken through the multifocal IOLs. For more details on the image acquisition and processing, see the Method section.


IOL
MTF
MTF area
TF MTF@50 lp/mm
AT Lara
AT Lisa
Restor
Mini Well
MTF
Frequency [lp/mm]
MTFarea
Far
Near
Blue
Green
Red
Polychromatic
MTF @50 lp/mm
Defocus [D]


Blue
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AT Lisa
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Restor
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Mini-Well
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