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TECHNICAL NOTE

Imaging quality of multifocal intraocular lenses: automated assessment setup

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Abstract

Purpose: A new technique for the assessment of the optical quality of multifocal intraocular lenses (MIOLs) under monochromatic and polychromatic illumination is presented.
Methods: The system provides, in a totally automated procedure, the modulation transfer function (MTF) of the lens under test for different axial positions of the object. The artificial eye admits different artificial corneas, to optimise the axial resolution in the sampling of the MTF of the MIOL under test, and different pupils, to test the dependence of the optical performance of the MIOL on the eye pupil diameter.
Results: The performance and sensitivity of the apparatus is tested with different commercial MIOLs. The through-focus MTF for a refractive MIOL was measured at different moments during the process of hydration of a hydrophilic lens. Next, to show the performance of our proposal, two commercial refractive and diffractive MIOLs were evaluated.
Conclusions: We have designed a precise and robust optical method for testing MIOLs *in vitro*. The proposed method represents a valuable technical improvement to make the procedure of MIOL evaluation more versatile, efficient and trustworthy.

Introduction

Although monofocal intraocular lenses are still frequently employed for treating cataracts, nowadays multifocal intraocular lenses (MIOLs) are an increasingly used modality that provides users good vision not only for far but also for near objects. The performance of these lenses has been reported in the literature in numerous objective studies performed both *in vivo* and *in vitro* (See for example Refs. 1–3 and the references therein). Particularly, to assess the optical quality of MIOLs several experimental setups were designed in which the Point Spread Function (PSF) and/or the Modulation Transfer Function (MTF), measured for the far and the near focus, are the essential merit functions. However, some valuable information, as for example the depth of focus (DOF), is missed if measurements are restricted to these two cases. The Defocus Transfer Function (DTF) was proposed as a theoretical tool for illustrating the OTF for all levels of defocus.[4] By calculating the DTF for a given spatial frequency, the simulated performance of implanted MIOLs on distance, intermediate, and near vision can be evaluated simultaneously. In order to properly sample the range of defocused planes between far focus and near focus, different methods, such as moving the detector (artificial retina) along the optical axis,[5,6] interposing negative lenses[7] or generating different vergences in the object space[8–10] have been proposed. In the last case, the movement of the object is frequently performed manually, resulting in a time consuming and sometimes not very accurate procedure. On the other hand in the methods that use negative lenses or move the retina, the magnification between far and near images is different and so the comparison between far and near images is not possible.

In this work, we describe in detail a new technique for the assessment of MIOLs response by means of a specially designed opto-mechanical setup. The system provides the trough-focus MTF (modulus of the DTF) of the lens under test in a totally automated procedure. Contrary to most of the commercially available setups, our system allows the measurement of diffractive MIOLs because, instead of using Hartmann-Shack[11] or interferometric principles,[12] it is based on an image forming setup. The performance and sensitivity of the apparatus is tested with different designs of MIOLs.

Methods

A schematic illustration of the experimental setup to determine the through-focus MTF is shown in *Figure 1a)*. The illumination system consists of a white LED [Luxeon™ V Portable (http://www.luxeonstar.com)], a holder for a band-pass filter, and a collimating lens L1 (focal length: 50 mm). A test object test is mounted on a stepping motored translation stage (travel range 300 mm, accuracy: ± 5 μm) and placed at the front focal plane of the achromatic Badal lens L2 (focal length: 160 mm). The artificial eye used in this paper is represented in *Figure 2*; it consists of an artificial cornea as described at the ISO/FDIS 11979-9:2006 standard[13] (LAO 034 achromatic lens) and the MIOL to be tested immersed in a wet cell with saline solution. The MIOL can be placed in different holders, with pupil sizes ranging from 2 mm to 6 mm. The entrance pupil diameter of the artificial eye is then the image of the eye pupil as seen through the cornea lens. Although the relative distances between the components, shown in *Figure 2*, are slightly different in our artificial eye than those reported in the above mentioned ISO-Norm, through numerical simulations performed with OSLO® optical design software (http://lambdares.com/), we found that the differences between the MTFs computed up to 100 cycles/mm for both artificial eyes are <4%.

The front focal plane of the artificial eye is located at the back focal plane of the lens (L2). A 8-bit CMOS camera (www.edmundoptics.com; EO-5012C 1/2″ CMOS Color USB Lite Edition Camera) with an image sensor having 2592 × 1944 pixels [pixel pitch of 2.2 μm (http://www.1stvision.com)]; attached to a 5 × microscope (focused on the far focal plane of the artificial eye) is used to capture the image formed by the eye, with the MIOL under test.

To assess the through-focus MTF, the object plane is axially displaced to generate the different eye vergences ranging from −1D to +6D in steps of 0.04D. For each position of the object, the retinal image is stored and analysed in a totally automatic procedure. The movements of the translation stage and the processing of the retinal images were controlled by a custom software programmed in LabView ®(http://www.ni.com/labview/).

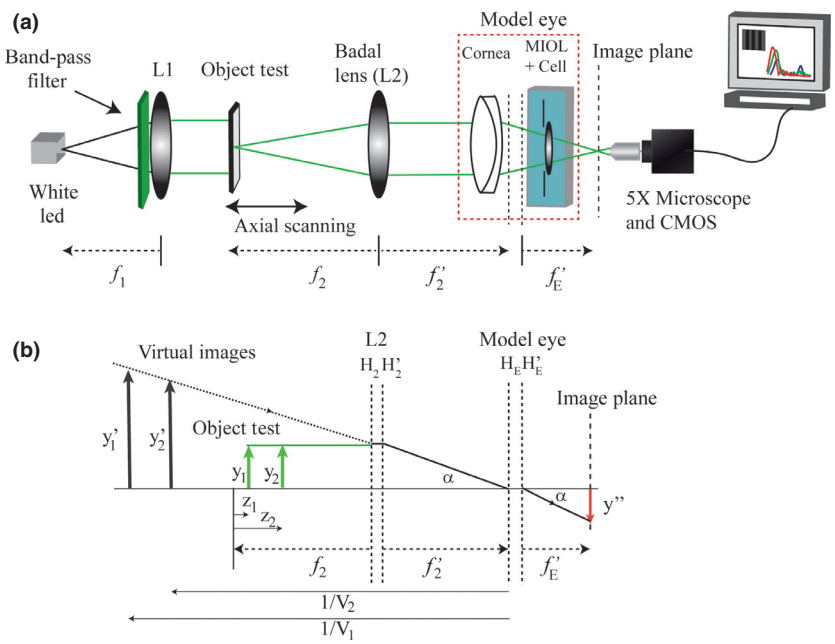

Figure 1. (a) Experimental setup. The illumination system is formed by a white LED, a collimating lens (L1) and eventually a band pass filter. The object test is mounted on a linear translation stage. The Badal lens allows different simulated vergences of the object. The artificial eye is formed by an artificial cornea and a wet cell in which the MIOL is located (see Figure 2 for details). The imaging system, including the CMOS and a 5×-microscope is connected to a PC. (b) Geometrical optics representation of the system illustrating the Badal (or focimeter) principle.

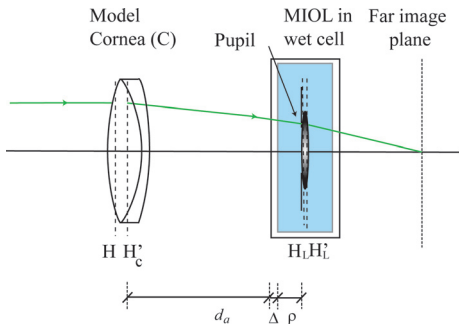

Figure 2. Artificial eye: Model Cornea = 27.8D (Melles Griot: LA0034), d_a = 9.27 mm, Δ = 3 mm, ρ = 3.9 mm.

One important issue to be taken into account in the measurement of MIOLs performance is that *the addition* (i.e. the difference between its *near* and *far* powers) is located at the MIOL itself instead of at the corneal vertex plane, as happens with contact lenses or spectacles. For this reason the *clinical addition* (*A*c) is different from the *nominal addition* of the MIOL (A_M) and, within the framework of paraxial optics, the relationship between both magnitudes can be easily obtained by matrix analysis[14] resulting as[10]

$$A_c = (-1 + dP_C)^2 A_M, \tag{1}$$

where P_C is the power of the artificial corneal and d (as shown in *Figure 2*) is the distance between the image principal plane of the cornea and the object principal plane of the MIOL defined as

$$d = H'_C H_L = d_a + \frac{\Delta}{n_g} + \frac{\rho}{n_h} \tag{2}$$

In Equation *2* n_g is the refraction index of the glass walls of the cell and n_h is the refraction index of the saline solution. The accuracy of Equation *1* was tested by using the OSLO® software to simulate our artificial eye. We found that for A_M in the range of 0.5D to 4.0D, the error committed when the paraxial approximation is done, is lower than 4%.

Note that in the proposed setup the cornea lens can be changed (and even removed) to obtain an artificial eye with a larger focal distance and consequently to obtain an improved axial resolution for the trough-focus MIOLs MTF. If the cornea lens is removed, the entrance pupil of the artificial eye coincides with the physical aperture of the MIOL's holder.

As we mentioned, the object principal plane of the artificial eye, H_E, is located at the back focal plane of the Badal lens (L2) (see *Figure 1b*), in this way, the apparent vergences of the object seen by the artificial eye, V_i can be varied through the object axial displacements z_i, as

$$V_i = z_i\, P_{L2}^2 \tag{3}$$

where, P_{L2} is the power of the lens (L2). Additionally, in this configuration, independently of the axial position of the test object, all the virtual images produced by L2 (y') always subtend the same angle α, and thus, the size of the final image (y_i'') is nearly constant during the trough-focus MTF measurement and its magnification is given by

$$\Gamma = \frac{f_E}{f_2}. \tag{4}$$

This fact allows a direct comparison between the *far* and *near* MTFs through the corresponding images produced by a given MIOL. The MTF is a measure of the contrast transmission capabilities of an imaging system, as a function of the spatial frequency. To calculate the monochromatic through-focus MTF the object test we employed is a bar target of v_0 = 5lp mm^{-1} (this spatial frequency corresponds to 14 cycles per degree (cpd) for the artificial eye which is approximately an object of size 20/40 in a visual acuity letter chart). For each object vergence, the image produced by the artificial eye is recorded and converted into a digital image. This image is pre-processed dividing it by a *background* image with no object in the setup in order to avoid both, the influence of the Badal lens in the results, and the errors introduced by the eventual non uniform illumination of the object. Then, for each image, the average of 1920 profiles along the horizontal coordinate, at different heights, is taken. This profile is the contrast transfer function (CTF) at frequency v^0 (see *Figure 3*). The Coltman formula[15] allows for the conversion of the CTF into its equivalent MTF, provided the CTF is measured at different frequencies; but since no modulation values are transmitted by the system above the cut-off frequency, the MTF can obtained approximately from the CTF using the following relationship

$$MTF(v) = \frac{\pi}{4} CTF(v), \tag{5}$$

which indeed is exact for frequencies greater than 1/3 of the cut off frequency. Actually, from a practical point of view, we found that the experimental values of the CTF obtained at a single frequency, are sufficient to compute the corresponding MTF for the whole range of frequencies, if this data is fitted to a cosine 1-D function

$$I(x) = A[1 + C\ \cos(2\pi\, x\, v_i\ + \phi)], \tag{6}$$

where A is a constant, $v_i\ = v_o/\ \Gamma$, j is the offset of the pattern, and C is the amplitude contrast ratio of the fitting

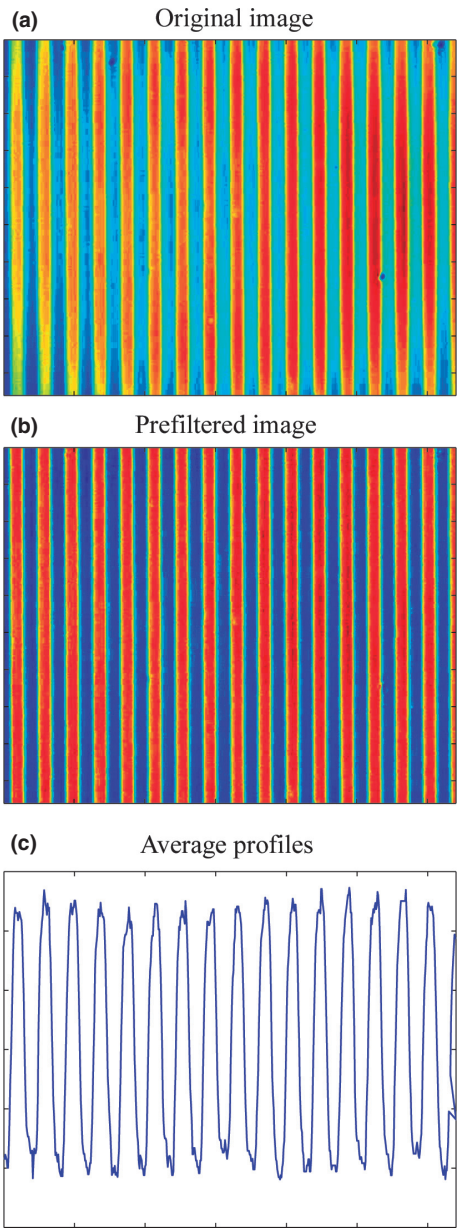

Figure 3. Typical result of an experimental Contrast Transfer Function (CTF). (a) Non pre-processed image showing a non-uniform illumination of the test object. (b) Pre-processed image obtained by the division between the original image and the *background*. (c) Average of horizontal 1920 profiles of the pre-processed image.

cosine function or 'modified' CTF. We employed the Levenberg-Marquardt fitting algorithm programmed in LabView. The MTF is computed with Equation *5* getting *C* from the fitted experimental values using Equation *6*. *Figure 4* shows a numerical simulation conducted for a monofocal intraocular lens. As can be seen the coincidence between the direct MTF and the simulated experimental MTF is perfect for the whole range of frequencies.

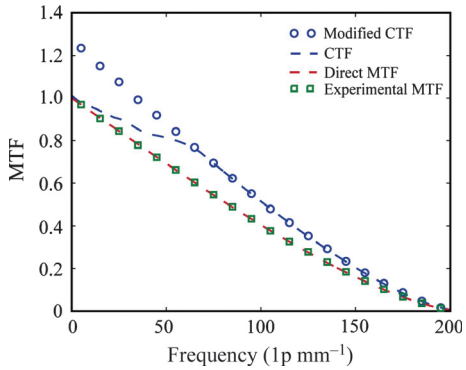

Figure 4. Numerical simulation of the Contrast Transfer Function (CTF); the 'modified' CTF, obtained by fitting the values of the CTF to a cosine function; the Modulation Transfer Function or MTF ('direct' MTF); and the experimental MTF, computed from Equation 5. These results correspond to a monofocal intraocular lens of power 19.5D with a pupil diameter 5.84 mm.

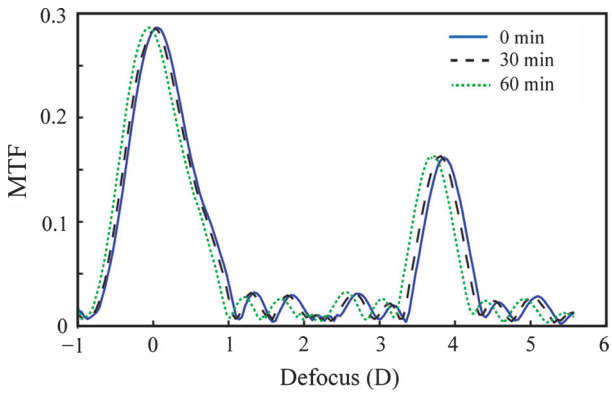

Figure 5. Through-focus Modulation Transfer Function at three different moments during the hydration process of a multifocal intraocular lens.

Results

The first result we want to show is the sensitivity of the experimental setup. The through focus MTF for a refractive MIOL was measured at different moments during the process of hydration of a hydrophilic lens. In this case measurements were performed without cornea lens in the artificial eye in order to achieve the highest axial resolution. As can be seen in *Figure 5* our system is able to measure small changes of the MIOLs response during this process.

Next, to show the performance of our proposal, two different commercial MIOLs were evaluated. The first one: ReZoom NXG1 (www.amo-inc.com/) is a multizone refractive MIOL with five concentric refractive alternating zones for distance and near vision. Aspheric transitions between the zones provide intermediate vision. The far distance power of the tested lens is +19.5D and the nominal

addition power +3.50D. The second one: Tecnis® ZM900 (www.amo-inc.com/) has refractive-diffractive characteristics. Actually it is a refractive lens with a fully diffractive surface that consists of 32 rings providing the addition power. In this case the far distance power is 22D and the nominal addition +4.0D.

The first set of measurements was performed without the cornea lens in the experimental setup. In this case taking into account the magnification of the system, the frequencies at the image plane (retina) of the test object are different: 15.6 lp mm^{-1} for the ReZoom lens and 17.6 lp mm^{-1} for the Tecnis but as we mentioned before in both cases the frequencies expressed in cpd is the same: 14 cpd. The polychromatic analysis capacity of our setup was evaluated by measuring the through-focus MTF for both lenses with a 4.2 mm pupil (that corresponds to a 6.84 mm entrance pupil of the artificial eye) for three different wavelengths selected with band-pass (10 nm) optical filters centred at 490 nm, 560 nm and 630 nm. As can be seen in *Figure 6a)*, in each case, the maxima for 560 nm is obtained for object vergences 3.50D and 4.06D which correspond to the nominal addition distance for the ReZoom and Tecnis respectively. Besides, the maxima for the MTF for ReZoom MIOL shows that the three wavelengths are separated approximately 0.34D at the far focus and 0.66D at the near focus. On the other hand, Tecnis MIOL shows a higher chromatic variation which is approximately 0.46D at the far focus, and 1.06D at the near focus. Note also that at the near focus, the diffractive lens shows a chromatic aberration that is opposite to one of the refractive lens. Moreover, for the diffractive MIOL the efficiency of each focus is highly dependent on the wavelength. The dependence of MIOLs response upon pupil size (one of the issues that ophthalmologists are very concerned about) is shown in *Figure 6b)*. The through-focus MTF was evaluated for monochromatic light (560 nm) and two different pupil sizes 2.7 mm and 4.2 mm, with the cornea lens in the artificial eye, the corresponding entrance pupil diameters are, in this case, 3.58 mm and 6.84 mm. The maxima of the MTF for the *near* vision are obtained at the object vergences of 1.36 (ReZoom) and 1.64D (Tecnis) these values correspond to

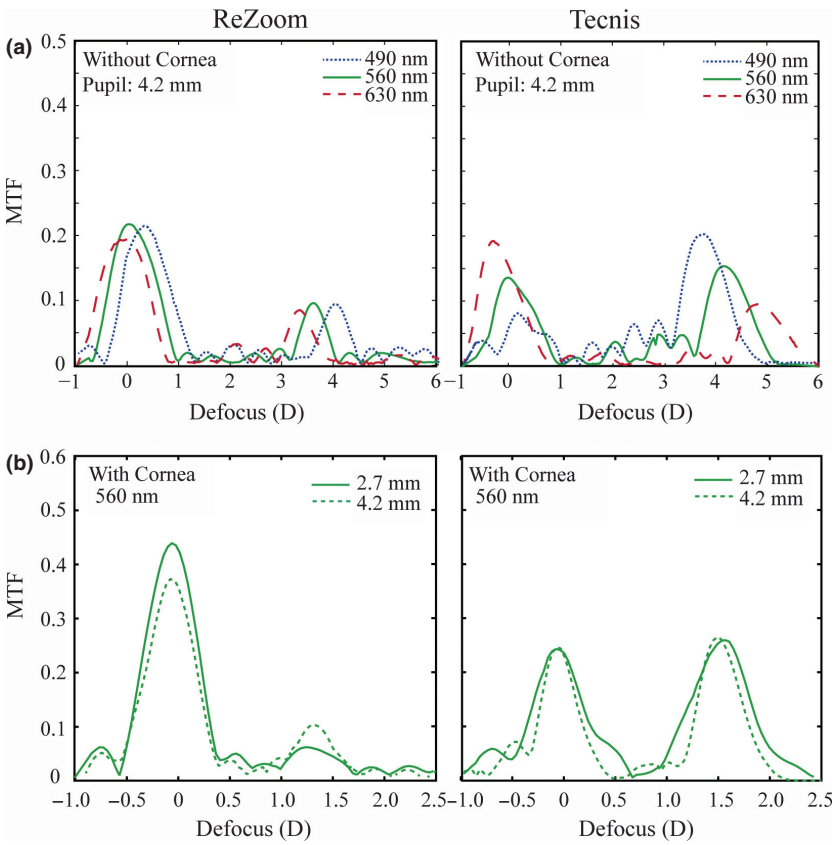

Figure 6. Through-focus Modulation Transfer Functions corresponding to a two commercial multifocal intraocular lenses measured. (a) without cornea and 4.2 mm pupil for different wavelengths (490, 560 and 630 nm) and (b) with cornea for two pupil sizes (2.7 and 4.2 mm) for 560 nm. Zero defocus corresponds to far vision.

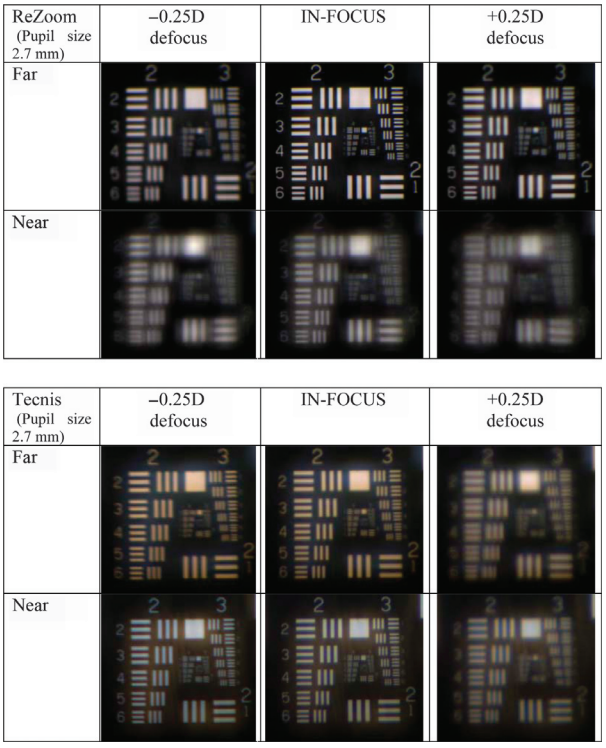

Figure 7. US Air Force(USAF) target images obtained with white light illumination for far and near objects.

additions measured at cornea vertex (see Equation *2*). As expected, with small pupil the *far* focus MTF for the ReZoom is higher.[6] The opposite happens for a 4.2 mm pupil. The MTF for the Tecnis has approximately the same value for the near and far focus for both pupil diameters.

Finally, a qualitative analysis of the optical performance of different MIOLs was performed under white light illumination in order to obtain images that approximate to real visual conditions. To this end the US Air Force Target (USAF), was employed as a multi-frequency object, with no band pass filters in the setup. Before obtaining the images, a white balance was performed with the software provided by the manufacturer. The *near* and *far* images produced by the artificial eye with the two commercial MIOLs are presented in *Figure 7*. In the same figure the image corresponding to a $\pm$ 0.25D defocused planes are also shown. Note that, one the one hand, these qualitative results match very well with the quantitative ones presented in *Figure 6*, and on the other hand, the better performance of the Tecnis MIOL at near is quite evident, in spite of its higher chromatic aberration.

Conclusions

We have designed a precise and robust optical method for testing MIOLs *in vitro*. In addition to characterising refractive MIOLs, as do most of existing methods, the proposed method opens the possibility of measuring diffractive MIOLs. The system is based on an image forming system that allows measuring the through focus MTF (the MTF for different axial positions of the object) in an automated way. It provides an accurate measurement of the addition at the MIOL itself instead of at the corneal plane. The new method enables a direct comparison between both the far and near MTFs and also between different MIOLs because the angle subtended by a given object is constant, as well as the spatial frequency of the object being expressed in cpd.

The optical system was tested with a ray tracing program and the potentiality of the setup is demonstrated by the assessment of two commercial MIOLs of different characteristics. The system is modular and versatile, allowing spherical or aspheric artificial corneas, and different pupil diameters in the artificial eye. The system can allow the study of the influence of tilts and decentrations of the MIOL in the artificial eye. This study can be done simply by mounting the wet cell in a high precision multi-axis positioner (for example on a tilt platform mounted on top of an XYZ stage). The system also permits the study of the MIOL monochromatic and polychromatic response. In the last case the polychromatic MTF can be calculated as the superposition of the three monochromatic (RGB) MTFs weighted by the spectral content of the illumination source, the MIOL material transmission, and the photopic response of the human eye [V(λ)]. Summarising, the proposed method represents a valuable technical improvement to make the procedure of MIOL evaluation more versatile, efficient and trustworthy.

Disclosure

All authors report no conflicts of interest or any proprietary connections to any of the products used or evaluated.

Acknowledgements

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