Optimizing Vision with Multifocal Intraocular Lenses: A Zemax Simulation Study for Cataracts with Presbyopia

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ABSTRACT— Cataracts, along with presbyopia, is a common age-related vision problem that can indeed make it challenging to achieve clear vision. Multifocal intraocular lenses (IOLs) have emerged as a promising treatment option to improve vision in individuals with cataracts and presbyopia. With their unique design, these lenses provide adequate vision at multiple distances and reduce the dependency on glasses. In this study, we utilized the Liou-Brennan model in Zemax software to simulate a healthy eye and then introduced cataracts with presbyopia to the model. Subsequently, we applied treatment in the form of multifocal intraocular lenses. The improvements in the patient's vision were indicated using spot diagrams and modulation transfer function for three different viewing distances: far, intermediate, and near at three different entrance pupil diameters.

KEYWORDS: Intraocular lens, Cataracts, Presbyopia, Diffractive Lens, Liou-Brennan model.

I.INTRODUCTION

Diseases such as cataracts and presbyopia pose significant challenges to global health, with profound impacts on individuals' vision and overall well-being. Cataracts occur when the eye lens becomes cloudy, leading to blurred vision, reduced contrast sensitivity, sensitivity to light and difficulty of seeing clearly. On the other hand, it is the leading cause of blindness worldwide, accounting for more than half of all cases of blindness according to the World Health Organization (WHO) [1]-[3].

Another age-related disease is presbyopia, which typically occurs between the ages of 40 and 50. In this condition, the individual experiences a decrease in near vision due to the loss of lens flexibility and weakness of ciliary muscle. So, the ability of accommodation decreased and consequently, the thickness of the eye lens and the sagging of the muscles that control the shape of the lens, changed drastically [4]. The coexistence of cataracts and presbyopia presents a distinctive treatment challenge. Addressing one condition may worsen the other, making simultaneous treatment a complex endeavor. For instance, while cataract removal and the implantation of intraocular lenses (IOLs) can significantly improve distance vision, they may exacerbate presbyopia, necessitating the use of glasses for near vision task [5].

Modeling plays a pivotal role in the field of vision optics, providing essential insights for research and understanding of conditions such as cataracts and presbyopia. A comprehensive model of the human eye is essential for accurately replicating its structure and function, enabling researchers to simulate various eye conditions and evaluate potential treatments [6]. The continuous evolution of intraocular lens (IOL) technology has revolutionized treatment options for individuals with cataracts and other vision impairments. IOLs are artificial lenses surgically implanted in the eye to replace the natural lens affected by cataracts. There are several types of IOLs available, each uniquely designed to address specific vision requirements. Monofocal IOLs offer clear vision at a specific distance, typically near, intermediate, or far, necessitating glasses for other distances. Multifocal IOLs provide multiple focal points for clear vision at various distances without the need for glasses. Toric IOLs correct astigmatism, a common refractive error, while also addressing cataracts to enhance overall vision quality. Accommodative IOLs replicate the natural focusing ability of the eye, enabling a range of clear vision without the reliance on external aids [7].

Diffractive IOLs represent a cutting-edge subset of multifocal lenses that offer tailored solutions to meet the unique visual needs of individual patients. These specialized lenses are designed to correct refractive errors such as nearsightedness and farsightedness, while also addressing cataracts to provide clear vision at multiple distances. By incorporating diffractive surfaces that manipulate light rays through diffraction, diffractive IOLs enable vision at various focal distances [7], [8]. The ability to customize these lenses for each patient plays a pivotal role in improving visual outcomes and reducing the dependence on corrective eyewear. Previous research has focused on designing different types of IOLs using optimization algorithms based on sinusoidal profiles [9] and characterizing bifocal IOLs through mathematical modeling [10]. Additionally, adaptive optics have been utilized to observe Zernike spherical aberration of diffractive IOLs [11], and ZEMAX software has been instrumental in analyzing the designed IOLs for correction of corneal aberration [12]. Although cataracts and presbyopia, treated with IOLs experimentally [13], [14] but there remains a gap in the literature regarding the modeling of the combined treatment of cataracts and presbyopia using these advanced lenses.

In this study, using ZEMAX software, we have evaluated how diffractive IOLs interact with light rays in the eye. By using the Liou-Brennan model, we modeled both healthy eye and eye affected by cataracts and presbyopia. Sag and phase changes of the designed diffractive IOL have assessed. Furthermore, we examined the impact of diffractive IOL treatment on vision improvement at three distances and three pupil diameters by investigation of modulation transfer function (MTF) and focal spot size at retina. This study aims to contribute to our understanding of treatment options and their potential benefits. Ultimately, simulating the effects of diffractive intraocular lenses in this study can provide valuable data to inform clinical decision-making, improve patient outcomes, and advance the field of vision optics and cataract surgery.

II. MATERIALS AND METHODS

In the Liou and Brennan's eye model, the normal relaxed eye is typically considered as aspheric, with a specific distance from the cornea to the retina, which in this case is 22.914 mm. This simplified spherical model allows researchers to study the basic optical characteristics of the eye and simulate how light is refracted and focused onto the retina.

In table 1, various parameters such as radius, thicknesses, refractive indices, and other characteristics of a healthy eye have been listed based on Liou and Brennan's eye model. These parameters play a crucial role in accurately representing the optical system of the eye and its interaction with incoming light.

Table 1. Lens Data Editor (LDE) of Zemax software to simulate a normal eye based on Liou and Brennan's eye model.

#	Suf: Type	Comment	Radius (mm)	Thickness (mm)	Glass	Semi-diameter (mm)
0	standard	Object	Infinity	Infinity	-	
1	Standard	Input Beam	Infinity	0.550	-	
2	Standard	Cornea	7.770	0.550	1.38, 50.2	5
3	standard	Aqueous	6.400	3.160	1.34, 50.2	5
4	standard	Pupil	Infinity	0	1.34, 50.2	1.25
5	Gradiant 3	Lens-front	12.400	1.59	1.368	5
6	Gradiant 3	Lans-back	Infinity	2.43	1.407	5
7	standard	Vitreous	-8.100	16.239	1.34, 50.2	5
8	standard	Retina	-12.000	-	-	5

In this eye model, the anterior and posterior lens surfaces of healthy eye, were simulated using Gradient3 surfaces, according to Eq. 1,

$$n = n_0 + n_{r2}\, r^2 + n_{z1}\, z + n_{z2}\, z^2 + ... \qquad (1)$$

where $r^2 = x^2 + y^2$ and the remaining coefficients of this equation are provided in Table 2. These coefficients are used to describe the shape and curvature of the lens surfaces, allowing for accurate modeling of the optical properties of a healthy eye.

Table 2. The coefficients of Gradient3 surfaces in Eq. 1.

Surf	n_0	n_{r2}	n_{z1}	n_{z2}
5	1.368	-1.978×10^{-3}	0.049	0.015
6	1.407	-1.978×10^{-3}	0.000	-6.605×10^{-3}

To simulate a patient eye with cataract the cloudy eye lens refractive index, n0, was set to 1.419 which blurs the vision. Also, to simulate the presbyopia the behalf of less flexible eye lens curvature (CRVT) was set to -0.123457, -0.174200, and -0.174 at far, intermediate and far vision, respectively which make difficulties in focusing on close objects [15]. These age-related changes in the lens affects the eye's ability to adjust and accommodate for all visions.

Table 3. Details of operands in multi-configuration

Operands	Surface	Configuration . 1	Configuration . 2	Configuration . 3
1: PRAM	3/2	0^0	-10^0	-20^0
2: MOFF	0	Far	Intermediate	Near
3: THIC	0	10^{10} mm	1000 mm	500 mm
4: APMN	3	1.5 mm	1 mm	0 mحقشیm
5: APMX	3	4 mm	1.5 mm	1 mm

To correct cataracts and presbyopia, it is prescribed to remove the lens from the eye and replace it with a multifocal IOL. These lenses have different zones for different vision, allowing the patient to see clearly at various distances. To correct vision in three different zones of focus in the software, namely near, intermediate and far distances, the object distance (thickness (THIC) of surface 0) is considered as 500 mm, 1000 mm, and infinity, respectively. Accordingly, the eye angle (tilt about *x*, which is parameter 2 of surface 3 (PRAM 3/2) was set to 0º, -10º, and -20º. These three conditions, along with the changes in the minimum radius value (APMN) and maximum radius value (APMX), are applied simultaneously in the settings of the software's multi-configuration. Table 3 provides the details of these three viewing distances and the corresponding adjustments made to the minimum and maximum radius values.

To replace a diffractive multifocal intraocular lens, the anterior and posterior lens surfaces of the lens are set as binary2 and even asphere surfaces, respectively.

The binary2 surface is a diffractive surface in which the added phase to each ray varies as a rotationally symmetric polynomial. The phase is added according to Eq. 2, where the coefficients A_i are in radians.

$$\Phi = M \sum_{i=1}^{N} A_i \, \rho^{2i} \tag{2}$$

where ρ represents the radial distance from the center of the lens surface, and the coefficients A_i determine the shape and characteristics of the diffractive surface. M represents diffraction order and N is the number polynomial coefficient in the series. In this study, the size of the pupil in average lighting conditions was set as approximately 2.5 mm in diameter.

The IOL was considered to be made of Poly(methyl methacrylate) (PMMA). Zero order of diffraction was considered to achieve near vision and one order of diffraction was considered to achieve far vision. In order to optimize the aberrations caused by the designed IOL, merit functions such as COMA (to eliminate coma aberration), LONA (to eliminate longitudinal chromatic aberration), XNEG and XXEG (minimum and maximum edge thickness) were added to the default merit functions in ZEMAX software. Then parameters such as polynomial coefficients were set as variables and optimization was done. This modeling approach allows for precise customization and optimization of the lens design for the patient's specific needs.

III. Results and Discussion

Fig. 1.a-c depicts the simulated 3D layout of a healthy eye in three vision modes; far (infinity), intermediate (1000 mm), and near (500 mm)

distances. The eye was rotated about 0º, 10 º, and 20º to simulate the three configurations, respectively (as displayed in Table. 3).

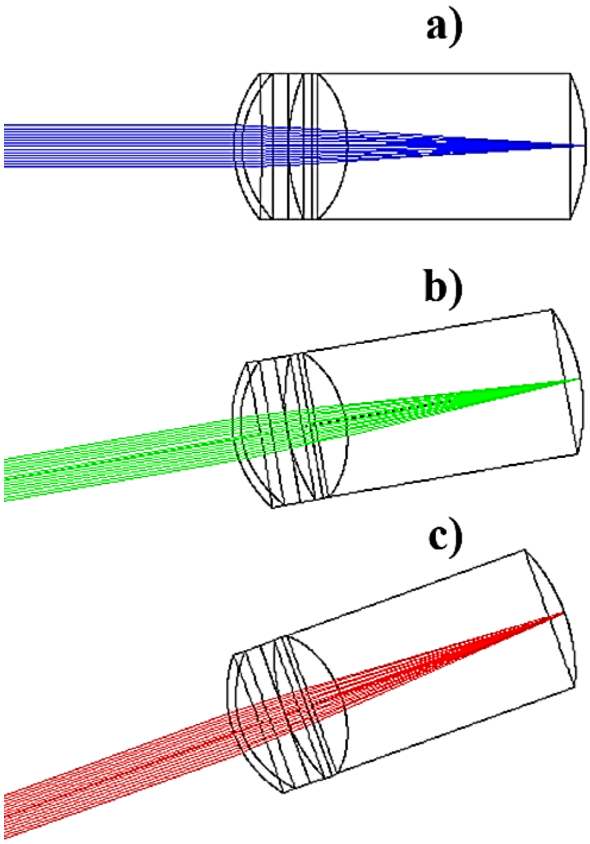


Fig. 1. Three-dimensional layout of human eye at a) far vision, b) intermediate vision, and c) near vision.

The Three-dimensional layout of eye affected with cataracts and presbyopia is represented in Fig. 2. As can be seen the light is not focused on the retina, properly.

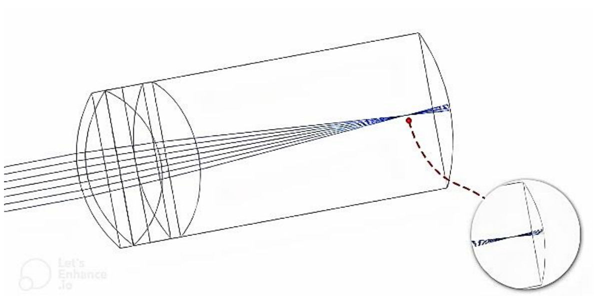


Fig. 2. 3D layout of eye affected with cataracts and presbyopia.

By adding merit functions related to diffractive IOL design and performing the optimization process, the polynomial coefficients of the binary2 surface (4th and 6th order terms) and the coefficients of added phase (*Ai* in Eq. 2) were obtained as shown in Table 4.

Table 4. The polynomial coefficients of the binary2 surface.

4^{th} order term	6^{th} order term	A_1 (Coef. on ρ^2)	A_2 (Coef. on ρ^4)	A_3 (Coef. on ρ^6)	A_4 (Coef. on ρ^8)
8.138×10^{-7}	3.318×10^{-8}	103.641	-847.193	-3.176	-2.678

The diffractive IOL functions as if there are two chirped diffraction gratings placed alongside each other. In each diffraction grating (as shown in Fig.3), the zero order diffraction (0th order beam) corresponds to the light that passes straight through the grating without being diffracted. This component is typically responsible for focusing light to create clear distance vision.

The first order diffraction (+1st order beam) represents the light that is diffracted at different angle by the chirped grating. This component is crucial for providing near vision correction. By concentrating a portion of the light energy into the first order diffraction, the lens can create a secondary focal point that allows for clear near vision. By controlling the distribution of light energy between the zero and first order diffractions, diffractive multifocal lenses can effectively provide a range of vision correction for both near and far distances.

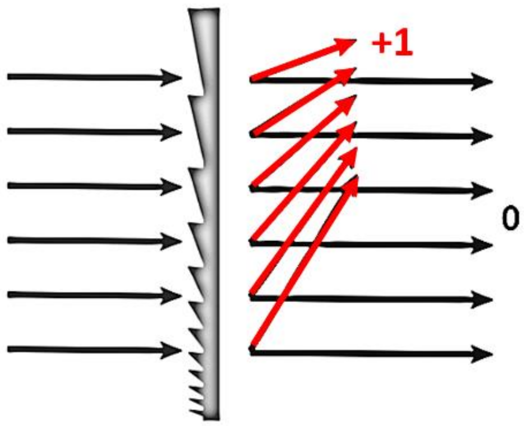


Fig. 3. Zero and first order diffraction of a chirped grating as far and near focal points, respectively.

The higher diffraction orders have a wider angle and are determined by the separation between the grating lines. As shown in Fig. 4, a diffractive multifocal lens combines both refractive and diffractive powers, where incoming light is primarily split into two main diffraction orders: 0 and 1.

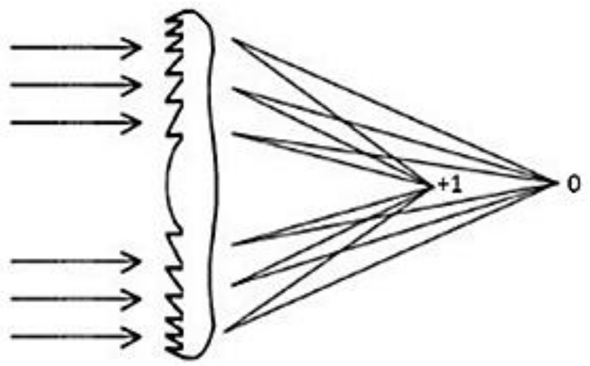


Fig. 4. The structure of a multifocal diffractive lens.

The diffraction zones gradually converge towards the lens edge, causing diffracted light to bend at a larger angle. The height of the steps in the diffraction structure determines the energy distribution in the diffraction orders. This diffraction structure is integrated onto a refractive base lens, resulting in light being focused at two distinct points. This design allows for close-range vision and offers more uniform vision compared to purely refractive lenses. The diffractive IOL lenses provide a wider range of vision from far to near distances. The design of substituted diffractive IOL is depicted in Fig.5.

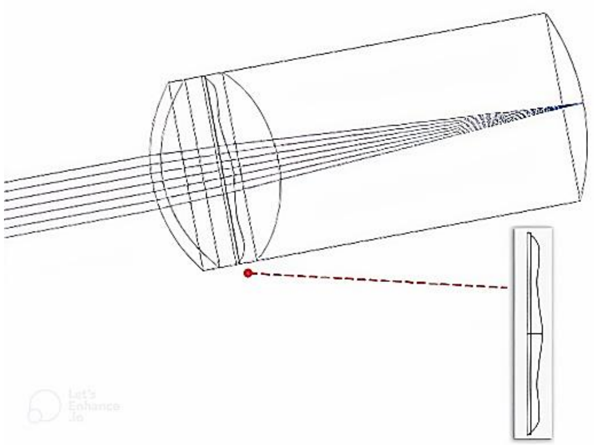


Fig. 5. Layout of designed diffractive IOL.

Once the parameters of the diffractive intraocular lens for cataract patients with presbyopia have been fine-tuned, the details of the designed surface can be extracted. Specifically, the surface profile reveals an increase in sagittal height from the periphery towards the center of the lens (as can be seen in Fig. 6).

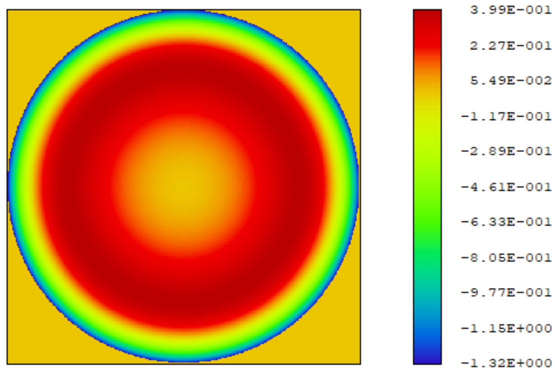


Fig. 6. Sag of the designed diffractive multifocal lens.

The grooves or lines present on the surface of the diffractive multifocal lens, like a diffraction grating, alter the phase of the wavefront. The wavefront map, in Fig. 7, illustrates the phase modifications induced by the diffraction lines on the lens.

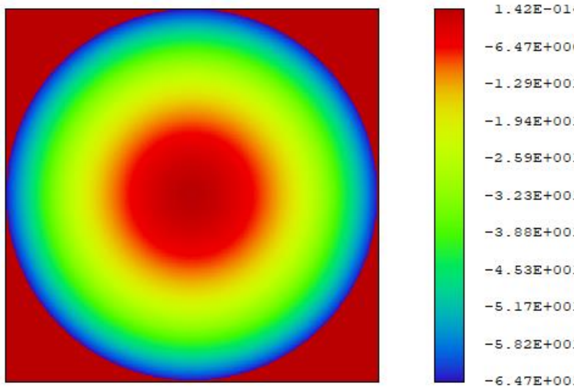


Fig. 7. Surface phase map of the designed multifocal diffraction lens.

At each step, the phase lattice undergoes a 2π shift in value. If we represent this surface in a contoured form to emphasize the lattice steps with a phase change of 2π, the regions and concentric circles of the diffractive IOL associated with the binary2 surface in the design can be clearly observed (as shown in Fig. 8).

It is evident that the central region of the lens is refractive, surrounded by a diffractive surface. The central circular area corresponds to far vision power. The concentric ring regions around it alternates between powers for achieving multifocal effects.

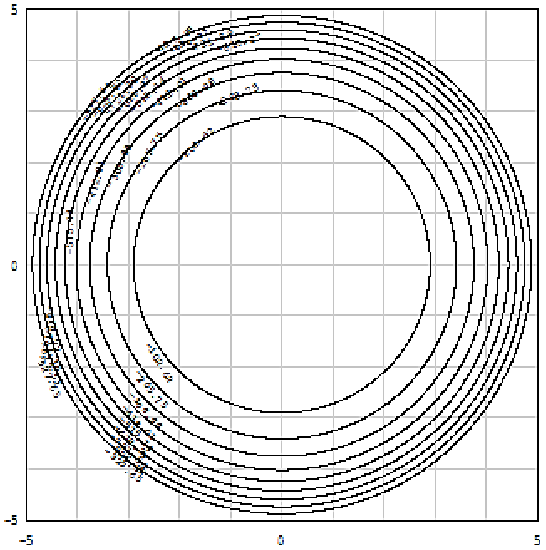


Fig. 8. Contours related to 2π Phase changes in binary2 surface of the designed lens.

In order to assess the quality of the image produced on the retina by the optimally designed diffractive lens, the primary diagram that is studied is the spot diagram. As observed, the diameter of the spot has significantly decreased in the treated eye compared to the patient's eye. Reduction in certain aberrations such as spherical aberration and longitudinal chromatic aberration can also be seen in this diagram. In Fig. 9, we witness changes in the diameter of the spot diagram (in micrometers) in three visions of patient, and treated eye, illustrating improvements in three vision modes: far, intermediate, and near.

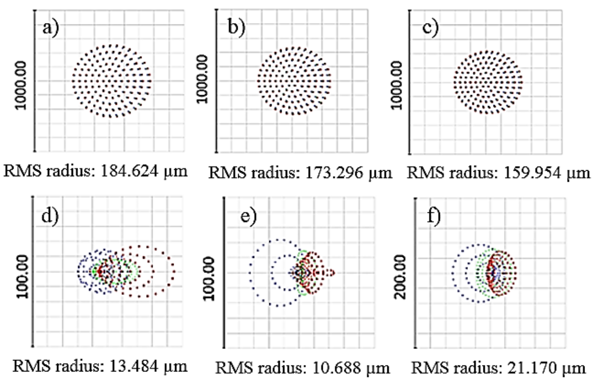


Fig. 9. Three views for the patient's eye at a) far, b) intermediate, and c) near vision and for the treated eye at d) far, e) intermediate, and f) near vision.

Another diagram used to investigate the sharpness and clarity of the image formed on the retina is the Modulation Transfer Function (MTF) diagram. This function essentially represents the transmission of different spatial frequencies of light through an optical system, such as a human eye, and indicates the number of line pairs per millimeter that can be resolved. The maximum spatial frequency required for image resolution by the eye is 30-line pairs per millimeter. Generally, humans require resolution higher than 0.4 to perceive line differences. A higher MTF value indicates better contrast transfer and, in general, better image resolution. Improvement in image contrast and resolution after treatment with an intraocular diffractive lens can be clearly observed in Fig. 10. This enhancement is noticeable in intermediate vision, followed by far vision, and ultimately near vision.

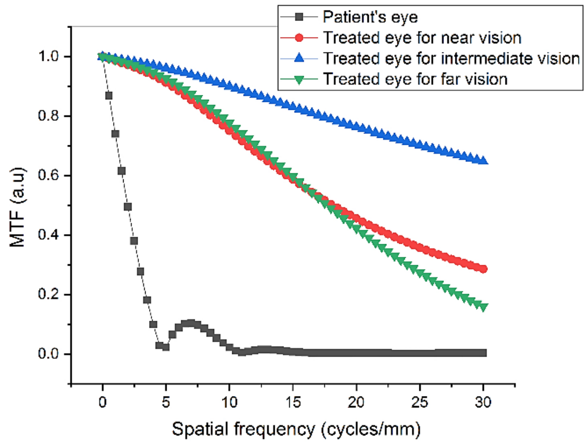


Fig. 10. Comparison of the MTF between the patient's eye and the treated eye in three vision modes: near, intermediate, and far.

Geometric images of letter F on retina, for the treated eye with designed IOL, which is the same at three visions, in caparison with the patient eye, are shown in Fig. 11.a, and b. The optimized vision is obvious in this figure.

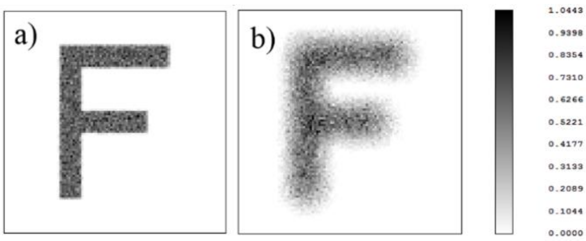
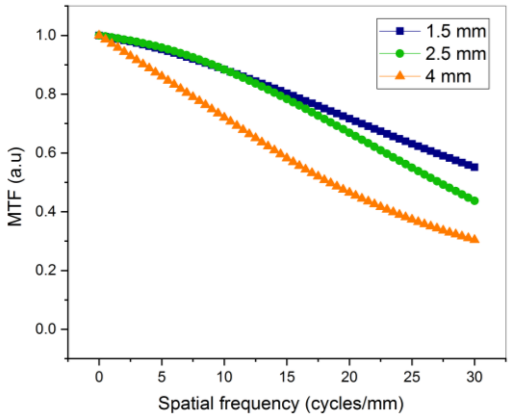
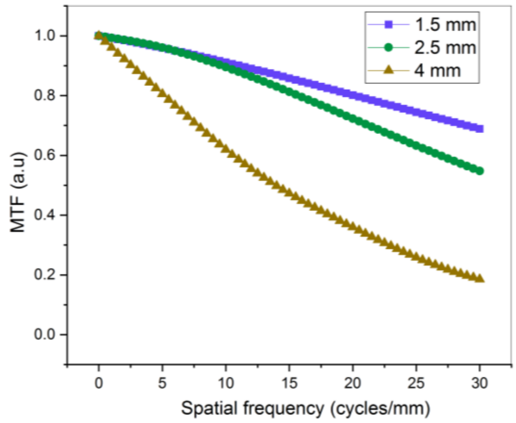


Fig. 11. Geometric images on retina of a) treated eye with IOL, and b) the patient eye.

The MTF was investigated for three different entrance pupil diameters (EPD), include 1.5, 2.5, and 4 mm [12], in daylight (as shown in Fig. 12).



(a)



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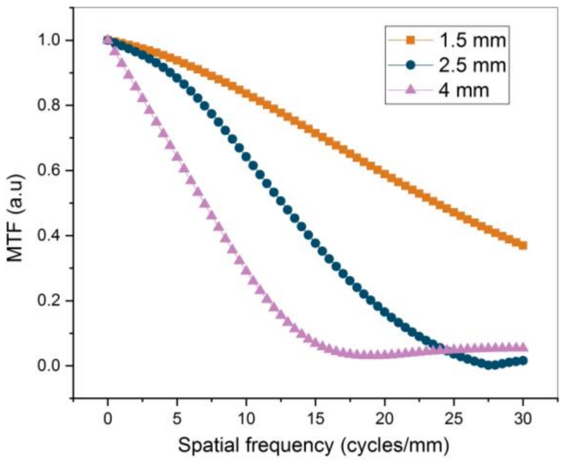

(c)

Fig. 1۲. The MTF comparison between the treated eyes for three pupil diameters in three vision modes: a) far, b) intermediate c) near.

Excellent aberration correction was observed at small EPDs in the three vision modes. However, the improvement diminished slightly at 4 mm EPD. It is obvious that increasing the EPD can lead to an increase in various types of aberrations, such as spherical aberration and coma. These aberrations can reduce the contrast of image formed on the retina, leading to a decrease in image resolution.

IV. Conclusion

Modeling of the eye and its diseases has critical role in the field of visual optics, specifically exploring the use of intraocular diffractive lenses to improve vision in patients. So, we have used Liou and Brennan's eye model to t the eye affected with cataracts accompanied by presbyopia. The results indicate that the use of multi-focal intraocular lenses leads to enhanced vision for patients at various distances. Spot diagram and Modulation Transfer Function graphs also confirm the improvement in patient vision. The study demonstrates that intraocular diffractive lenses can be a suitable option for treating patients with cataracts and presbyopia. These lenses improve image contrast and resolution, reduce dependence on glasses, and enhance the visual experience for patients.

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