Placement of a crystalline lens and intraocular lens: retinal image quality

Damian Siedlecki
Jerzy Nowak
Marek Zając
Wroclaw University of Technology
Institute of Physics
Wybrzeze Wyspianskiego 27
50-370 Wroclaw, Poland

Abstract. The influence of changes of both crystalline lens and intraocular lens (IOL) misalignment on the retinal image quality was investigated. The optical model of the eye used in investigations was the Liou-Brennan model, which is commonly considered as one of the most anatomically accurate. The original crystalline lens from this model was replaced with an IOL, made of rigid polymethylmethacrylate, in a way that recommend obligatory procedures. The modifications that were made both for crystalline lens and IOL were the longitudinal, the transversal, and the angular displacement. © 2006 Society of Photo-Optical Instrumentation Engineers. [DOI: 10.1117/1.2358959]

1 Introduction

The human eye is one of the most sensitive detection systems created by nature. About 80% of all information reaching our brains are the information derived from sense of sight. Therefore it is very important for the image created on the retina to have as a high quality as is possible. The quality of the image depends, among other things, on the shapes of surfaces that refract rays of light and on their mutual position. This refers particularly to the crystalline lens. An eventual misfit in the lens placement, which can be, for example, an effect of mechanical injury (stroke), can significantly decrease the retinal image quality, which can even result in the visual acuity change. The topic of lens alignment in the eye became especially essential in connection with increasingly rapid development of intraocular lens (IOL) implantation, employed in the cataract treatment. IOLs usually are implanted in a rather random way. This can result in the angular displacement of the IOL in relation to the optic axis, its vertical or longitudinal displacement. The aim of this work was to investigate the influence of changes of crystalline lens and the IOL alignment on the retinal image quality, generated both in mono- and polychromatic light. The authors also tried to determine the tolerances of IOL alignment inside the eye globe. An additional result of these investigations was the calculation of longitudinal chromatic aberrations of the anatomically accurate Liou-Brennan eye schematic model and the same model with an IOL implanted.

2 Methods

In the first step of our investigation, we determine the influence of the crystalline lens alignment on the retinal image quality. In this case, Liou's and Brennan's[1] optical system of

the eye was used, which is the most reliable model of the real eye.[2,3] The parameters of this eye model are given in Table 1. The crystalline lens used in this model consists of two gradient index media, which are insulated by a vertical surface of infinite radius. The gradient index distribution in the anterior medium is given by the following equation:

$$n_a(x,y,z) = 1.368 + 0.049057z - 0.015427z^2$$
$$- 0.001978(x^2 + y^2), \qquad (1)$$

and the gradient index in the posterior medium varies according to the following equation:

$$n_p(x,y,z) = 1.407 - 0.006605z^2 - 0.001978(x^2 + y^2). \quad (2)$$

In the present work, this eye schematic model was used to investigate how the properties of retinal image do change with the change of the horizontal displacement of the crystalline lens, the vertical displacement of the crystalline lens, and the angular displacement of the crystalline lens. The changes of lens alignment are presented in Fig. 1.

In the next step of the experiment, the influence of inaccuracy in the IOL's placement on the retinal image was investigated. To explore this, the authors also used the Liou-Brennan optical model of the eye, but the gradient index media which, simulated the crystalline lens, were replaced with a convex-plane IOL made of polymethylmethacrylate (PMMA). The PMMA is a rigid material, which is still being used in production and implantation of IOLs.[4–6] According to the accepted procedure,[7] the parameters of such IOL were selected. It was assumed that the A-constant of IOL used in simulations equals to 118. *A-constant* is a parameter that depends on the specifics of the IOL design (the value of this parameter is always given by the IOLs' manufacturer) and which is related to the position of the IOL within the eye. Then, if we have the value of A-constant, the axial eye length (AEL) equal to

Address all correspondence to Damian Siedlecki, Wroclaw University of Technology, Institute of Physics, Wybrzeze Wyspianskiego 27, 50-370 Wroclaw, Poland; Tel: +48–71–3202205; Fax: +48–71–3283696; E-mail: Damian.Siedlecki@pwr.wroc.pl

Table 1 The parameters of the Liou-Brennan eye schematic model.

Surface	Radius (mm)	Asphericity	Thickness (mm)	Refractive index at $\lambda = 0.555 \ \mu$m
1	7.77	−0.18	0.50	1.376
2	6.40	−0.60	3.16	1.336
3	12.40	−0.94	1.59	$n_a(x,y,z)$
4	infinity	—	2.43	$n_p(x,y,z)$
5	−8.10	+0.96	16.27	1.336

Table 2 The values of the normalized human eye sensibility function for wavelengths used in simulations.

Wavelength (μm)	Normalized eye sensibility
0.4861	0.18
0.5876	0.78
0.6563	0.04

23.95 mm according to Liou's and Brennan's eye model, and the total corneal power K of 42.11 D, the power of IOL, which replaces the original crystalline lens, was calculated from the Sanders-Retzlaff-Kraff (SRK) II formula:

$$IOL = A\text{-}constant - 2.5AEL - 0.9K \approx 20 \ [\text{D}]. \quad (3)$$

According to ISO standards,[8] the radius of curvature of the anterior surface of the convex-plane 20-D IOL made of PMMA is equal to 7.775 mm, and the axial thickness of such a lens is 0.9 mm. Next, according to Retzlaff,[9] the distance of such an IOL from the anterior surface of the cornea was calculated to be 4.96 mm. This distance was accepted by the authors as a reference distance for further calculations, and the IOL placed in this position was tilted and decentered.

Both in the case of the crystalline lens of the Liou-Brennan model and IOL, as a measure of retinal image quality the following quantities were accepted:
- Strehl ratio;
- spatial frequency for which the modulation transfer function (MTF) drops to a value of 0.5. This quantity seems to describe the characteristic of the MTF in a better way than the cutoff frequency because of numerical error of the simulations. For the use of this work, let this parameter be denoted with a symbol $\nu_{0.5}$.

Liou and Brennan gave also the dispersion formula that is valid for all media from their eye model

$$n(\lambda) = n(0.555) + 0.0512 - 0.1455\lambda + 0.0961\lambda^2, \quad (4)$$

where $n(0.555)$ refers to the value of the refractive index of a particular medium for the wavelength equal to 0.555 μm. For gradient index media, which are used in crystalline lens, this equation should be combined with Eqs. (1) or (2), respectively. The parameters of the above dispersion formula were matched in the way that the chromatic aberration of the theoretical model meets the values of chromatic aberration measured by Sivak.[10] So the chromatic aberration of the Liou-Brennan model stays in agreement with the chromatic aberrations of real eyes. Due to Eq. (4), it was possible to determine the properties of retinal image for a polychromatic
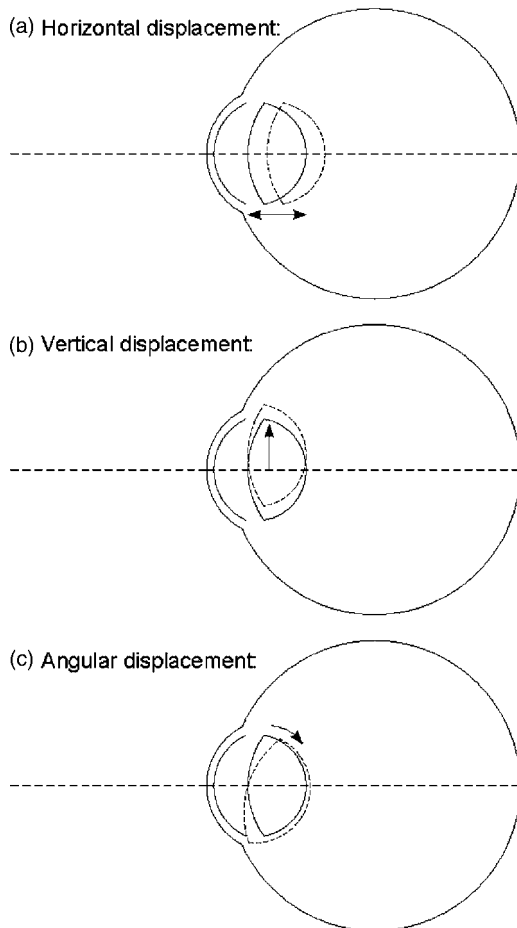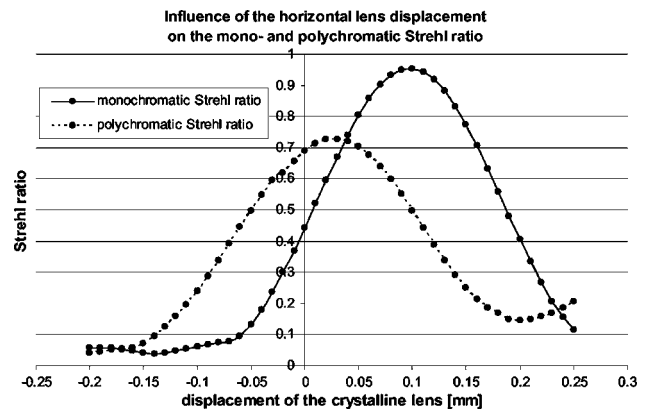

Fig. 1 A draft of changes in lens alignment used in calculations: (a) horizontal displacement, (b) vertical displacement, (c) angular displacement. Arrows indicate the direction of changes.

Fig. 2 Changes of mono- and polychromatic Strehl ratio with horizontal displacement of crystalline lens for the Liou-Brennan eye schematic model.
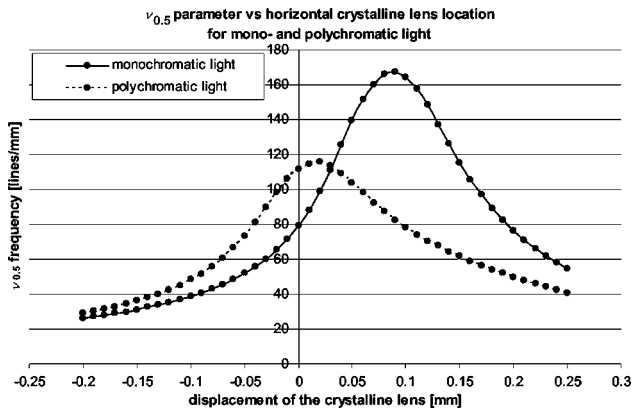
Fig. 3 Changes of $\nu_{0.5}$ frequency for mono- and polychromatic light with horizontal displacement of crystalline lens for the Liou-Brennan eye schematic model.

Fig. 5 Changes of $\nu_{0.5}$ frequency for mono- and polychromatic light with vertical displacement of crystalline lens for the Liou-Brennan eye schematic model.

light, for which also the Strehl ratio and $\nu_{0.5}$ parameter were calculated. The dispersion data of PMMA are given in literature.[11] To investigate the image properties in polychromatic light, the typical sensibility curve of the human eye[12] was used. The values of eye sensibility for three wavelengths taken into consideration are presented in Table 2. All the calculations were performed using the Zemax® Optical Design Program.

3 Results

Figures 2 and 3 present characteristics of changes of the Strehl ratio and the frequency $\nu_{0.5}$ with the longitudinal deposition of the crystalline lens with reference to the position of 3.66 mm measured from the anterior corneal surface (see Table 1).

These diagrams indicate the fact that, although particular parameters of the Liou-Brennan model were matched for the wavelength 0.555 μm, this model in the retinal plane fits much better with the real eye in the polychromatic light than in the monochromatic light. First, the position of the crystalline lens corresponding to the maximum of Strehl ratio in the polychromatic light occurs closer to the reference position of
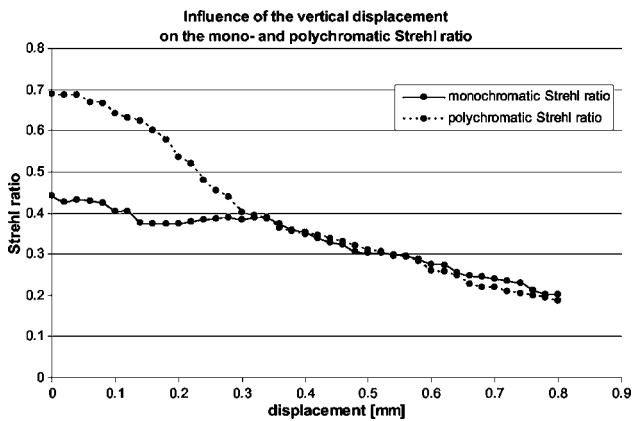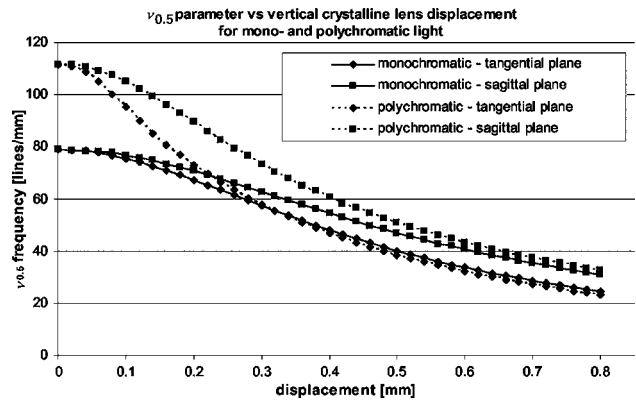
the lens given by the authors of the model than in the monochromatic light (about 0.08 mm). Second, for the distance given by Liou and Brennan (3.66 mm), the value of the Strehl ratio is about 1.5 times higher for poly- than for monochromatic light. Also the frequency $\nu_{0.5}$ is higher for polychromatic light. Both these facts prove that the point spread function (PSF) in the polychromatic light is higher and narrower than in the monochromatic light, which results in better imaging in polychromatic light.

Figures 4 and 5 show the mono- and polychromatic Strehl ratio and frequency $\nu_{0.5}$ in the tangential and sagittal plane as a function of transversal dislocation (decentration) of crystalline lens. The analysis of the Fig. 4 also confirms the statement that the Liou-Brennan eye model ensures better imaging in polychromatic light than in monochromatic light. To the value of vertical displacement of 0.3 mm, the polychromatic Strehl ratio is much higher than its monochromatic equivalent. For higher vertical displacements, both Strehl ratios are practically equal. Also the frequencies $\nu_{0.5}$ for polychromatic light are higher than for monochromatic light. It is interesting that the higher the values of vertical displacement are the closer the values of frequencies calculated for the polychro-
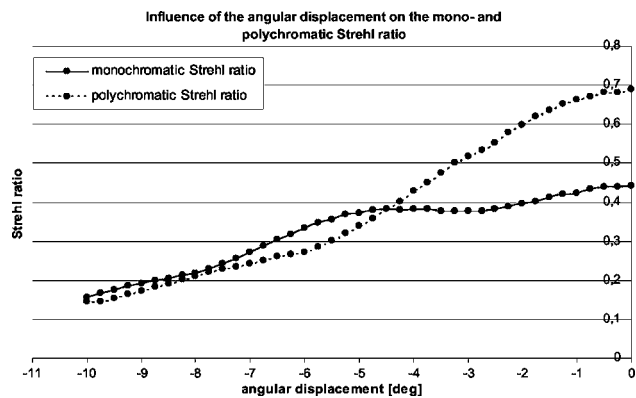

Fig. 4 Changes of mono- and polychromatic Strehl ratio with vertical displacement of crystalline lens for the Liou-Brennan eye schematic model.

Fig. 6 Changes of mono- and polychromatic Strehl ratio with angular displacement of crystalline lens for the Liou-Brennan eye schematic model.
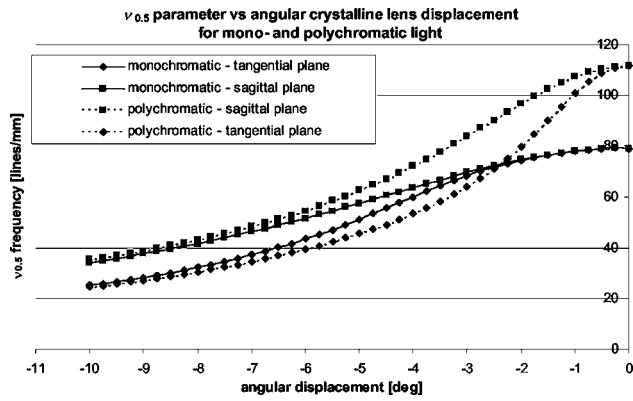
Fig. 7 Changes of $\nu_{0.5}$ frequency for mono- and polychromatic light with angular displacement of crystalline lens for the Liou-Brennan eye schematic model.

Fig. 9 Changes of $\nu_{0.5}$ frequency for polychromatic light with horizontal displacement of IOL.

matic light are to the values of frequencies calculated for the monochromatic light—this effect is observed in both the tangential and sagittal planes.

In Figs. 6 and 7, the mono- and polychromatic Strehl ratio and frequency $\nu_{0.5}$ in the tangential and sagittal planes as a function of angular displacement of the crystalline lens are presented. These figures show that for the angular displacement of about −4.5 deg the imaging in polychromatic light is better and the retinal image has higher quality. For angular displacements greater than ±4.5 deg, the values of the mono- and polychromatic Strehl ratio are almost equal. The situation is similar for the $\nu_{0.5}$ parameter. Similar to the case of vertical displacement of crystalline lens, a significant decrease of changes between mono- and polychromatic images is clearly visible.

The next step was to investigate the image quality while the crystalline lens (according to the Liou-Brennan model) was replaced by the IOL. The reference position of IOL was calculated in agreement with obligatory procedures and standards. Figures 8 and 9 present the influence of longitudinal displacement of IOL and $\nu_{0.5}$ parameter, respectively. The first fact, which can be noticed, is a significant deterioration of image quality, when IOL is located in the standard position (Strehl ratio about 0.28) in comparison to the image given by
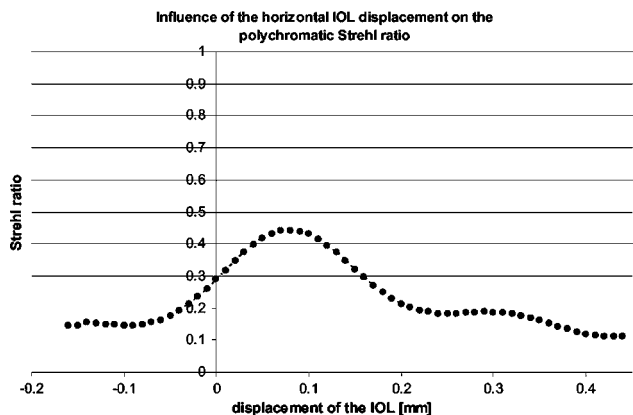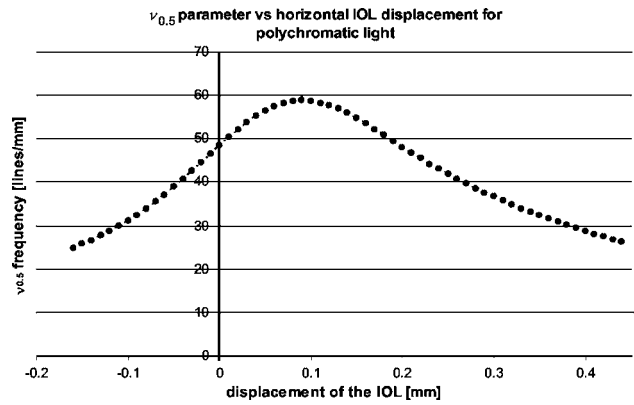
the Liou-Brennan model (polychromatic Strehl ratio about 0.69, see Fig. 3). However, shifting the IOL by ~0.1 mm toward the retina causes an increase in the Strehl ratio up to 0.45. The same conclusion follows from the analysis of the dependence of $\nu_{0.5}$ frequency on the IOL shift. For IOL located in the standard position, $\nu_{0.5}$ parameter is equal to 49 lines per millimeter, while for IOL shifted 0.9 mm toward the image plane, it is equal to 59 lines per millimeter.

The influence of vertical displacement of IOL on the polychromatic Strehl ratio and $\nu_{0.5}$ parameter is presented in Figs. 10 and 11. If one compares these figures to Figs. 4 and 5, a noticeable difference can be seen. In the case of IOL, the values of Strehl ratio and $\nu_{0.5}$ parameter first slightly increase and then decrease. The range of Strehl ratio changes for the vertical displacements between 0 and 0.96 mm equals about 50% of its maximum value.

Influence of angular displacement of IOL on the polychromatic image quality is presented in Figs. 12 and 13.

At this point, the chromatic aberration was taken under consideration. Figure 14 shows the longitudinal chromatic aberration of the anatomically accurate model by Liou-Brennan. Figure 15 shows the analogous aberration for the same model with "implanted" IOL. The IOL is located in the standard position of 4.96 mm from the anterior corneal surface, but with shift of 0.2 mm does not cause any significant changes
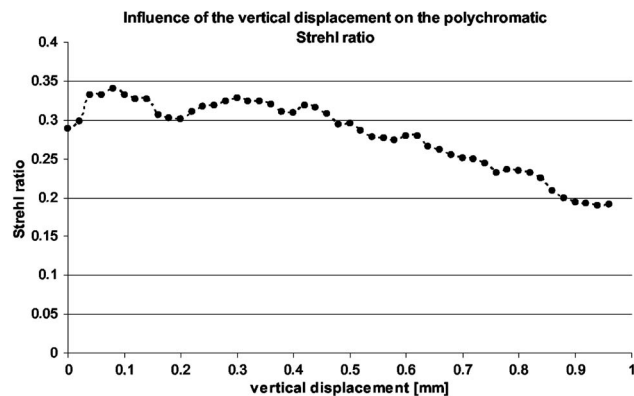

Fig. 8 Changes of polychromatic Strehl ratio with horizontal displacement of IOL.

Fig. 10 Changes of polychromatic Strehl ratio with vertical displacement of IOL.

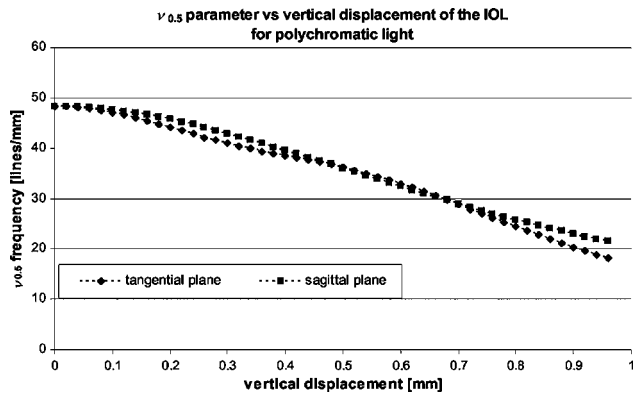**Fig. 11** Changes of $\nu_{0.5}$ frequency for polychromatic light with vertical displacement of IOL.

Fig. 13 Changes of $\nu_{0.5}$ frequency for polychromatic light with angular displacement of IOL.

in the curve of the chromatic focal shift. During simulations, the maximum focal shift range (calculated for 0.400 μm $\leq \lambda \leq 0.700$ μm) varies from the value of 633.94 μm for the IOL positioned 0.2 mm further from the cornea to the value of 634.57 μm for the IOL positioned 0.2 mm closer to the cornea. Such a small change in the values means that the influence of the IOL position on the total chromatic aberration is neglectably small. On the basis of these two characteristics, it can be concluded that the chromatic aberration of the eye with the implanted IOL has the same sign as the Liou-Brennan model, but its magnitude is almost two times larger than the chromatic aberration of the model by Liou-Brennan, which significantly corresponds to chromatic aberration of the real eye. It is connected with the chromatic dispersion of PMMA material that the IOL is made of. It is higher than the dispersion of a real crystalline lens.

4 Conclusions

The present simulations concerning the eye schematic model of Liou and Brennan showed that for the monochromatic light of wavelength 0.555 μm, for which the parameters of this model were chosen, the optimum imaging (maximum Strehl ratio) occurs for a slight displacement of the crystalline lens—0.12 mm closer to the retina than was proposed by the authors of the model. Therefore, it seems that this model was
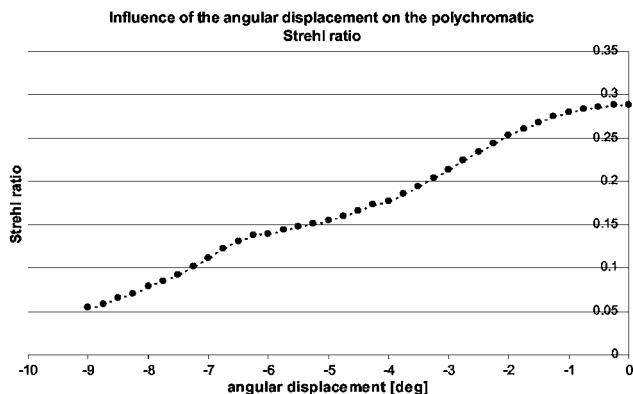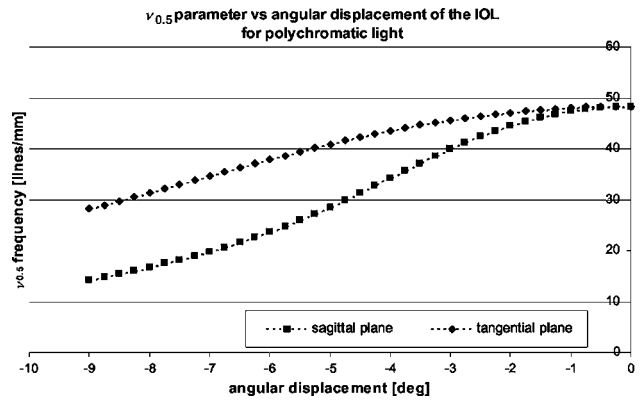
developed with the use of paraxial methods. However, if one uses the polychromatic light with parameters adjusted to the human eye sensibility curve, then adapts the dispersion formula given originally by Liou and Brennan to all of the ocular media, and if one calculates the image quality with use of diffraction methods, it appears that an improvement to be done, in order to ensure the optimal projection on the retina, is negligibly small. To conclude, it appears that this model is very reliable also in polychromatic light.

Investigations concerning the influence of crystalline lens localization on the retinal image quality have shown that the tolerance of lens alignment is relatively high—both in the case of the lens longitudinal and the vertical displacement and the tilt. A very interesting conclusion is the fact that, for higher changes in the lens localization, the Liou-Brennan eye model is able to project exactly the same frequencies both in mono-as in polychromatic light—in both perpendicular planes, that is, tangential and sagittal.

The optical system of the eye with an IOL instead of the crystalline lens ensures significantly worse imaging in the meaning of physical terms. If one compares Fig. 2 to Fig. 8 and Fig. 3 to Fig. 9, it can be concluded that the polychromatic Strehl ratio for such system is almost 40% lower than for Liou's and Brennan's model, and the $\nu_{0.5}$ parameter, which
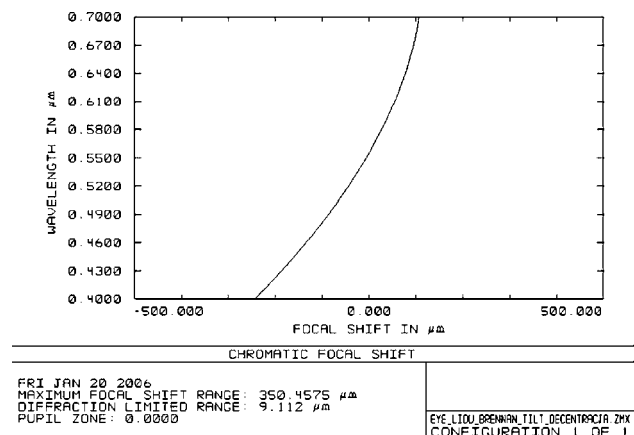

Fig. 12 Changes of polychromatic Strehl ratio with angular displacement of IOL.

Fig. 14 Chromatic focal shift of the Liou-Brennan eye schematic model.

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FRI JAN 20 2006
MAXIMUM FOCAL SHIFT RANGE: 634.2483 μm
DIFFRACTION LIMITED RANGE: 8.468 μm
PUPIL ZONE: 0.0000
                                    EYE_LIOU_BRENNAN+PMMA 2 NORM.ZMX
                                    CONFIGURATION 1 OF 1
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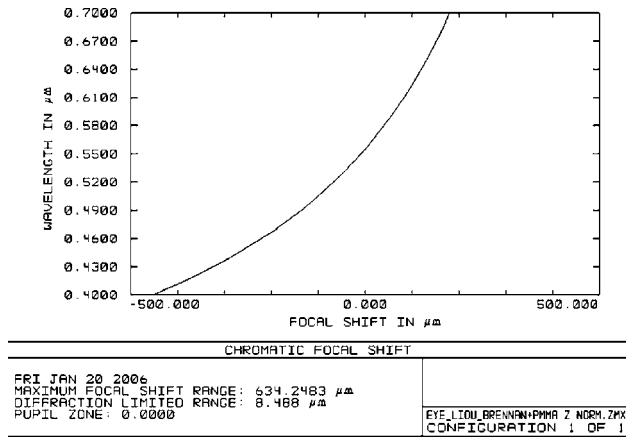
Fig. 15 Chromatic focal shift of the eye schematic model with a PMMA IOL "implanted."

characterizes the MTF as about 50% lower. Although, the IOL alignment in the eye has a relatively high tolerance. For example, the vertical displacement has no significant influence on the image quality measured with the Strehl ratio (only 15% change of Strehl ratio within the range of 0.5 mm of vertical displacement—see Fig. 10). However it may cause the retinal image dislocation, which can result in noncentral fixation. The tolerance of the transversal dislocation of IOL is relatively high. If one takes the longitudinal dislocation under consideration, and if one assumes that admissible decrease of Strehl ratio is about 20%, then the admissible dislocation of IOL should not be higher than 0.7 mm. Analogous conclusion can be drawn on the basis of analysis of $\nu_{0.5}$ frequency for which the MTF drops to the value of 0.5. In the case of the angular displacement of IOL—if we accept the same criterion—the tolerance is about 3 deg.

The chromatic aberration of the Liou-Brennan model meets the chromatic aberration of the real eye. For this model, the chromatic focal shift is about 350 μm. This value corresponds to the chromatic aberration of the range 1.5 to 1.7 D, which are the values of chromatic aberration of a real eye. The chromatic aberration of the eye model with the IOL instead of the crystalline lens is significantly higher (about 3 D). This level of chromatic aberration may cause discomfort of vision for patients with such an IOL implanted.[13,14] It might be possible to match the IOL parameters so that the chromatic aberration of the system eye−IOL equals the chromatic aberration of a real healthy eye and the discomfort is reduced, by an appropriate design of an IOL. One of the methods to obtain such correction is the use of diffractive elements that already are used in implantology; however, they play a completely different role—they are elements forming "the second focus point" in the multifocal IOLs.

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