Presbyopia compensation with a light sword optical element of a variable diameter

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Abstract—This paper presents the preliminary results of numerical analysis of imaging quality of a refractive light sword optical element (LSOE) in the function of its diameter. For comparison other optical imaging elements with extended focal depth, such as the bifocal lens, and the forward axicon, were also checked. The parameters of all elements were assumed according to the human eye parameters in order to check possibilities of presbyopia compensation. Obtained results allow to state that contrary to other analyzed elements neither LSOE's performance nor the length of a focal segment depends on its diameter.

Accommodation, i.e., the ability of the human eye to change its power by changing the shape of a crystalline lens is gradually decreasing as the person ages. This dysfunction, termed as presbyopia, becomes apparent about the age of 40-50, when accommodation ability becomes significantly smaller than required 4 dioptres and the presbyopic subject begins to need to wear reading glasses. Proposed solutions of this problem consist in replacing natural crystalline lenses by multifocal intraocular lenses (MFIOL), which implies an invasive eye operation. There are two main kinds of MFIOL: refractive [1] and diffractive [2]. The performance of both types of MFIOL was recently compared [3]. Other proposed solutions are multifocal contact lenses or correction of both eyes for near and distant vision separately (monovision).

Our study is aimed for non-invasive contact lenses with an expanded depth-of-field. We compare imaging properties of a bifocal lens with 2 zones of different optical power (The LifeStyle Company Inc., Morganville, NJ) with results attainable by means of a forward axicon [4-6] and LSOE [7-9]. Imaging simulations were performed assuming a simple model of the human eye containing contact lens, iris and one lens representing the optical power of the whole eye. The optical power of the human eye accommodated on infinity was taken equal to 60 dioptres. Additional optical power of up to maximum 4 dioptres was provided by a contact lens correcting presbyopia.

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An LSOE is a thin optical element, which phase function has the following form in the polar coordinate system:

$$\Phi(r) = -\frac{kr^2}{2\left[f + \left(\Delta f \theta / 2\pi\right)\right]}, \tag{1}$$

where r, θ are respectively the radial and angular coordinates, $k=2\pi/\lambda$ and λ is the wavelength of light. The parameters f and Δf define the focal length and the focal range of the element. For a fixed value of the angular coordinate θ the phase function $\Phi(r)$ is equivalent to that of a Fresnel lens with a focal length $f+\Delta f\,\theta/2\pi$. Therefore in the first approximation the LSOE focuses an incident plane wave into a focal segment of width Δf. When $\theta \in [0,2\pi)$, then the segment is stretched from a distance f to a distance $f+\Delta f$ behind the LSOE plane. According to the ray tracing method based on the paraxial approach, an infinitesimal angular sector of the LSOE focuses light into a small line segment instead of a point lying on the optical axis. This segment is oriented perpendicularly to its sector [8], [9]. Therefore focusing realized by the LSOE has an off-axis character. The focal spots corresponding to different output focal planes rotate around the optical axis. Owing to the off-axis focusing, energy flow changes its main direction and therefore mutual disturbance between focal spots or images corresponding to different focal lengths is not very harmful. In consequence, the point spread functions and modulation transfer functions almost conserve their shape and character for a wide range of defocusing parameters.

Therefore the LSOE exhibits superiority for imaging with an extended depth of focus over optical elements with symmetry of revolution and its applicability for presbyopia compensation could be expected.

The best solution for the problem of presbyopia would be an optical element which can image sharply for all distances. It could be an element with mechanical accommodation (variable optical power or variable position) or element focusing light into a segment along the optical axis. The first solution needs to replace the crystalline lens with an artificial lens which can change its focal length or its distance to the retina. It means that it must be applied in an invasive medical operation. The second solution requires specially designed contact lenses and is not invasive. In this work we analyze these elements as additions of specially designed aberration to the crystalline lens.

The human eye can be studied as an optical imaging system containing a lens, iris and retina as a screen. Additionally, the human eye exhibits abilities of accommodation (optical power changes) and adaptation (light intensity changes). We neglected the complicated structure of the eye assuming for the needs of our analysis that the distance between the main surface of the whole eye's optical system and retina is 16,667 mm. Such an eye needs the optical power of 60 D to see far objects and 64 D for a reading distance equal to 25 cm. The focal distance of this lens should then change from 15,625 mm to 16,667 mm, hence the length of the focal segment has to be only 1,042 mm. This range will make it possible to perceive sharply objects in the distance from d_p=25 cm to infinity ($d_w \rightarrow \infty$). Additionally, we suppose that the iris diameter in normal conditions is R=4,5 mm. We assumed that the presbyopic eye completely lost accommodation so its optical power is 60 D and images sharply only distant objects.

In our simulation a quartic forward axicon was assumed i.e., a lens with spherical aberration being an approximation of a logarithmic axicon. The phase function of this axicon was taken after ref. [4]. In the case of forward axicon rays from the inner part of the axicon cross the optical axis before rays from the outer part and consequently its phase function can be written as follows:

$$\Phi(r, \quad \theta) = -k\left(r^2/2d_p - Ar^4\right). \tag{2}$$

On the other hand, the phase function of the LSOE given in Eq.(1) after making similar approximation is expressed by:

$$\Phi(r, \quad \theta) = -k\left(r^2/2d_w + B\theta r^2\right). \tag{3}$$

We wanted to identify the first term with an eye lens and the second term with aberration, thus Eq.(2) will be rearranged as follows:

$$\Phi(r, \quad \theta) = -k\left[r^2/2d_w + \left(A_{dd}r^2/2\right) - Ar^4\right], \tag{4}$$

where $A_{dd}=1/d_p-1/d_w$. The parameters A and B can be found by boundary conditions for the ray-tracing equation for analyzed elements. This equation is given by:

$$\frac{d\Phi(r, \quad \theta)}{dr} = -\frac{r}{d(r, \quad \theta)}, \tag{5}$$

where $d(r,\theta)$ is the local focal length. Putting boundary conditions into this equation we obtain:

$$A = -\frac{A_{dd}}{4R^2}, \qquad B = \frac{A_{dd}}{4\pi}. \tag{6}$$

In the simulation parameters of the modeled element were assumed to be similar to Accuvue Bifocal (Johnson & Johnson Vision Care, Inc., Jacksonville, FL). Bifocal lens was composed of central circular zone of radius 0,97 mm with no optical power designed for far vision, followed by annular region from 0,97 mm to 1,60 mm with optical power 4 D (near vision). The peripheral part of the lens surface was also designed for far vision (O D of optical power). This contact lens was composed of a 60 D lens representing the eye's optical power.

We simulated the imaging properties of described elements by calculating the convolution of its point spread function with an ideal image. As an object we used the Snellen 20/20 E optotype. According to the assumed simulation method, the size of an imaged object varies so as to produce an image of constant height. The Snellen optotype size was designed with an angular extent of 5 minutes of height and 1 minute of width for details.

The diameter of the eye's iris is not constant. According to this fact we checked how a decrease in the aperture diameter changes the imaging properties of a lens with designed aberrations. In Figures 1 and 2 we present the results of imaging simulations by the same elements with a decreased aperture. For every element in two columns a series of images with an aperture 2 mm and 4,5 mm are shown.

In Figure 1 one can see a growing depth of focus with a decreasing aperture for the presbyopic eye. In the case of the bifocal lens and forward axicon a smaller aperture leads to elimination of regions with specific optical power and disappearance of some focus points and related sharp images.

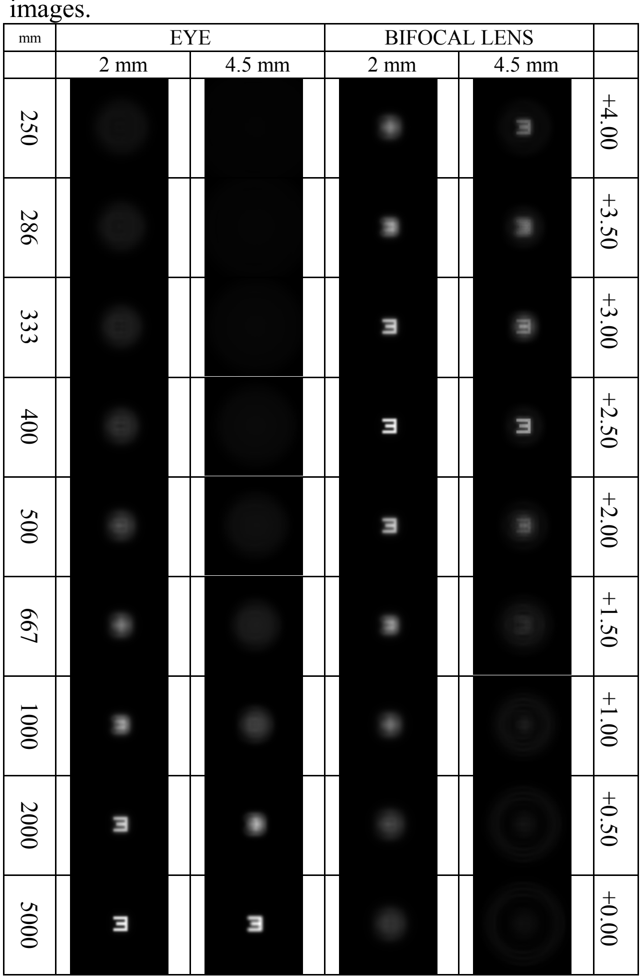

Fig. 1 Results of imaging simulations for the presbyopic eye and the eye corrected with a bifocal contact lens with its aperture (iris) diameter of 2mm and 4,5 mm. The first column shows object distances.

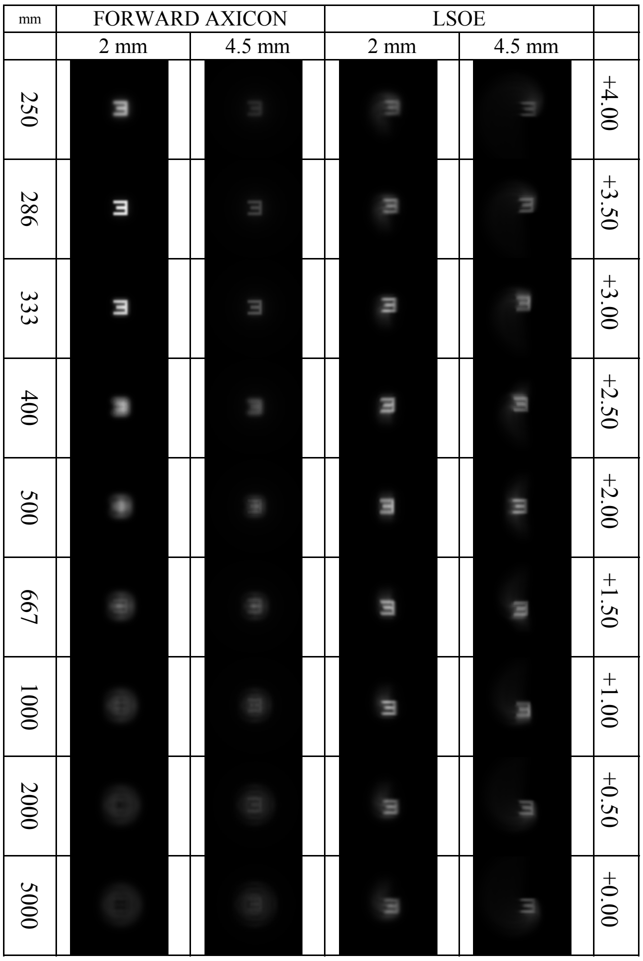

Fig. 2 Results of imaging simulations for an eye lens with spherical aberration and linear angular aberration (LSOE) with an aperture (iris) diameter of 2mm and 4,5 mm. The first column shows object distances.

On the other hand, in the case of an LSOE it can be seen that its imaging properties does not become worse with a decreasing aperture. Additionally, we can see that the contrast of images increases (normalized to the contrast of an eye image in infinity).

In conclusion, it can be stated that the light sword optical element has many advantages in non-invasive correction of accommodation loss. Contrary to other elements, its optical power does not depend on the aperture [10-12] or, consequently, on the variations of iris diameter due to the varying conditions of illumination. Moreover, the quality of obtained images is better than in other cases, both in terms of resolution as well as focus depth. On the other hand, the image changes slightly its position for different points along the focal segment.

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