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Determination of positions of optical elements of the human eye

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***Abstract*. An original method for noninvasive determining the positions of elements of intraocular optics is proposed. The analytic dependence of the measurement error on the optical-scheme parameters and the restriction in distance from the element being measured are determined within the framework of the method proposed. It is shown that the method can be efficiently used for determining the position of elements in the classical Gullstrand eye model and personalised eye models. The positions of six optical surfaces of the Gullstrand eye model and four optical surfaces of the personalised eye model can be determined with an error of less than 0.25 mm.**

Keywords: *optical eye model, wavefront, correlation function.*

1. Introduction

The quality of vision can be improved by different methods, for example, by using conventional contact lenses or glasses. However, it is often inconvenient for sportsmen, travellers and reading people, while good vision for pilots, policemen, and drivers is very important. Therefore, such people need vision-correction operations.

Refractive surgery has undergone a long evolutionary development for the last fifty years [1 – 3]. However, the widely applied methods of refractive laser surgery correct mainly sphero-cylindrical errors as the most widespread aberrations of the human eye. The authors of a number of papers devoted to the discussion of the results of operations [4 – 7] point out the increase to some or another degree in the higher-order eye aberrations such as coma or spherical aberrations, which sometimes considerably deteriorate the vision quality. It is known that refractive operations produce sometimes complications such as flicker, doubling, halo around objects, etc. As a rule, these complications are manifested at the night time, when the pupil of a patient is expanded. It is the fear of such complications that repels many potential patients from the procedure of laser correction of vision.

When conventional methods of diagnostics such as keratoscopy, aberrometry and pupillometry are used [7, 8], only 2/3 of operations prove to be successful [3, 4]. Moreover, the vision quality is deteriorated at all in a number of cases [3 – 7]. It was pointed out [4] that to calculate the correct shape of a cornea at which the best vision quality is achieved, it is necessary to take into account the geometrical position of the optical elements of the eye. The methods for determining the optical structure of the eye being developed at present are based on the solution of the inverse problem, when the parameters of the human eye being simulated (for example, the radius of curvature, the refractive index of the crystalline lens, etc.) are fitted by measured total aberrations [9 – 11]. It is obvious that such an approach is basically ambiguous and therefore cannot yield reliable results.

In this paper, we propose an original method for direct measurements of the position of optical elements of the eye for constructing accurate personalised optical models of patient eyes.

2. Method for determining positions of elements of intraocular optics

The original method for measuring the position of optical elements of the human eye was developed taking into account the possibility of measuring the total aberrations of the eye and consists in the following. By using laser radiation sources, two separated point sources are produced on the eye retina. After scattering from the retina surface, radiation beams from these sources propagate in the opposite direction, acquiring phase incursions determined by the aberrations of elements of the intraocular optics (Fig. 1). The local tilts of the wavefronts of the beams are simultaneously measured in a plane optically conjugated with the cornea by using a Shack – Hartmann sensor [12] consisting of a CCD camera and a microlens raster. The microlens raster quantizes the wavefront, measuring its local tilts as the average gradient of the phase by each of the microlenses. Then, the spatial correlation function of the wavefront tilts of the first and second beams is calculated and averaged in time. The correlation function is described by the expression

$$C(\delta) = \left\langle \sum_{i,j} s_{ij}(t) s'_{i+\delta,j}(t) \right\rangle,$$

where $s_{ij}(t)$ and $s'_{ij}(t)$ are the local tilts of wavefronts on the (i, j) microlens of the Shack – Hartmann sensor for the first

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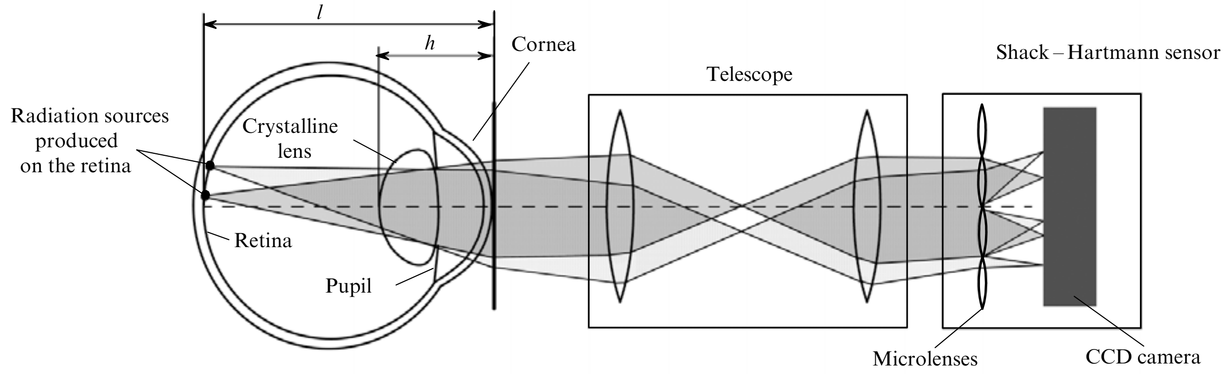

Figure 1. Determination of the positions of optical elements of the human eye (h is the distance from the cornea top to the optical element surface, l is the eye depth).

and second beams, respectively; i and j are the numbers of microlenses of the raster along the x and y axes, respectively; $i, j = 0, 1, 2, \ldots N$; N^2 is the number of microlenses; and δ is the increment of the number i of a microlens along the x axis ($\delta = 0, \pm1, \pm2, \ldots$). Because light beams pass through the same optical elements, the correlation function has peaks corresponding to these optical elements: several surfaces of the crystalline lens, two surfaces of the cornea, etc. The displacements of the correlation peaks with respect to the 'centre' ($\delta = 0$) depends on the location of optical elements to which these peaks correspond. We obtained the dependence of the distance h from the cornea top to an optical element on the correlation-peak displacement $\varDelta_{\mathrm{s}}$ from geometrical considerations. It has the form

$$h(\varDelta_{\mathrm{s}}, \varphi, l) = \frac{\varDelta_{\mathrm{s}}}{\varphi/d + \varDelta_{\mathrm{s}}/l}. \tag{1}$$

Here, φ is the angle between the beams; d is the microlens size; and l is the eye depth. The measurement error δ_h of h is described by the expression

$$\delta_h = \sqrt{(\mathrm{d}h_\delta)^2 + (\mathrm{d}h_l)^2}$$

$$= \sqrt{\left[\frac{d}{\varphi l^2}(l-h)^2\delta_\varDelta\right]^2 + \left[\left(\frac{h}{l}\right)^2\delta_l\right]^2}, \tag{2}$$

where $\delta_\varDelta$ is the measurement error of the correlation-peak position and δ_l is the measurement error of the eye depth. The error δ_h nonlinearly depends on the distance to an optical element. It can be minimised by changing the angle φ.

The maximum distance $h_{\max}$ measured by this method is determined by the angle φ between the beams and the diameter D of the beams on the sensor:

Table 1. Parameters of the Gullstrand human eye model.

Surface number	Surface	Radius of curvature/mm	Thickness/mm	Refractive index
1	External surface of the cornea	−7.7	0.5	1.376
2	Internal surface of the cornea	−6.8	3.1	1.336
3	External surface of the crystalline lens	−10.0	0.546	1.386
4	External surface of the crystalline-lens core	−7.911	2.419	1.406
5	Internal surface of the crystalline-lens core	5.76	0.635	1.386
6	Internal surface of the crystalline lens	6.0	16.8	1.336

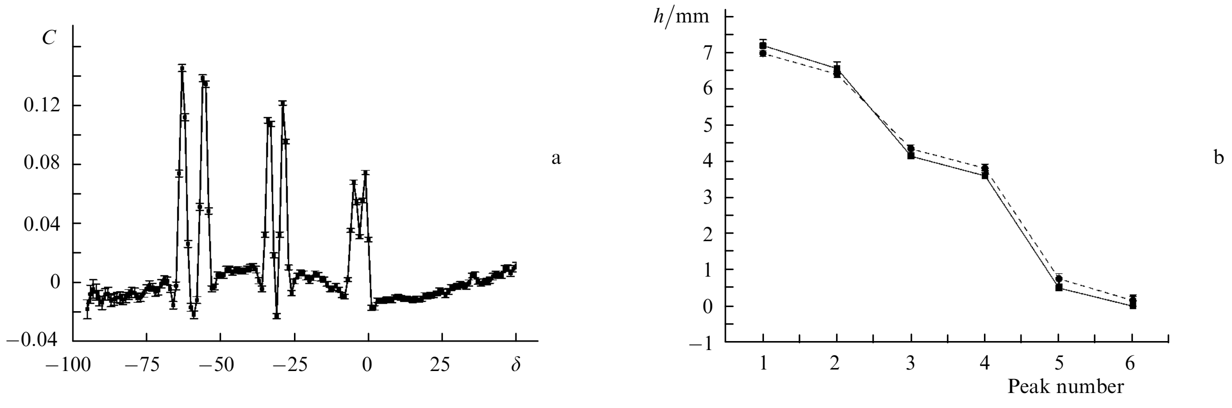

Figure 2. Correlation function $C(\delta)$ obtained for the Gullstrand model at $d = 39$ μm (a), and measured (●) and specified (■) distances h from eye elements to the cornea (b).

Table 2. Parameters of the personalised mathematical model of the right eye of patient AD.

Surface number	Surface	Radius of curvature/mm	Conic constant	Thickness/mm	Refractive index
1	External surface of the cornea	−7.72	−0.26	0.55	1.373
2	Internal surface of the cornea	−6.5	0	3.05	1.334
3	External surface of the crystalline lens	−10.2	−3.0	4.0	1.416
6	Internal surface of the crystalline lens	6.0	−1.0	16.55	1.333

$$h_{\max} = \frac{Dl}{2l\tan(\varphi/2) + D}. \qquad (3)$$

The application of this method for determining the position of optical elements of the eye was tested by using the classical Gullstrand model [13, 14] (Table 1). Note that this method operated efficiently if the correlation function is averaged over a sufficient number of measurements of the eye aberrations of a patient. Because the Gullstrand model does not describe fluctuations of human eye aberrations [15, 16], we specified random phase perturbations on the optical surfaces of the model. In addition, to describe the behaviour of higher-order aberrations within the framework of the Gullstrand model, we introduced additional small-scale aberrations of optical surfaces. The obtained results are presented in Fig. 2. One can see that the correlation function has six peaks corresponding (from left to right) to the internal surface of the crystalline lens, the internal surface of the crystalline-lens core, the external surface of the crystalline-lens core, the external surface of the crystalline lens, the internal surface of the cornea, and the external surface of the cornea. The method proposed in the paper determines the positions of all the six optical surfaces with an error of smaller than 0.25 mm. For the personalised model* (Table 2), we obtained similar results.

3. Conclusions

We have proposed the original method for measuring the positions of elements of the intraocular optics. The method is based on measurements of the wavefront of two reference sources with a wavefront sensor, which allows the simultaneous measurement of the eye aberrations of a patient. The possibility of accurate measurements of the optical elements of the human eye is an important step in the development of the adequate personalised human eye models.

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[*] The personalised eye model [9], developed based on the Navarro mathematical human eye model [17], consists of four conic surfaces. To describe experimental axial and off-axial aberrations, the model parameters such as conical constants of surfaces, the eye depth, the pupil displacement, etc. were optimised.