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CATARACT

Depth of focus in pseudophakic eyes

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Abstract
Purpose To assess depth of field/depth of focus in pseudophakic eyes as function of visual acuity. Setting: Department of ophthalmology of National Medical Academy of Postgraduate Education.
Methods Forty-three pseudophakic eyes of 43 patients after implantation in the capsular bag of monofocal posterior chamber IOLs were examined. All patients had visual acuities at least 20/20 for distance. Visual acuity was examined by charts consisting the Landolt's rings under defined constant illumination within distance from 3 m to 20 cm from patients' eyes at various distances with difference of 10 cm (29 measurements). Depth of field was calculated in diopters.
Results The mean value of the depth of field in pseudophakic eyes with pupil diameter of 3±0.3 mm was as follows: 1.12 D for visual acuity 20/20, 0.62 D for visual acuity 20/13, and 0.47 D for visual acuity 20/10.
Conclusions Depth of focus correlates to normal levels of visual acuity. The higher the visual acuity, the lower the depth of focus. The ability of clear vision due to depth of focus-pseudoaccommodation is passive function. Separating the pseudoaccommodation from artificial accommodation in eyes with accommodative IOLs requires strict standardization of methodology especially regarding diameter of pupil, size of test objects, and level of illumination.

Keywords Depth of focus · Apparent accommodation · Amplitude of accommodation · Pseudoaccommodation · Visual acuity

Introduction

Depth of focus of optical system of the human eye is variation in image distance which can be tolerated without incurring an objectionable lack of sharpness in focus projected into free space; this dioptric interval defines the depth of field of the eye [1]. An important consequence of physiological optical aberrations is the existence of significant depth of focus. In previous studies, investigators obtained controversial data regarding the depth of focus from ±0.02 D (Oshima) to ±1.25 (von Bahr) [2–9]. The depth of focus is no longer considered a subject of theoretical speculation. It has become an important practical application, for instance, in the evaluation of efficacy of accommodating IOLs .

This article reports on our findings regarding the measurement of the depth of focus in pseudophakic eyes.

Material and methods

Patients

Examination was made on 43 eyes of 43 patients with a mean age of 58.7±9.1 (ranged from 35 to 78 years). The surgery involved phacoemulsification through clear cornea incision and implantation of one of two types of monofocal

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posterior chamber IOLs in the capsular bag. Thirty-two eyes received AcrySof MA60AC and 11 eyes SA60AT (Alcon Laboratories). All surgeries were performed at the Eye Microsurgery Centre, Kiev, Ukraine by one surgeon (Y. N.K.). The mean postoperative follow-up was 8.3 months (ranging from 4 to 18 months). Postoperative workup included slit-lamp examination, pupil size measurement, autorefractometry, ophthalmometry, and best corrected visual acuity (BCVA) examination. All patients had BCVA of at least 1.0 for distance (5 m). Exclusion criteria were the pupil diameters less than 2.7 mm and larger than 3.3 mm. Patients with PCO, induced corneal astigmatism more that 1.0 D, opacity of ocular media or retinal diseases were also excluded from the study. All participants were informed about the investigational nature of the procedure and their written informed consent was obtained.

Apparatus and method

The approach used in the evaluation of the depth of field consisted in placing visual acuity charts at various distances from patients whose visual acuity was tested. All the experiments were performed in the same room with uniform artificial illumination of 210 lux.

A board for fixation of visual acuity charts illuminated by two lamps was mounted on a movable platform (Fig. 1). Visual acuity was examined at a distance of 3 m to 20 cm from patients' eyes at intervals of 10 cm (3 m, 2.9 m, 2.8 m, 2.7 m, etc., down to 0.2 m). The patient's head was stabilized by means of a forehead rest. The other eye was covered. The set of optotypes consisting of Landolt's rings were designed to test visual acuity at the defined test distances. Visual acuity at the every distance was calculated by equation V = d/D in which V is visual acuity, d the distance used for examination and D the distance on which the optotype fulfills the demand of 1′ visual angle".

Visual results were registered in the protocol if the patient had correctly located opening of the Landolt's ring in at least four of the six attempts. All tests were performed in the same room under the same illumination conditions. The gained data was imported into the computer program. A schematic representation of the received data of visual acuity expressed in minutes of arc was made for each eye investigated. Figure 2 shows results of the examination of the eye with visual acuity of 20/10. The depth of field defined by the area *pr* of the highest visual acuity is regarded as the depth of field which was calculated in diopters by the following formula:

$$F = 1/P - 1/D$$

Where F = depth of field, P = distance to the near point of the depth of field, D = distance to the far point of the depth of field.

The statistical analysis was performed by Statistica for Windows 5.0 (Stat Soft Inc.). The data are presented as means and standard deviations. A P value less then 0.05 was considered as significant.

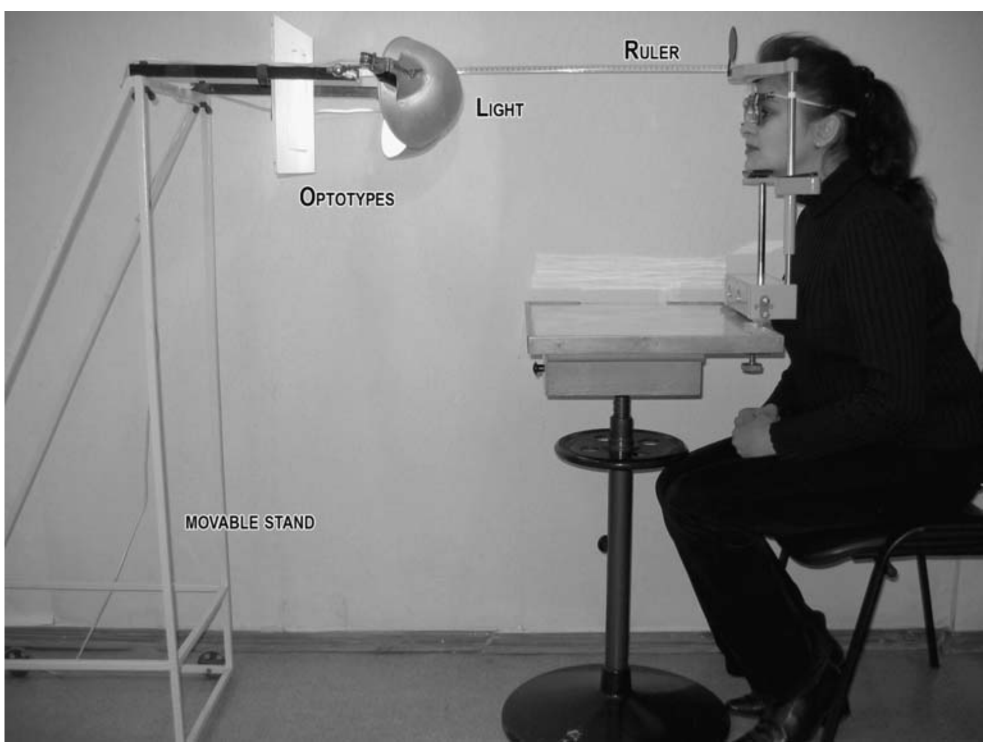
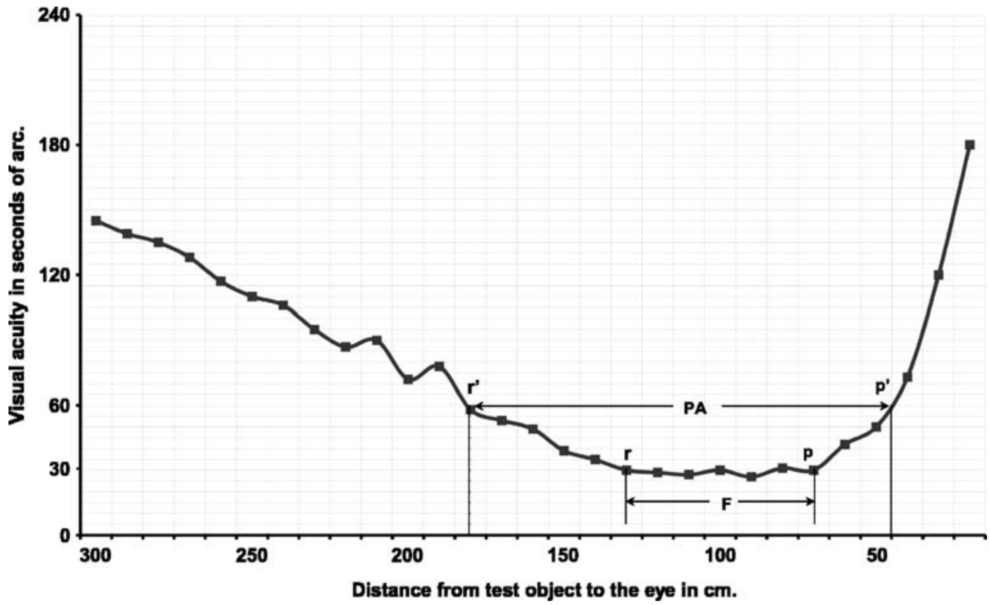


Fig. 1 Apparatus for measurements of visual acuity at different distances

Fig. 2 Visual acuity at different distances of the eye with BCVA 20/10. *F* depth of field; *pr* distance where the visual acuity 20/10 was found; *p'r'* space of slightly defocused image; however, distinction of the optotypes of visual acuity 20/20 is possible. Data of visual acuity are transformed into angles measured in minutes of arc



Results

The mean values in diopters of the depth of focus were 1.12±0.035 D, 0.62±0.021 D and 0.47±0.027 D for visual acuity 20/20, 20/13 and 20/10, respectively (Table 1). There was a statistically significant difference between the adjacent groups ($p<0.05$)

The overlapping results of visual acuity measurements in two eyes with BCVA 20/20 and 20/10 as shown in Fig. 3.

Discussion

Our findings are consistent with those provided by other studies [5, 6, 8, 9]. The most important finding of this study presents a moderate correlation between visual acuity and depth of the field. Visual acuity 20/20, 20/13, and 20/10 expressed in angle of arc is 60″, 39″, and 30″, respectively. Except impact of optical aberrations on visual performance the state of neuro-retinal system presents another important factor. The size and density of the photoreceptors in the foveola area can limit visual acuity. Evaluation of the photoreceptor sampling makes it possible to assume that retinal limit of visual acuity lays near 15″of arc, what means 20/80 [10]. Visual acuity of vast majority of population determines by optical aberrations. This circumstance has induced the investigation of the possibility of supernormal vision [11].

Table 1 Values of depth of focus in eyes with visual acuity 20/20, 20/13, and 20/10

Visual acuity	Depth of focus/depth of field (D) Mean ± SD	Number of eyes
20/20	1.12±0.086	25
20/13	0.62±0.058	10
20/10	0.47±0.055	8

There is a logistic relationship between the depth of focus and the amount of aberrations. Gullstrand's schematic eye possesses a better quality of optical system and therefore negligible depth of focus 0.2 D [3]. The amount of aberrations varies widely among the human population. A higher degree of aberrations results in a greater depth of focus and lower visual acuity.

In this study, visual acuity examination was conducted under conditions of natural pupils of 3.0±0.3 mm in diameter. Pseudophakic eyes with such a pupil were selected from a group of nearly 150 patients. The natural pupil has advantages in comparison with artificial aperture. The series of visual acuity examinations are a fatiguing procedure. With an artificial pupil utilized, it would be difficult to control centering of the aperture to optical axis when performing all these examinations. Misalignments would be inevitable, so the exposure of different (in terms of quality) optical areas would have a negative impact on preciseness of measurements. Thus using natural pupils helps to avoid this problem.

After removing the cataract, the remaining elements of accommodative system continue to function [12–13]. This circumstance became basis for engineering of some accommodative IOLs models, for instance those based on the focus-shift principle.

To exclude movement of IOLs completely this study concentrated on eyes that were operated on from 4 to 18 months earlier (average 8.3±1.2). This time was sufficient for capsular bag fibrosis to substantially evolve. As a rule, the activity of even accommodative IOLs decreases following capsular bag fibrosis [14–15].

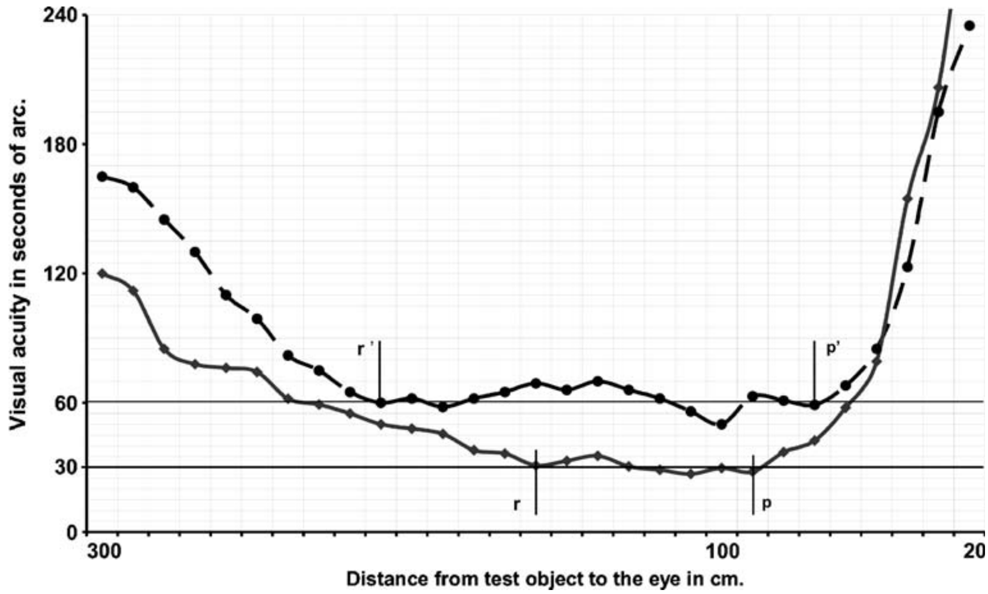


Fig. 3 Superimposed data of visual acuity measurements of two eyes with visual acuity 20/10 (*solid line*) and 20/20 (*broken line*); *pr* and *p'r'* are depth of field of these eyes

The depth of focus for visual acuity of 1.0 and 2.0 in real proportion to eyeball dimensions is shown in Fig. 4.

Certainly, the depth of focus in the living human eye is not rigid and stable even under the conditions of constant pupil aperture. The precorneal tear film, which is subject to changes practically every second, influences the amount and structure of aberrations and in turn the depth of focus [16]. We detected some deviations in the visual function within the depth of field. Lines *pr* and *p'r'* have no horizontal direction (Fig. 3). This minimal deviation may be explained by at least two causes:

- a subjective character of the visual function examination and unstable attention of the patients;
- a changeable state of the precorneal tear film.

The depth of field as well as the depth of focus does not coincide with the amplitude of accommodation. The point is what size of test objects is used for measuring the amplitude of accommodation. In Fig. 2, segment *pr* relates to the depth of field (0.6 D) and depth of focus for visual acuity of 2.0. It does not mean that the amplitude of accommodation is 0.6 D as well. If we use test-objects for 1.0 visual acuity, clear vision will be possible within distance *p'r'*. When the test-objects are localized at the ends on this distance, the out-of focus blurring is negligible and does not eliminate the ability for distinct reading. In this case, the volume of accommodation reaches 1.46 D. Sometimes researchers use even larger test objects perceived by visual acuity of 0.7–0.5. As a consequence, results for measuring volumes of accommodation increase.

In the literature, a question of terminology regarding accommodative function was raised [17–18]. Langenbucher [17] uses the term "pseudophakic accommodation" to designate a dynamic change in the refractive state caused by interactions between the contracting ciliary muscle and the zonules-capsular bag-IOL, leading to changes in refraction. The term "pseudophakic pseudoaccommodation" is used to denote static optical properties of the pseudophakic eye. We completely agree with this defini-

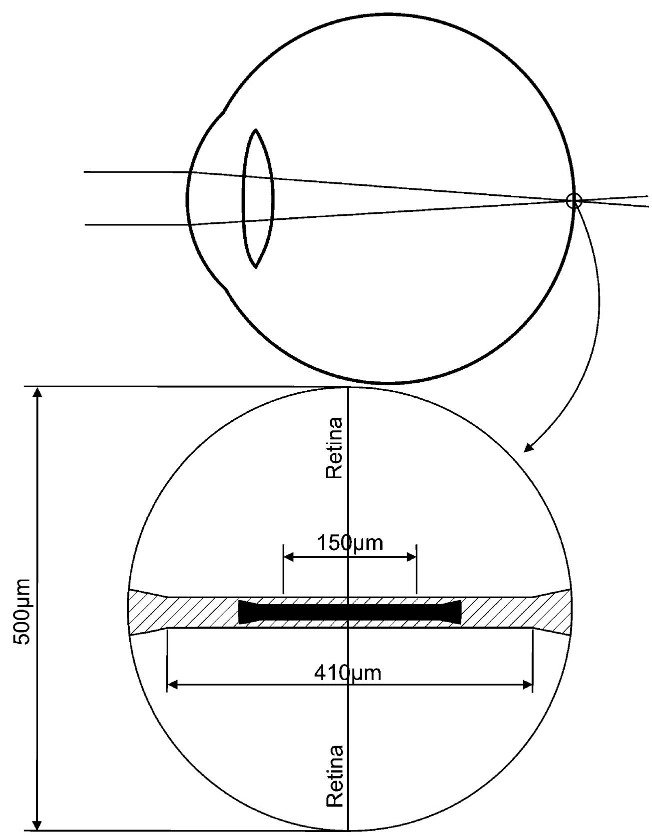


Fig. 4 Depth of focus of eyes with visual acuity 20/10 and 20/20 scaled to the dimensions of the human eye

tion. "Pseudophakic accommodation" is an accommodative function generated by the active control of the brain that alters the optical system of the eye. A clinical effect is produced by the artificial design (accommodative IOL) attached to remnants of the natural accommodative system of the eye. In our opinion, the term "pseudophakic accommodation" has a synonym, "artificial accommodation". The phrase "static optical properties of the pseudophakic eye" [17] can be viewed as the depth of focus characterizing pseudophakic eye. The depth of focus results in "pseudophakic pseudoaccommodation" or "apparent accommodation". In our opinion, it would be more convenient to use a simple term "pseudoaccommodation", which means passive ability to have clear vision produced by the depth of focus.

The challenging task faced by ophthalmologists is to separate pseudoaccommodation (a passive ability) from active accommodative function, for instance in eyes with accommodative IOLs.

The term "pseudoaccommodation" is commonly used when discussing the issue of artificial accommodation. It is incorrect to refer to "pseudoaccommodation" as an accommodative ability of eyes into that shift-focus accommodative IOLs have been implanted. For instance, the ICU (Humanoptics) provides accommodative ability consisting of two components: (1) artificial accommodation resulting from axial optic movement and (2) pseudoaccommodation, which is a consequence of a particular depth of focus.

Thornton [13] reasonably argues that the natural accommodative mechanism includes increasing sphericity of the lens and its anterior movement. The ICU provides the pseudophakic eye only with anterior lens shift and regulates the alteration of optical power, which can be called artificial accommodation. According to our preliminary evaluation related to early postoperative periods, the proportion between artificial accommodation and pseudoaccommodation of the ICU (Humanoptics) model is nearly 1:2.

The methodology, which should be elaborated upon, for separating pseudoaccommodation resulting from the depth of focus and active artificial accommodation will facilitate evaluation of the efficacy of accommodating IOLs and to avoid controversies and misunderstandings [19–20].

To summarize, we have shown a correlation between depth of focus and visual acuity. Higher visual acuity results in a lower depth of focus. The ability for clear vision generated by the depth of focus-pseudoaccommodation is a passive function. In order to separate pseudoaccommodation from artificial accommodation in eyes with accommodative IOLs, it is necessary to rigidly standardize methodology. This especially applies to pupil diameters and angular size of test objects.

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