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Paraxial Analysis of the Depth-of-Field of a Pseudophakic Eye with Accommodating Intraocular Lens

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Abstract

Purpose—To investigate the depth of field of pseudophakic eye implanted with translating-optics accommodating Intraocular lenses (AIOLs).

Methods—Theoretical analyses using paraxial optics equations were used. The crystalline lens in the Navarro eye model was replaced with an AIOL modelled as a thin-lens system with either a single lens element (1E-AIOL) or two-element (2E-AIOL). To quantify the depth of field, a reference limit for retinal blur circle diameter was adopted from typical values of depth of field of the normal eye. Effect of various factors including AIOL type, lens element power, implant position and pseudophakic accommodation on depth of field were analysed.

Results—Depth of field increased with more posterior positioning of the AIOL and decreased with pseudophakic accommodation by translation of optics. However, the changes did not exceed 0.02 D over the range of factors tested. Effective depth of field, defined as the magnification adjusted depth of field, is relatively independent of the implant position and power combination of AIOL. Effects of varying design factors on the depth of field of AIOL are too small to be clinically observable.

Conclusions—While depth of field extends the range of near vision with AIOL, varying design and surgical factors such as depth of implantation and optical power of lens element(s) within clinically practical limits modifies depth of field by an insignificant amount. In the practical sense, attempting to enhance the depth of field of AIOL by varying design factors such as the position of implantation would be unrewarding.

Keywords

accommodating IOL; depth of field; effective depth of field; paraxial optics; optical design

An individual's perception of blur depends on two main factors: first, the physiological factor which is determined by perceptual tolerance to blur and size and distribution of photoreceptors on the retina^{1,2} and second, the optical factors which are responsible for focusing light entering the eye on the retina. Foveally, defocus is the more dominant factor responsible for visual blur. The human eye often suffers from error of refraction and other optical aberrations leading to certain degrees of blur. Perhaps conveniently, the visual system does not detect blur until the magnitude of defocus exceeds a perceptual tolerable range termed the depth of focus whose conjugate in object space is termed the depth of field.

Many studies have investigated the factors influencing the depth of focus of the human eye^{3–12}. One determinant of depth of focus is the maximum size of a blur circle (assuming a

circular pupil) projected from a point object on to the retina that does not elicit significant visual blur. This in turn depends on the size and density of photoreceptors, along with other physiological factors such as the Stiles-Crawford effect^{3,4}. For example, depth of focus is greater in the peripheral retina, where rods and cones are more sparsely distributed, than in the foveal region⁵. It has been well understood that the primary factors influencing depth of focus of the human eye include the refractive power of the eye⁶, axial length⁷ and pupil diameter^{8,9}. Some other factors such as luminance³, contrast^{3,10}, colour¹¹, visual acuity⁷ and accommodation¹² have also been associated with depth of focus.

The importance of depth of field in extending the range of near vision is well understood. Its effect is more evident and arguably of greater importance in pseudophakic eyes, implanted with conventional intraocular lenses (IOL), as no accommodation is available due to the loss of the natural crystalline lens. Studies have been reported in which pseudophakic individuals implanted with rigid monofocal IOL can achieve better than predicted near visual acuity without optical aid^{13,14} despite the assumed complete loss of accommodative ability. This is a phenomenon familiar to the clinicians. In addition to the apparent accommodation or pseudo-accommodation¹⁵, improved depth of focus¹⁶ is often credited as a factor associated with spectacle independence in these eyes; though a study¹⁶ reported no difference in depth of focus between phakic and pseudophakic groups.

Whether theoretically predicted or clinically measured, depth of field alone is insufficient for practical near vision. A post-operatively emmetropic pseudophakic eye is typically expected to require about +2.50D of near correction at spectacle plane for clinically acceptable near vision assuming a standard working distance of 40 cm. In the attempt to provide a greater range of near vision by restoring the ability to change focus for near vision in pseudophakic eyes, various types of accommodating intraocular lenses (AIOL) have been introduced^{18,19}. AIOLs that employ a single optical element (hereafter called “1E-AIOL”) are already in clinical use, while two-element AIOL (2E-AIOL) are still investigational to date. These AIOLs are designed to accommodate by axial translation of the lens elements.

Clinical reports investigating the performance 1E-AIOL in terms of achieved accommodation and near vision varies with mixed interpretation of the results^{20,21}. Near vision after implantation of 1E-AIOL reported in the literatures^{22–25} is higher than expected from theoretically predicted accommodation^{26–29}. Clinical intuition might attribute such improved performance to extension of the range of near vision due to improved depth of field. Hence, it would be of interest to understand any relationship between factors relating to AIOL design and implantation and the depth of field that may be achieved. Such knowledge would also be useful for optimising the near vision performance of AIOL. Although some press articles have alleged improved near performance of AIOL due to improved depth of focus relating to position of implantation relative to the nodal point³⁰, to our knowledge, no scientific literature exists investigating the influence of design and implementation factors on the depth of field.

Given the foregoing, we sought to investigate, by theoretical paraxial optics, the effect of design and implantation factors on the depth of field of 1E-AIOL and 2E-AIOL. The factors investigated in the present study included types of AIOL design (1E or 2E), amount of lens element translation (to bring about accommodation), power combinations of lens elements and implant depth (antero-posterior positioning).

While the term “depth of focus” is commonly used in the literature, the range of acceptably clear vision in the object space is more correctly termed “depth of field”. In this study, calculations of depth of field were referred to in dioptric units and hence quantitatively,

“depth of focus” and “depth of field” are equivalent. Throughout this manuscript, except where reference sources employ otherwise, we use the term “depth of field”

METHODS

Eye and AIOL Models

The finite model eye of Navarro *et al*³¹ (see Appendix A, available at [LWW insert link]) was modified for use in this investigation. We have used this eye model in earlier studies to evaluate the accommodative performance of AIOLs^{26,27,32}. The Navarro eye model consists of ocular parameters that are accommodation dependent and could facilitate comparison of the results between the phakic and pseudophakic conditions. The original model of the eye was considered as the reference eye for comparison of results with that from the pseudophakic eye.

Two types of AIOL designs were tested. In the first, a single thin-lens element replaced the crystalline lens of the model eye to simulate a single element 1E-AIOL. In this model, the power of the AIOL was selected so that at the initial implantation position the eye was rendered emmetropic. During accommodation the lens element was translated axially in the forward direction. The second AIOL type consisted of an idealized thin-lens model of a 2E-AIOL. In this model, the power of the front element was varied from + 20.0 D and + 40.0 D in 5 D steps. The power of the back element was calculated to return the model eye to emmetropia at the initial implantation depth and with the 2E-AIOL at its distance-focus setting.

The basic scheme and descriptions of the eye model with AIOL are illustrated in Figure 1. The effect of implantation depth, defined as the distance from the pupil plane to the front element of the AIOL, was studied by varying the position of the front lens element from 0.00 mm (minimum) to 2.00 mm (maximum) behind the pupil. Initial (minimum) and final (maximum) separation between the lens elements of the 2E-AIOL was 0.00 mm and 2.00 mm respectively. The distance from the back lens element of the AIOL to the Back Reference Plane was varied to maintain a constant total eye axial length of 23.94 mm, which is the axial length for establishing an emmetropic state to the model eye with natural crystalline lens.

For the 2E-AIOL model, two variants of lens element translation were considered to simulate accommodation. The first variant portrayed a system whose front lens element is mobile, and translates forward axially while the back element remained static. The second portrayed a mobile back lens element that translates backward axially with the front element remaining static. Both variants employed a positive powered front lens element and a negative power back lens element as these power combinations have been shown to provide the best accommodative efficiency (change in power versus distance of lens translation) as well as providing ‘positive’ accommodation (i.e. the AIOL increases in power as the lens elements separate^{26,27}). For the front element mobile model, the stationary back element is located at the back reference plane. For the back element mobile model, the stationary front element position coincided with the pupil.

Calculation of Depth of Field

We defined the depth of field as the dioptric difference between the vergences emanating from the anterior corneal surface for rays that originate from the outside and inside focal points (see Figure 1). Mathematically depth of field may be expressed as:

$$DoF = L_o - L_i \quad (1)$$

where L_o and L_i are the final vergences at the anterior corneal plane for axial rays originating from the outside and inside focal points respectively.

Vergence calculations at each optical boundary in the reference eye and the eye-AIOL model were carried out using an Excel spreadsheet (Microsoft Office 2007). In this process, the limit size of the retinal blur circle (d) of the reference eye was determined first by using the “Solver” add-in function with a target depth of field of 0.5 D. Though a wide range (± 0.01 D to ± 1.85 D) of depth of field for normal phakic eyes has been reported^{9,32}, this value represents approximately the average depth of field for a 4 mm pupil diameter^{3,5,34}. Using this value of blur circle diameter, the positions of the inside and outside foci with respect to the back reference plane of the reference eye were calculated from equations:

$$\text{Inside Focus } I = T_v - \frac{dl}{D+d} \quad (2)$$

and

$$\text{Outside Focus } O = T_v - \frac{dl}{D-d} \quad (3)$$

where T_v is the vitreous chamber depth (distance between back reference plane and retina), d is the diameter of the retinal blur circle, l is the distance from the exit pupil to the retina and D is the exit pupil diameter. Details of the derivation of equations are provided in Appendix B (available at [LWW insert link]).

Starting from the inside and outside foci, vergence calculations were carried out for various accommodation levels of the reference eye and eye-AIOL model and for the experimental settings described above (AIOL type, power combination of the lens elements, implantation positions and the accommodated states of the AIOL). From these calculations, the final vergence of the rays emanating from the anterior corneal plane was determined, followed by the calculation of the depth of field using Equation 1.

Effective Depth of Focus

Depth of field measurements in a vision science laboratory are typically carried out taking into consideration additional factors such as object and retina image size of the test target to arrive at the true value of depth of field. However, in the clinic, a more typical method for establishing the range of near vision for a patient is to direct the patient to view a small target on a near-point chart. The chart is then moved away and towards the patient's eye until the chosen target letter is no longer legible to establish the range of clear near vision. This method is influenced, among other factors, by the magnification of the eye and any optical devices involved.

With a higher magnification due to pseudophakic accommodation, the size of the retinal image is increased³². As a result, a greater amount of blur is required before the target letter is no longer legible. An AIOL that produces a higher image magnification would produce a smaller blur size relative to the overall size of the object. Thus, for the same target letter viewed, the AIOL with the higher magnification would exhibit an apparently greater range of near vision.

In order to simulate this aspect of clinical estimations of range of near vision, we derived a parameter called the “effective depth of field” which is calculated using an adjusted retina

blur size limit that takes into account the magnification of the AIOL. Since the retina blur size limit required to affect image resolution would be directly proportional to the retinal image magnification; the adjusted retina blur size limit is calculated as:

$$d' = d \times M \quad (4)$$

Where d' is the adjusted blur circle diameter; d is the actual diameter of the blur circle; and M is the magnification of the eye given by:

$$M = \frac{L'_M}{L_M} \quad (5)$$

where L'_M is the product of all the vergences of rays leaving the optical boundaries and L_M is the product of all the vergences of rays incident on the optical boundaries of the system

RESULTS

The results for depth of field, and effective depth of field with different depths of implantation, translation for accommodation and combinations of lens element power are shown in Figures 2 and 3. The rates of change of depth of field with change in depth of implantation, accommodated power (effect of translation) and front lens element power (lens element power combination) were calculated by multiple linear regression and summarized in Tables 1 and 2.

Depth of field increased slightly with more posterior implantation depth for all AIOLs tested. However, the type and implantation depth of the AIOL have less effect on effective depth of field, particularly for the 2E-AIOL (Figure 2). There was virtually no change in effective depth of field when the implant depth and power combinations of the 2E-AIOL were changed though a slight change in depth of field was found for a 1E-AIOL (Figure 3).

Pseudophakic accommodation decreased the depth of field in all types of AIOL, but increased the depth of field in the reference eye. At 3 mm implant depth, i.e. when the front element of the AIOL is located 3 mm behind the pupil plane, the depth of field of a 2E-AIOL with a front element power of +30 D was approximately identical to that of the reference eye at distance focus. Increasing the power of the front lens element of a 2E-AIOL very slightly decreased the depth of field at all near viewing distances. In contrast the effective depth of field increased with the pseudophakic accommodation.

DISCUSSION

We evaluated the depth of field of pseudophakic eyes implanted with AIOLs in relation to types, implant position and power combination using analyses based on paraxial optics. We have adopted the conventional definition of depth of field, which is the range of acceptably clear vision without perception of blur. This concept refers to a static state of the eye and AIOL (i.e. a given focal position of the AIOL with its lens element in a fixed position) and is not to be confused with (although is often misused thusly), for example, “range of clear vision”, which includes the effect provided by AIOL lens element translation. The values of depth of field for the reference eye in the current results are in good agreement with the values reported by Campbell³ and Charman and Whitefoot⁸ for normal eyes. Both of the authors estimated a minimum depth of focus of ± 0.3 D under ultimate conditions at a pupil diameter of 3 mm in normal eyes. A slightly higher mean value of objective depth of focus

(± 0.59 D) at 5 mm pupil diameter was reported recently³⁵. In our experiment, the depth of field of the pseudophakic eye is consistently lower than that of the reference eye.

Subjective and objective depth of focus of pseudophakic eyes reported in the literature are consistently higher than our theoretically predicted values. Published values range from ± 0.85 D to ± 1.82 D^{17,36–38}. One obvious reason for the smaller values in the current experiment is that it is based on paraxial geometrical optics constructs and, unlike in real eye conditions, the results are free from the influence of other optical and physiological factors which may affect depth of field such as optical aberrations and postoperative astigmatism. The current study demonstrates that implant position of an IOL virtually has no effect on depth of field. In a clinical setting the spherical aberration of the eye may enhance the depth of focus by reducing the sharpness of the retinal image³⁹ which is not evaluated in the current study. The purpose of the present study was to evaluate if AIOLs produce a significant improvement of the depth of field, beyond what can be expected from the contribution of spherical aberrations. For AIOL and eye combinations exhibiting aberrations that depart significantly from normal values, it would be worthwhile repeating this study by incorporating factors such as optical aberrations, the influence of the exact image point-spread and Stiles-Crawford effect in the analyses.

In the clinical setting, comparison of the depth of field of different AIOL would most likely employ test-letter types of the same size. Thus, an AIOL that provides greater magnification of the object may give apparently a greater measured or clinical depth of field for the same true or theoretical depth of field. The metric, effective depth of field introduced in this experiment attempts to take into account this factor and shows that depth of implantation affects depth of field by only a very small amount (less than 0.01 D). This apparently compensatory effect of magnification on effective depth of field seems to also apply for near vision. With an accommodative translation of the AIOL, magnification is increased³², which eventually reduces the difference in depth of field for different types of AIOL at near focus state.

We conclude that the depth of field of an AIOL-eye combination is linked to its magnification. Importantly, however, the effects of all the tested variables are far below those observable clinically and are hence of no practical significance. The change in depth of field due to changes in implantation depth, element translation (accommodation) and combination of lens element power within practical limits never exceeded 0.02 D. Hence claims that the near visual acuity in pseudophakic eyes is improved due to improved depth of focus cannot be supported. In the practical sense, our results also do not support the statement of improved depth of focus with more posterior implantation of an AIOL.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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APPENDIX

Appendix A is available at [LWW insert link].

Appendix B is available at [LWW insert link].

Figure 1.

Basic schema of the vergence calculation starting from inside (solid line) and outside (dotted line) retinal focal positions through the two AIOL (F_1 and F_2) elements and finally emanating from the corneal plane. Depth of field is defined as the difference between the vergence starting from the outside retinal focus to that starting from the inside retinal focus at the corneal plane.

Figure 2.

Effect of implantation depth on depth of field for: 1E-AIOL (A) and 2E-AIOL with translating front (B) or translating back (C) element. Each line represents a different implantation depth. Depth of field is plotted along vertical axis. The amount of accommodation achieved with translation is plotted along horizontal axis. Labels on plots represent implantation depth of AIOL (distance between the iris plane and front surface of the lens).

Figure 3.

Effect of implantation depth (t_f) on effective depth of field for 1E-AIOL (A) and 2E-AIOL with translating front (B) or translating back (C) element. Each line represents a different implantation depth. Effective depth of field is plotted along vertical axis. The amount of accommodation achieved with translation is plotted along horizontal axis. (distance between the iris plane and front surface of the lens).

Table 1

Summary of the change in depth of field of single-element (1E) and two-element (2E) accommodating IOLs (AIOLs) with implant depth, lens translation, accommodated power and power combinations 2E-AIOL. Note the units of milli-dioptres (1 mD = 0.001 D).

Change in Depth of Field with Change in:	Reference Eye	1E-AIOL	2E-AIOL	
			Front element mobile	Back element mobile
Implantation Depth (mD/mm)	–	7.69	7.73	7.61
Accommodated Power (mD/D)	4.11	–2.01	–1.64	–0.65
Front Lens Power (mD/D)	–	–	0.04	0.00

Table 2

Summary of the change in effective depth of field of single-element (1E) and two-element (2E) accommodating IOLs (AIOLs) with implant depth, translation, accommodation and power combinations of the 2E-AIOL. Note the units of milli-dioptres (1 mD = 0.001 D).

Change in Effective Depth of Field with Change in:	Reference Eye	1E-AIOL	2E-AIOL	
			Front element mobile	Back element mobile
Implantation Depth (mD/mm)	–	–1.71	–1.71	–1.71
Accommodated Power (mD/D)	1.26	1.51	1.51	1.51
Front Lens Power (mD/D)	–	–	0.04	0.00