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CATARACT

The clinical depth of field achievable with trifocal and monofocal intraocular lenses: theoretical considerations and proof of concept clinical results

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Abstract
Background To estimate the depth of field (DOF) achievable with multi-and monofocal intraocular lenses (IOLs) and compare with actual measurements of DOF in cases implanted with a trifocal IOL and biconvex monofocal IOL
Methods I) Computer simulations were produced to describe the relationship between DOF, pupil size, preoperative ametropia, and retinal blur tolerance limit for a model eye implanted with either multi- or monofocal IOLs. II) Monocular DOF and pupil size were measured under distance viewing conditions between 3 and 6 months postoperative following uneventful cataract surgery. Cases were implanted with either i) trifocal aspheric IOL ($n = 36$), or ii) biconvex aspheric monofocal IOL ($n = 26$). DOF was also measured at 0.33 m in cases implanted with i).
Results Simulations revealed significant associations between DOF, pupil size, and retinal blur tolerance limit. The mean (±SD) DOF & pupil sizes were at distance for i) above 2.59D (0.68) & 3.54 mm (0.377), and for ii) above 1.67D (0.51) & 2.90 mm (0.351), and for i) above 3.16D (0.46) at near. The difference between groups were significant for DOF and pupil size at distance ($p < 0.001$). DOF was significantly greater at near compared with distance in i) above ($p < 0.001$). For a pupil size of 3 mm, the simulations produce similar DOF values when the tolerance limit of retinal blur is 10 μ.
Conclusions The DOF was significantly better after implanting the trifocal IOL compared with the monofocal IOL, and DOF is increased under near viewing conditions. The clinical results are similar to calculated DOF values when the tolerance limit of retinal blur is 10 μ.

Keywords Depth of field · Intraocular lenses · Pupil · Retinal blur

Introduction

Advances in the design of multifocal intra-ocular lens continue, with the aim of improving visual outcomes and further reducing undesirable complications in the pseudophakic eye.

The perfect eye features an ideal image at the retina when looking at any object irrespective of the distance between the eye and the object of regard. The pseudophakic eye is far from perfect simply because multifocal intra-ocular lenses have preset focal lengths and are fixed in situ. A variety of optical designs have been developed in a bid to improve the range of relatively clear vision from far to near. In brief, bi- or trifocal and diffractive IOLs produce a pseudophakic eye with both a distance and one if not more near foci. A multifocal IOL produces a pseudophakic eye with an extended range of relatively clear vision between far and near. This is achieved by creating a multifocal effect resulting from the spreading of light over a portion of the visual axis. However, it has long been recognised that the pseudophakic eye fitted with a monofocal IOL has better near acuity than expected [1–3]. This better than expected outcome has been attributed to the depth of field associated with the pseudophakic eye.

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The depth of field of the eye is defined as the distance, in dioptres, a viewed object can be moved towards or away from the eye until the retinal image is judged as no longer reasonably clear by the subject whilst the eye remains in a fixed refractive state [4]. The depth of focus is the distance between two extreme axial points directly in front of, and behind, the retina at which the image is judged to remain in focus by the subject. Depth of field is often confused with the depth of focus. To avoid such confusion, this paper will concentrate on depth of field (DOF) only.

In theory, DOF depends on the limit of resolution at the retina when the eye is stationary. In turn, this limit is associated with the size of individual foveal cones (about 3 μ), but calculating the DOF also depends upon the size of the pupil. For a retinal cone and pupil diameter of respectively 3 μ and 3 mm, the calculated depth of field is 0.12D [4]. In an extensive review on the experimental measurement of the depth of field, Wang and Ciuffreda [5] cited values ranging from ±0.01 to ±1.8D for the condition of viewing along the visual axis. The reported DOF values after implanting monofocal IOLs range from 0.80D to 1.65D [6–8]. These values increase after implanting bi- multi- or diffractive IOLs from around 1.8D to 4.5D [6, 9, 10]. The exact value of the measured DOF will also depend on the prevailing experimental conditions, for example, external factors such as the exact configuration of the viewed target, ambient lighting and the method used to present the target. Thus, external factors in association with differing optical properties of the eyes can be regarded as sources of discrepancy between one set of DOF values and another. Smaller reported values for the DOF are generally associated with young trained phakic observers. Is this person truly representative of the typical pseudophakic patient encountered in clinical practice?

The eyes do not remain completely stationary during any visual task. The eyes are constantly in motion. The consequence of this motion is a dynamic retinal image that is constantly changing. Involuntary eye movements coupled with natural ocular tremor and blinking will shift the retinal image by up to 20 μ under normal everyday viewing conditions [11]. This 20 μ at the retina translates to an equivalent visual angle of approximately 100 arcsecs and Snellen acuity of about 20/33. Your eyes have been moving constantly during the last few minutes spent reading this paper but, you are unaware of this motion until you pay attention to it. Your retinal images were shifting continuously, but the perceptual consequences of these phenomena remain in your subconscious until you concentrate on them. It has long been recognised that involuntary eye movements do not affect measured visual acuity in the presence of a shifting non-constant retinal image [12]. A dynamic state of perceptual equilibrium prevents the confusion that would otherwise follow on as a consequence of rapidly changing retinal images. Thus, when predicting DOF it would be more useful to adopt a limit of up to 10 μ and not just 3 μ as a more realistic value for the tolerance of retinal blur in the pseudophakic eye, and compare with real DOF data obtained from eyes implanted with IOLs designed to improve both distance and near vision.

The aim of this study was to compare the calculated DOF that could be achieved over a range of pupil sizes for a model eye implanted with a theoretical designs of IOLs with the clinical measurement DOF values obtained from real eyes implanted with a trifocal or monofocal IOL under standard clinical conditions.

More realistic computed values for DOF should result from using a more realistic clinically viable model eye. Thus, model featuring gradient index optics within the cornea and aspheric ocular boundaries was used for this purpose. The exact procedure for ray tracing and the numerical details of the model are described in other publications [13, 14]. The curvatures of the correcting IOLs were calculated for theoretical pre-operative axial ammetropia ranging from −3.00D to +3.00D.

The DOF was calculated, after incorporating the IOL and appropriately adjusting the axial length, by ray tracing through the model for a pupil size of 3 mm and an object placed at infinity. The object was brought closer to the eye in 0.1D steps until the diameter of the blur circle at the retina changed by up to 3 μ. Where appropriate, for the DOF at near the object was placed at 0.33 m and firstly pulled away from the eye in 0.1D steps until the diameter of blur circle at the retina changed by 3 μ (i.e., increasing object distance = d1), then secondly pulled towards the eye in 0.1D until the diameter of blur circle at the retina changed by 3 μ (i.e., decreasing object distance = d2). The DOF range is the sum, d1 + d2. The procedure was performed for pupil sizes of 3 mm, 5 mm ,& 7 mm and blur circle changes of 3 μ & 10 μ.

Materials and methods

Calculation of depth of field (DOF)

Monofocal IOL

The surface radius of an equi-convex IOL was calculated for an emmetropic eye using the same model eye. We chose an IOL central thickness of 0.85 mm and refractive index of 1.55 (typical for materials such as Acrysof by Alcon Laboratories, Fort Worth, TX, USA) placed 4.05 mm from the back surface of the cornea along the optic axis. The value of 4.05 mm was chosen because this is a typical average post-op position for modern IOLs measured by ultrasonography [15]. The DOF value was calculated for distance viewing conditions. These computations were repeated for pre-op axial ametropia values of −3.00D to +3.00D. The calculated DOF values were subjected to multilinear regression to compute a single least squares equation incorporating each of the dependant variables.

Multifocal (centre-near design) IOL

The radius at the centre of the back surface of an IOL with a spherical front surface radius of 32 mm was calculated for a pseudophakic emmetropic eye corrected to view objects at 0.33 m. The IOL central thickness was 0.85 mm, with a refractive index of 1.55 and placed 4.05 mm from the back surface of the cornea along the optic axis. The value of the asphericity at the back surface was identified for the condition where the transverse spherical aberration (TSA) of the pseudophakic eye when viewing objects at infinity was minimal and equalled the TSA when viewing objects at 0.33 m. This was achieved using an iterative procedure. In essence, along the optical axis this asphericity would cause the point spread function at distance and near to remain more or less the same. In keeping with our procedure for the monofocal IOL, the calculated DOF values were subjected to multilinear regression to compute a single least squares equation incorporating each of the dependant variables.

Patient selection and clinical measurement of the depth of field

DOF was measured in two groups of eyes, one implanted with a tri-focal IOL (group 1, Zeiss AT LISA tri 839MP, Carl Zeiss Meditec AG, Germany) and the other implanted with a monofocal IOL (group 2, Alcon SN60WF, Alcon Laboratories, Fort Worth, TX, USA). All patients underwent uneventful routine cataract surgery. All subjects were examined between 3 and 6 months after surgery. Exclusion criteria included all patients with signs of inflammation, capsular and/or corneal opacities within the pupil area, irregular astigmatism, irregular pupil, BCVA distance acuity worse than 20/30 and post-op distance refraction outside the range ±1.00DS for the sphere and ±0.50 DC for the cylinder.

All measurements were taken on a consecutive case-by-case partially masked randomised basis.

Description of implanted IOLs

Zeiss AT LISA tri 839MP (Carl Zeiss Meditec AG) is preloaded, trifocal, aspheric, diffractive intraocular lens. The optical zone of the lens has a +3.33D near addition and a +1.66D intermediate addition. It has asymmetrical light distribution of 50, 20, and 30% for far, intermediate and near foci respectively. The IOL is fabricated from a hydrophilic acrylic material with a 25% water content and hydrophobic surface. Power range is 0.00 to +32.00 D in 0.50D increments. This is single-piece IOL with 6.0 mm optic diameter. Central 4.34 mm zone includes trifocal optic and the peripheral 1.66 mm zone is bifocal optic. It has a four-haptic design with an angulation of 0 degree and a 360-degree square edge to prevent posterior capsule opacification.

Alcon SN60WF (Alcon Laboratories) is a biconvex aspheric monofocal IOL fabricated from a soft acrylic material. This is a single-piece IOL with 6.0 mm optic diameter. Power range is +6.00 to +30.00 D in 0.50D increments. It has a twin haptic design with an angulation of 0 degree.

Surgical procedure

Surgery was performed under topical anaesthesia, through a 2.2 to 2.5 mm clear cornea incision at steepest meridian. Circular capsulorhexis of 5.0 mm size was performed followed by lens hydrodisection and phacoemulsification. Intraocular lenses were implanted in the capsular bag. The surgical wound was closed by stromal hydration. IOL powers were preselected with standard techniques using IOL-Master and A-scan.

Measurement of pupil size

The infra-red monitoring screen for checking ocular alignment during standard auto-refractometery was used to measure the pupil size. The horizontal and vertical pupil diameters of the pupil were measured on screen with a millimetre ruler as the patient looked at the auto-refractometer viewing the built-in target at infinity. The average of the two measurements was recorded and corrected for magnification (about ×7) for both vertical and horizontal meridia depending on the particular auto-refractometer.

Procedure for clinical measurement of DOF at distance

DOF can be estimated by measuring and plotting the defocus curve [16–19]. The defocus curve pairs the power of trial lenses before the corrected eye (*x* axis) and associated visual acuity (*y* axis) with the power. This is a stimulus–response curve that can be derived using a variety of psycho-physical techniques. However, in a clinical setting, obtaining data to construct the defocus curve is both time-consuming and prone to several sources of error including patient boredom. We decided to use a simpler, more rapid, long-established technique used by many of the investigators reviewed by Wang and Ciuffreda [5]. It is a modification of the basic technique still in current use [20, 21]. The patient was asked to look at the 20/30 line of Snellen optotypes through the best-corrected distance spectacle prescription. Plus sphere was increased in the refractor head in 0.25D steps until the patient reported that the optotypes were no longer acceptably clear. This was performed on a monocular basis under routine ambient light conditions (350 lux) in both groups. Bénard et al. [20] determined subjective DOF using 20/50 high-contrast letters. Yao et al.

[21] employed high-contrast square wave gratings incorporated within a Badal lens setup. The two groups of researchers used different setups, but the DOF results they found were very similar.

Procedure for clinical measurement of DOF at near

The best-corrected distance spectacle prescription was increased by an addition of +3.00D in the refractor head, and the patient was asked to look at a line of J2 print at 0.33 m. The plus power in the refractor head was increased in 0.25D steps until patient reports blur (+x dioptres). The procedure was repeated using negative lenses (−y dioptres). Removing the negative sign, the depth of field at near = (x + y) dioptres. This was performed on a monocular basis under routine ambient light conditions (350 lux) in the cases implanted with the trifocal IOL.

Analysis of collected data

The data were analysed to

1) Compare theoretical calculations of DOF with the clinical data obtained for the trifocal and monofocal IOLs.
2) Compare independent measures of DOF at distance between monofocal and trifocal IOLs (t- test).
3) Determine if there was any association between measured pupil size and measures of DOF at distance for the monofocal and trifocal IOLs (Pearson correlation coefficient)
4) Determine if there was any association between measured pupil size and measures of DOF at near for the trifocal IOLs (Pearson correlation coefficient)

Results

The main results of this investigation are shown in Table 1 and Figs. 1 and 2.

From ray tracing

The computed results in Table 1 show that DOF values range from 0.2D to 2.8D depending on the exact conditions of the computation. The results of the multilinear regression analysis, of the results encapsulating DOF, pupil size (x_1, mm), and pre-op ametropia (x_2, D), are listed for the conditions (x_3, mm^{-1}) defined as: (1) = viewing at distance, retinal blur circle changing up to 3 μ (both cases), (2) = viewing at near (0.33 cm), retinal circle changing up to 3 μ (for the conditions of the multifocal IOLs only), (3) = viewing at distance, retinal circle changing up to 10 μ (both cases), (4) = viewing at near (0.33 cm), retinal circle changing up to 10 μ (for the conditions of the multifocal IOL only).

Monofocal IOL

$$DOF = 0.844 - 0.168x_1 - 0.028x_2 + 0.377x_3 \quad (1)$$

($r = 0.935$, $F = 32.37$, $p < 0.001$, $r_1 = -0.541$, $r_2 = 0.135$, $r_3 = 0.751$)

Multifocal (centre-near design) IOL

$$DOF = 0.719 - 0.194x_1 + 0.024x_2 + 0.436x_3 \quad (2)$$

($r = 0.912$, $F = 52.64$, $p < 0.001$, $r_1 = -0.494$, $r_2 = 0.090$, $r_3 = 0.763$)

The low r_2 values reveal an insignificant association between DOF and pre-op ametropia. The higher r_1 values confirm the expectation that DOF is pupil-dependent.

Clinical measurements

Main results are shown Figs. 1 and 2. The mean (±sd range) pupil size and DOF values at distance were 3.54 mm (0.377, 3.00–4.50 mm) and 2.59D (0.68, 0.75–3.75D) in the trifocal cases ($n = 36$), 2.90 mm (0.351, 2.50–3.60 mm) and 1.67D (0.51, 1.00–2.25D) in the monofocal cases ($n = 26$). The difference between groups were significant for both pupil size and DOF (unpaired *t*-test, $p < 0.001$ for pupil size and DOF). In the trifocal cases, the mean (±sd range) DOF at near was 3.16D (0.462.25–4.00D). This was significantly greater compared with the DOF at distance (paired *t*-test, $p < 0.001$).

The computed data in Table 1 for the monofocal IOL where the pupil size is 3 mm and blur circle limit of 10 μ compare well with the mean clinical result of 1.67D. In contrast, the mean clinical result obtained from the trifocal IOL was approximately 1.15D greater at distance and 0.68D greater at near compared with the averaged values expected from the computation conditions of a 3 mm pupil and blur circle limit of 10 μ.

Linear regression did not reveal a significant relationship between pupil size and DOF in either the trifocal cases (at distance $r = -0.131$, $p = 0.223$, $n = 36$. At near, $r = -0.223$, $p = 0.096$, $n = 36$) or monofocal cases (at distance $r = -0.157$, $p = 0.221$, $n = 26$).

Discussion

Our computations reveal that DOF increases as pupil size reduces and limit of retinal blur increases. These findings are not surprising, but this cannot be said for the difference between IOL types and ametropia. Glancing over Table 1 and equations 1–3, there is no appreciable difference in DOF at distance when comparing one IOL design with another, and pre-op ametropia has an insignificant bearing on DOF.

Table 1 Myope refers to a −3D axial ametropia prior to implantation resulting in full distance correction, and hyperope refers to a +3D axial ametropia prior to implantation resulting in full distance correction. Pupil sizes limited to 3, 5, & 7 mm and blur circle changes of 3 μ (*) & 10 μ (**)

IOL type	Pupil (mm)	Myope distance		Emmetrope distance		Hyperope distance	
Monofocal	3*	0.5		0.6		0.6	
	5*	0.3		0.3		0.4	
	7*	0.2		0.3		0.3	
	3**	1.5		1.9		1.8	
	5**	0.9		1.0		1.1	
	7**	0.6		0.7		0.8	
	Pupil (mm)	Distance	Near	Distance	Near	Distance	Near
Centre near IOL	3*	0.4	0.7	0.4	0.8	0.5	0.9
	5*	0.2	0.4	0.2	0.5	0.2	0.6
	7*	0.2	0.4	0.2	0.4	0.2	0.4
	3**	1.4	2.0	1.6	2.4	1.4	2.8
	5**	0.7	0.8	0.7	1.4	0.8	1.6
	7**	0.4	0.8	0.5	1.0	0.5	1.0

Our literature search revealed one publication where the authors found that pseudoaccommodation was higher in pseudophakic previously myopes than in pseudophakic hyperopes [22] but this finding was not supported by others. We did not encounter a significant association between pupil size and DOF in either trifocal or monofocal clinical cases. This does not come as any surprise on closer examination of the data. Theory predicts a fall in DOF of about 1D when pupil size increases from 3 to 7 mm. The range of pupil sizes in the 37 trifocal cases was 1.52, and 0.5 mm in the 26 monofocal cases. The maximum shift in DOF we can expect to encounter over such a small range in pupil size is about 0.40D. This is less than the standard deviations in the measured DOF values for the total number of cases evaluated. Thus, for this reason alone, we should not expect to detect a significant correlation between pupil size and DOF in our cases. Investigators have attempted to plot the defocus curve to show the range of relatively clear vision with multifocal IOLs [16–19]. The defocus curve is the change in acuity with increasing plus and minus lenses placed before the eye. This is a convenient pictorial demonstration of the achieved range in acuity. However, characteristics of the defocus curve depend on several factors such as pupil size, precise details of the acuity chart, and order of lens power presentation. The shape of the defocus curve may be prone to hysteresis. In addition, authors rarely include error bars on the published defocus curves, though there are exceptions [23].

Nakazawa and Ohtsuki [24] noted that pupil size together with anterior chamber depth and corneal power contributed to the calculation of DOF and in turn, the calculated DOF was highly associated with measured pseudoaccommodation in pseudophakes. On the other hand, Fukuyama et al. [25] found

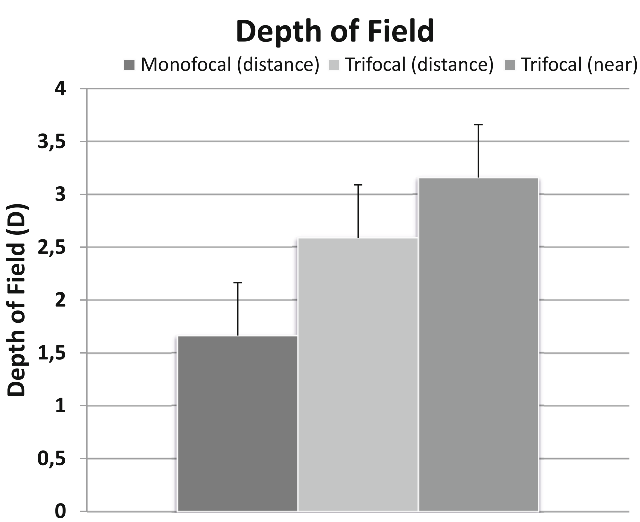

Fig. 1 Mean measured depth of field in patients implanted with, from left to right, standard monofocal IOL at distance and trifocal IOL at distance followed by near. The *'T' bars* represent the positive standard deviations. The differences were significant (where appropriate, paired or unpaired *t*-test, $p < 0.001$)

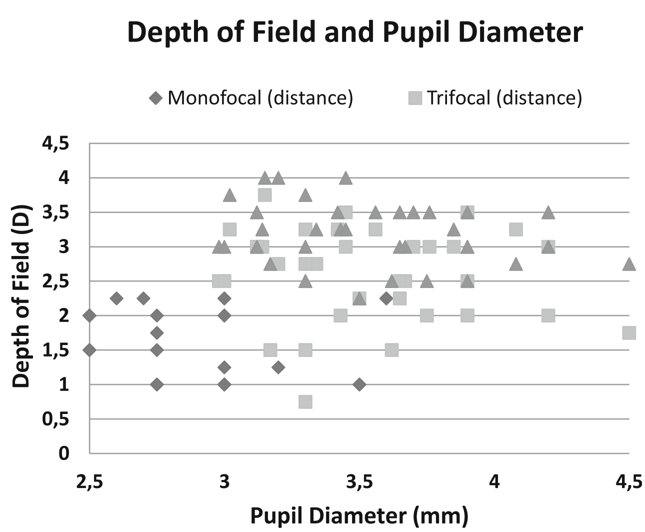

Fig. 2 Comparison between pupil size and measured depth of field values obtained from each patient. A significant association between pupil size and measured depth of field was not detected in each of the three conditions (standard monofocal IOL at distance, trifocal IOL at distance and near) over the range of data

corneal multifocality was a more prominent factor linked to pseudoaccommodation in pseudophakes than corneal power and pupil size. We did not consider the corneal topography and the exact anterior chamber depth value in each single case. However, these two factors could have contributed to the variability in our data, masking any real effect of pupil size on measured DOF in our cases.

For distance viewing conditions, Table 1 shows the predicted DOF varies from 0.2 to 1.9D in multifocal cases. Clinical measurements of DOF in pseudophakes implanted with monofocal lenses range from 0.80D to 1.65D, averaging at around 1D [2, 6–10, 22, 24–26]. Our mean (±sd) result of 1.67D (0.51) for the monofocal cases was on par with the expected. However, within the normal phakic eye the typical reported values range between 0.59D for a 4 mm pupil [27], 0.7D for a 3–4 mm pupil [28], and 0.64D for a 3 mm pupil [29]. For a 3 mm pupil, our calculations based on a 3 μ limit range from 0.4D to 0.6D. Of course, our calculations were based on pseudophakic eyes, but the figures compare favourably with these clinical data from phakic eyes. However, our calculations based on a 10 μ limit range from 1.1D to 1.9D for a 3 mm pupil. These are higher than the clinical estimates on phakic eyes, but remarkably similar to the values reported for real pseudophakic eyes. Wang & Ciufredda [5] produced an extensive list of factors influencing the measurement of DOF under normal viewing conditions. The overwhelming conclusion is that for a trained critical subject, the DOF is expected to be smaller and within a narrower range when all extrinsic factors are tightly controlled during the measurement process. Thus, the more naïve untrained subject is expected to demonstrate a larger DOF when compared with a trained hypercritical subject Nevertheless, under normal everyday conditions measuring DOF values of ±1.00D is not unreasonable [30, 31].

Glancing over Table 1 and Fig. 1, the 10 μ limit may be a more realistic representation of the blur limit when calculating DOF for the phakic eye performing non-critical visual tasks. This suggests that the 10 μ limit is an even more realistic value to consider for the typical older phakic eye.

Under near viewing conditions, Tucker & Rabie [2] estimated the DOF was about 2.8D at 40 cm for a pseudophake implanted with a monofocal IOL when viewing an N5 letter. Our computations reveal that for a hypothetical multifocal IOL, based on the 10 μ limit for a 3 mm pupil, the DOF extends from 2.0D to 2.8D. These match this earlier estimate [2] but, fall short of the typical clinical reports for multifocal IOLs of 3.0D to 4.5D [6, 9, 10]. This suggests that the 10 μ limit is a more realistic representation of the blur tolerance limit when calculating DOF for the pseudophakic eye. Furthermore, at near the mean DOF in our trifocal cases, 3.16D, exceeded the calculated expectations but still remained within the published clinical range between 3.0D to 4.5D [6, 9, 10].

In the trifocal group, we found the DOF was significantly larger at near compared with distance. This was expected and supported by theory. The mean pupil size was significantly larger in this group than in the monofocal group. This should have affected the measured DOF by lowering the recorded value. At distance, the mean DOF was approximately 80% greater than expected. This greater than anticipated result was most likely associated with unique design features of the trifocal IOL. Multifocal IOLs are designed to split the available light towards more than one focal point over the visual axis. This alters the pattern of light distribution over the retina, and is expected to contribute to the different pupil sizes between the trifocal and monofocal groups. Therefore, even in the presence of a slightly larger pupil size in our trifocal cases, they were biased towards a larger rather than lower DOF compared with the monofocal cases. The larger than predicted DOF value suggests that the trifocal IOL should allow a relatively acceptable range of vision from far to close up with minimal, if any, disruption. Of course, the objective evaluation of the retinal image may not support this view. It has been shown that the DOF can be influenced by specific ocular high-order aberrations (HOAs) or a combination thereof [20, 32–34]. Bénard et al. [20] reported DOF could increase by up to 62% by combining and carefully adjusting the fourth and sixth order HOAs by fixed amounts. Their investigation was based on three pre-presbyopic subjects, but it demonstrated what could be achieved while maintaining a reasonable level of acuity.

The eye and visual perceptual process do not operate fully in accordance with basic optical theory. If they did, then DOF would be near zero. The higher than expected values for the DOF of the trifocal IOL may be associated with the higher order aberrations induced by the IOL. It is possible to further increase the DOF of a multifocal IOL by controlling particular HOAs in conjunction with the blur tolerance limit of the central retina.

Conclusion

The mean clinical DOF achieved after implanting the AT LISA tri 839MP trifocal IOL was almost 1.00D greater compared with the DOF achieved with a monofocal IOL. Calculations of the DOF using a model eye show closer agreement with real clinical values when the blur tolerance limit is extended to 10 μ.

Compliance with ethical standards

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Conflict of Interest All authors certify that they have no affiliations with or involment in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speaker's bureaus; membership, employment, consultancies, stock ownership or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge, or beliefs) in the subject matter or materials discussed in this manuscript.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards.

Informed consent Informed consent was obtained from all individual participants included in the study.

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