Comparison of retinal image quality with spherical and customized aspheric intraocular lenses

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Abstract: We hypothesize that an intraocular lens (IOL) with higher-order aspheric surfaces customized for an individual eye provides improved retinal image quality, despite the misalignments that accompany cataract surgery. To test this hypothesis, ray-tracing eye models were used to investigate 10 designs of mono-focal single lens IOLs with rotationally symmetric spherical, aspheric, and customized surfaces. Retinal image quality of pseudo-phakic eyes using these IOLs together with individual variations in ocular and IOL parameters, are evaluated using a Monte Carlo analysis. We conclude that customized lenses should give improved retinal image quality despite the random errors resulting from IOL insertion.

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OCIS codes: (170.4460) Ophthalmic optics and devices; (220.2740) Geometric optical design; (330.4460) Ophthalmic optics and devices; (330.5370) Physiological optics; (330.7326) Visual optics, modeling.

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1. Introduction

Intraocular lenses (IOLs) are used for replacing the crystalline lens of the human eye in cataract surgery. Their design has evolved to correct optical aberrations, specifically spherical aberration, partly as a result of the development of ocular wavefront technology in recent years. Wavefront guided IOL designs, with rotationally symmetric aspheric, toric and customized aspheric surfaces are being developed [1–9], especially for cataractous eyes that have had previous corneal treatments or corneal conditions causing significant large corneal aberrations [10–13]. The corneal shape and eye length, obtained in the clinical environment, are the main measurements that determine the IOL design characteristics and IOL selection [14–16]. However, individual eyes, even though having similar corneal topography and eye lengths, may vary in other individual parameters (for example, lens shape and axial position).

Ray-tracing eye models are useful to evaluate the IOL design and power calculation [17–27]. The use of an individual eye model based on personal eye parameters best represents the optics of real eyes and is useful to obtain the design and evaluation of IOLs optical performance [17,25,28,29]. The main purpose of this paper is to introduce the use of individual ray-tracing eye models to investigate whether the variety of un-measured and unpredictable pseudo-phakic parameters would eliminate the retinal image benefit of having aspheric and individually customized IOL designs based on the corneal topography and eye length. A two layered parameter grouping and analysis method is presented.

2. Method

The optics of the eye including anterior and posterior cornea, pupil and the curved retina, excluding the crystalline lens, was modeled based on Gullstrand’s #1 schematic eye model and typical aged eye biometry parameters were adopted from recently published data [30,31]. The anterior and posterior corneal surfaces were described by radius of curvature and conic coefficient. The curvature centers of each surface were on the same optical axis. The model had an eye length (along optical axis from vertex of anterior cornea to the retina) of 23.0 mm. Considering only the optical image quality and the computation speed, three wave lengths (486, 588 and 656 nm) with equal contribution and five field points (central fovea at 4 degree horizontally and 4 others ±1 degree horizontally and vertically away from the fovea) with the central field point having twice the contribution compared to the other 4 equal fields, were used in the optical ray-tracing computations. The optical object was located at 6 meters from the eye. This model was the baseline for generating further individual eye models.

Starting with the above primary model, every individual eye has many specific biometry and physiological parameters. These parameters were separated into two groups in this study. The Group 1 parameters were those that are usually available (clinically measurable) before the cataract surgery, which included the corneal anterior and posterior radius of curvature and conic coefficient, anterior corneal irregularity, axial thicknesses of each part of the eye (corneal thickness, anterior chamber depth, vitreous depth, for example as measured on a LenStar LS900) and the overall length of the eye. In passing we note that many of these parameters provided by commercial instruments are not necessarily accurate as arbitrary calibration factors, for example refractive indices, are assumed but not provided by the manufacturers. The selectable IOL paraxial power also belonged to this group. Since the Group 1 parameters are usually used for determining the selection of the IOL, we also call them determinant parameters.
Table 1. Statistics of group 1 determinant parameters of selected 15 eye models

| Parameter                              | Mean ± Standard Deviation |
|----------------------------------------|---------------------------|
| Corneal anterior radius of curvature (mm) | 7.819 ± 0.355            |
| Corneal anterior conic constant        | −0.136 ± 0.196           |
| Corneal posterior radius of curvature (mm) | 6.331 ± 0.333          |
| Corneal posterior conic constant       | −0.24 ± 0.197            |
| Corneal thickness (mm)                 | 0.496 ± 0.071            |
| ACD before surgery (mm)                | 3.869 ± 0.149            |
| Eye length (mm)                        | 23.007 ± 0.023           |

Corneal anterior Zernike coefficients (μm) in 7 mm diameter circle

| Coefficient | Mean ± Standard Deviation |
|-------------|---------------------------|
| C(2, −2)    | 0.72 ± 0.81               |
| C(2, 2)     | −1.8 ± 3.4                |
| C(3, −1)    | −0.16 ± 0.92              |
| C(3, 1)     | 0.091 ± 1.0               |
| C(3, −3)    | 0.33 ± 0.90               |
| C(3, 3)     | 0.068 ± 1.1               |
| C(4, 0)     | 0.58 ± 1.1                |

The Group 2 parameters were those not unusually known before IOL implantation and those with individual distributions, which included refractive index of cornea, refractive index of aqueous and vitreous, pupil decentrations and tilts, angle Kappa (angle subtended by line of sight and pupillary axis), thickness of the photoreceptor layer and curvature of the retina, and also included the IOL attributes in the pseudo-phakic eyes after the IOL implantation into the crystalline bag, such as IOL tilts and decentrations, IOL rotation, axial position, refractive index of IOL, surface irregularity of both IOL anterior and posterior surfaces. This group also included the corneal anterior change before and after the cataract surgery [32,33] and those relatively small random measurement noises of Group 1 determinant parameters due to the operators and equipment. The Group 2 parameters are also called variational parameters. The primary conception of this study is to investigate if variational parameters can cancel the retinal image benefit of different IOL designs based on the determinant group of parameters. The pupil size was treated separately and was not assigned to either of the two groups.

Large numbers of optical eye models with different statistical parameter distributions were derived from the baseline eye model by varying the Group 1 determinant parameters with a uniform distribution. That is to say that many aphakic eyes were modeled with different corneal anterior and posterior radius of curvature, conic coefficient, anterior corneal topography and thicknesses of each part of the eye. The corneal topography of anterior corneal surface from its best fit quadratic sphere was decomposed with Zernike polynomials of astigmatism (Z(2,−2), Z(2,2)), comas (Z(3,−1), Z(3,1)), trefoils (Z(3,−3), Z(3,3)) and spherical aberration (Z(4,0)). These eyes share same eye length of 23.007 mm (except for small measurement error which is 0.005 ± 0.023 mm for the selected eye models). The Group 1 parameters were then extracted from these eye models and listed for clear inspection. Fifteen representative eye models were selected, particularly covering typical ranges of the determinant parameters with some extension attempting to incorporate corneal surface irregularity after laser surgery [30,31,34–37]. Table 1 lists the averages and standard deviations of these parameters of the 15 selected eye models.

Mono-focal IOLs with two continuous refractive surfaces were then sequentially designed for the above 15 eye models. Both spherical and aspheric anterior and posterior IOL surfaces, and both rotationally symmetric and non-rotationally symmetric surface designs were considered, which included: IOL1, equal spherical surfaces with opposite radius of curvature; IOL2, based on IOL1 with aspheric anterior conic coefficient; IOL3, based on IOL2 with aspheric anterior higher order radial terms \( r^4 \) and \( r^6 \); IOL4, based on IOL3 plus aspheric anterior surface with extra \( r^2 \) item; IOL5, non-equal spherical surfaces; IOL6, based on IOL5 with aspheric anterior conic; IOL7, based on IOL6 with three anterior radial terms \( r^2 \), \( r^4 \) and \( r^6 \); IOL8, based on IOL5 with both aspheric anterior and posterior conic coefficients; IOL9, based on IOL5 with both aspheric anterior and posterior conic and \( r^2 \), \( r^4 \) and \( r^6 \) terms; and IOL10, spherical posterior surfaces but customized anterior surface with all terms above plus individual non-rotationally symmetric Zernike polynomials of astigmatism, trefoil and coma.

The original thickness of the IOLs was set as 1.1 mm and refractive index \( n_D = 1.459 \). The IOLs were initially placed at the same distance from the posterior corneal surface in the 15
Table 2. Group 2 variational parameters and their minimum/maximum ranges deviating from their nominal values. The relatively small measurement noises are not listed. Every parameter was randomly selected from the range following Gaussian distribution to be the perturbations for each individual pseudo-phakic eye model.

| Cornea                  | posterior RMS irregularity (µm) | refractive index |
|-------------------------|---------------------------------|------------------|
|                         |                                 | −0.85 0.85       |
|                         |                                 | −0.005 0.005     |
| Anterior surface,       | C(2,-2)                         | −0.34 0.34       |
| including surface      | C(2,2)                          | −1.70 0.85       |
| change after cataract   | C(3,-1)                         | −0.17 0.85       |
| surgery in Zernike      | C(3,1)                          | −0.34 0.34       |
| coefficient (µm)       | C(3,-3)                         | −0.34 0.34       |
|                         | C(3,3)                          | −0.17 2.0        |
|                         | C(4,0)                          | −0.71 0.80       |

| Iris                    | axial position (mm)             | −0.02 0.02       |
|                        | decentration x (mm)             | −0.2 0.2         |
|                        | decentration y (mm)             | −0.2 0.2         |
|                        | tilt about x (degree)           | −3 3             |
|                        | tilt about y (degree)           | −3 3             |

| Retina                  | retinal thickness (mm)          | −0.1 0.1         |
|                        | retinal curvature               | −0.8 0.8         |

| Others                  | Angle Kappa inferior - superior (degree) | −1 1 |
|                        | Angle Kappa nasal - temporal (degree)   | −2 2 |
|                        | aqueous refractive index             | −0.0005 0.0005   |

| IOL                     | axial position (mm)              | −0.3 0.3         |
|                        | central thickness (mm)           | −0.01 0.01       |
|                        | decentration along x (mm)        | −0.6 0.6         |
|                        | decentration along y (mm)        | −0.6 0.6         |
|                        | tilt about x (degree)            | −5 5             |
|                        | tilt about y (degree)            | −5 5             |
|                        | rotation (degree)                | −8 8             |
|                        | Refractive index                 | −0.0006 0.0006   |
|                        | anterior RMS irregularity (µm)   | −1.0 1.0         |
|                        | posterior RMS irregularity (µm)  | −1.0 1.0         |

eye models and their surfaces were optimized to minimize the spot size on the retina averaged by the three wavelengths and five field points. The IOL edge thickness was restricted so that only certain combination of surface’s parameters could be selected to provide edge thickness within 0.1 to 1 mm. The optimization procedure was implemented by customized script macros in the optical design software Zemax (Zemax Development Corporation, version Feb-2011) with a damped least square optimization algorithm. Three pupil sizes (5.2, 4.7 and 4.2 mm) were sequentially involved to do the optimization of the 10 IOL designs, in order to later analyze and find out which pupil size was more suitable for different designs after comparisons of the retinal image quality. All surface variables of the ten IOL designs were saved after the optimization, which would be afterwards loaded into individual eye models varying in Group 2 variational parameters.
Table 2 shows the range of the main parameters in the variational parameter group. The variational parameters played the role of distinguishing individual pseudo-phakic eyes. Each of the above first stage 15 eye models were further divided into 16 individual pseudo-phakic eye models with a random effective combination of variational parameters shown in Table 2. The system measurement noises used in the analysis were relatively small, are not shown in this Table. Applying Monte Carlo analysis, a Gaussian distribution was assigned to each of the variational parameters chosen from their ranges. The ranges shown in Table 2 are representative of those given in publications [32,38–40]. After this step, 16 second stage individual models carrying variational parameter distributions were constructed for each 15 eye models, giving a total of 240 models. Then the pre-designed IOLs saved previously, possessing 45 groups of IOL designs (15 models by 3 design pupil sizes), were sequentially loaded into each of the individual eye model. Three chromatic optical metrics for the image formed on the retina, i) modulation translation function (MTF) at 25, 50, 75 and 100 lp/mm, ii) RMS spot size and iii) Strehl ratio, were computed. This was performed for each individual model with each of 10 IOL designs. The four MTF values were averaged as a mean MTF value. All the computations were performed and averaged at 3, 4, and 5 mm diameter pupil sizes.

The three retinal metrics were each normalized by their maximum values to be all within the range 0 to 1 and then the root mean squared value calculated. This procedure yielded a composite metric with a single number (larger value representing better retinal optical quality over the central 2 degree field of view) for comparison of IOL designs.

Figure 1 gives a simplified flow chart summarizing the method discussed above.

3. Results

First the optimal design pupil size was determined. Two-tailed (two-sided) paired statistical $t$-tests at $p = 0.05$ level were used to compare the composite retinal metrics for the 10 IOL designs at different design pupil sizes. The optimal pupil size for designing spherical IOLs
Fig. 2. Comparison of 10 IOL designs by normalized retinal composite metric

(IOL1 and IOL5) was found to be 4.2 mm. For an IOL with anterior conic coefficient (IOL2), the 4.2 mm pupil was significantly better than 5.2 mm but not significantly different to 4.7 mm pupil. For all other IOLs, including individual IOL, there were no significant differences with design pupil sizes.

Considering the optimal design pupil sizes, IOL1, IOL2 and IOL5 designed at a 4.2 mm pupil size and other IOLs at 5.2 mm pupil size were used in the following further analysis and the results are shown in Fig. 2. In this figure, the black dots are the average composite metric of the second stage 16 eye models grouped by the first stage 15 models and the corresponding error bars show ±1 standard error. There is a slight difference between the two spherical IOLs (equi-curvature IOL1 and non-equi-curvature spherical IOL5), $p = 0.03$, with IOL5 having on average a 4% larger metric value than IOL1. This suggests that for spherical IOLs, the optimal shape factor ($(R_2 + R_1)/(R_2 - R_1)$) can slightly improve the optical quality of pseudo-phakic eyes regardless of parameter variability of these eyes, which is in line with some other authors for example [41].

The aspheric IOLs, whether rotationally symmetric or individually customized, have a significantly higher value of the metric than both spherical IOLs. The individually customised IOL (IOL10) has a significantly larger value ($p < 0.001$) of the quality metric than any other designs. There are no significant differences between each pair of aspheric IOLs with anterior and posterior rotationally symmetric surfaces, which suggests that limited improvement could be achieved with extra radial rotationally symmetric IOL surfaces $(r^2, r^4, r^6)$, and also suggests that it may not be necessary to aspherize both anterior and posterior surfaces since there is no evident retinal image quality improvement. Following this conclusion, only anterior aspheric IOL results are discussed below.

Figure 2 also shows the percentage improvement of composite metrics of other designs to the equi-spherical IOL design with vertical bars. The error bars on the vertical bars are 95% confidential intervals for the improvement percentage. It can be seen that all the aspheric IOL design improved upon IOL1, especially the individual one which on average improves by 65%.
4. Discussion

It is interesting to know whether the improvements of aspheric IOLs over equi-spherical IOL, especially for those rotationally symmetric IOLs, are mainly due to the correction of spherical aberration. Pearson correlations were calculated to estimate the relationship between the residual Zernike spherical aberration (Z(4,0)) with the equi-spherical IOL in a 5 mm pupil, and the percentage improvement of the composite metric of the other IOLs. The improvement of IOL2, IOL3 and IOL4 have weak correlations with residual spherical aberration of IOL1 (correlation coefficient 0.26 at \( p = 0.35 \), 0.48 at \( p = 0.07 \) and 0.48 at \( p = 0.07 \) respectively). The individually customized design IOL10 has a significant correlation value (correlation coefficient 0.53 at \( p = 0.04 \)).

As for astigmatism aberrations, IOL2, IOL3, and IOL4 are found to be significantly negatively correlated with square root of sum of square of Zernike astigmasms Z(2,-2) and Z(2,2) of IOL1 design (correlation coefficient \(-0.57 \) at \( p = 0.03 \), \(-0.58 \) at \( p = 0.03 \) and \(-0.55 \) at \( p = 0.03 \) respectively). This means that astigmasms deteriorate correction of rotationally symmetric aspheric IOLs. However for IOL10, the corresponding coefficient is 0.68 at \( p = 0.01 \) level which shows a significantly positive correlation. These results suggest that an individual IOL design has equivalent ability to suppress the spherical aberration and better ability to suppress astigmasms induced by variational parameters in individual pseudo-phakic eyes, compared to rotationally symmetrical IOL designs.

The modern IOL is a foldable design, leading to a smaller incision during cataract surgery. Soft IOL surfaces may gain irregularity and deformation, during its manufacturing, the implantation surgery and/or after long term implantation. Indeed, IOL dioptric power has been allowed to have evident power error tolerance [42]. The surface deformation (irregularity) of the individual IOL was further investigated to see how the surface irregularity will affect the optical quality of the IOLs. To have an estimate of the magnitude of the RMS surface irregularity, the point spread function of spherical IOL measurement data from reference [43] was modeled. The RMS irregularities decomposed by Zernike low order astigmasms, comas and trefoils were found to be in the range of microns (i.e. ± 1µm used in Table 2). Monte Carlo analysis was performed for the 15 individual IOL designs (IOL10) in a 5 mm pupil with the variational parameters as the random perturbations while different RMS levels of IOL anterior and posterior surface irregularities were sequentially altered. RMS spot sizes on the retina of 128 Monte Carlo simulations for each individual IOL design and RMS irregularity level were averaged, and then 15 designs were averaged. Figure 3 shows the results. The RMS spot size is plotted against the RMS surface irregularity. The spot size was normalized by the RMS spot size of the corresponding equi-spherical IOLs which had RMS surface irregularity range within ±1 µm. The error bars in this figure are the 95% confident interval of the RMS spot size ratio and the number above them shows the \( p \) value of the measure of their mean difference from 1.0 which corresponds to the spot size of the equi-spherical IOL design. It can be seen from this figure that average RMS spot size increases slowly with the surface irregularity. This suggests the individual IOL is relatively robust against its surface irregularity.

In order to estimate the effect of the Group 2 variational parameters on the retinal image quality, the retinal RMS spot sizes before and after the inclusion of variational parameters were compared. For the two spherical IOL design (IOL1 and IOL5), the spot size is 10% bigger after variational parameters are included; for the two aspheric IOLs with only conic coefficients, the RMS spot increased 30% (IOL2) and 35% (IOL6) respectively; for the five aspheric IOLs with higher radial order asphericity (IOL3, IOL4, IOL7, IOL8, IOL9) the increase percentages are within 40% to 45%; and for individual IOL design (IOL10), it is 100%. The spherical IOLs, although not best optical correction, provide the best tolerance against immeasurable and unpredictable variational parameters, while the individually customized IOL is more sensitive to these.
Fig. 3. Retinal RMS spot sizes of individually designed IOLs at varied RMS surface irregularities. The dashed horizontal line shows the equi-spherical IOL design with ±1 µm RMS surface irregularity.

Figure 4 compares the sagittal and tangential averaged geometric MTF calculated from the 15 models before and after the variational parameters involved. Only IOL1, IOL2, IOL3 and IOL10 are shown here since the IOL5 result is similar to IOL1 and other rotational symmetric IOLs are similar to IOL2 and IOL3. The calculation pupil size is 4 mm. The neural threshold is also shown in (a), (b), (c) and (d) in this figure, which shows the necessary and sufficient neural limit on the contrast of different spatial frequencies [44]. (e) and (f) directly compare the three IOLs before and after variational parameters involvement. From these figures similarly we can see that individually customized IOL is the most sensitive to variational parameters than other IOLs but still provides the best MTF especially in low and middle spatial frequencies. Analysis from the Strehl ratio holds the same conclusion.

As we know, individually customized IOLs are yet available in the current market. But the spherical aberration correction and aberration neutral IOLs have been used in clinics. Many authors found that these IOLs are able to reduce the spherical aberration or even coma [45,46] of pseudo-phakic eyes and provide improved contrast sensitivity but usually not significant improved visual acuity compared to spherical IOLs [47–49], which is possible evidence that the variational parameters are playing a role as addressed by this paper. Some other theoretical studies [50,51] noticed that the selection of an aspheric IOL should be based on more ocular parameters which are within the variational parameters group in this study, while the current study presents a solution methodology. Extensively include the eyes that previously underwent corneal refractive surgery, our results that an aspheric IOL provides better retinal image quality, coincides with theirs.
5. Conclusion

Ray-tracing eye models combined with Monte Carlo analysis are a useful tool to evaluate and compare different IOL designs, taking into account variational (Group 2) factors. The main conclusion of this study is that aspheric IOLs provide better on-axis retinal image quality than spherical ones, but that the rotationally symmetric aspheric IOL with extra higher order even
radial terms are not statistically different to the lower order ones. Although more sensitive to perturbations, rotationally symmetric aspheric IOLs provide better optical correction for pseudo-phakic eyes than spherical IOLs, and individually customized IOLs provide the best image quality, regardless of many undetermined and unpredicted parameters of the eye and the IOL.

Acknowledgments

We are grateful to Enterprise Ireland (IR-2008-0014) and Science Foundation Ireland (07/IN.1/1906) for financial support.