Multifocal intraocular lens providing optimized through-focus performance

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A widespread type of multifocal intraocular lens (MIOL) is based on expanding the depth of focus with specific amounts of spherical aberration. However, knowing the optimal wavefront aberration for multifocality does not directly provide a MIOL geometry. To overcome this issue, we present a new strategy to design MIOLs. The method optimizes directly the IOL surface geometries (aspheres with aspherical coefficients up to tenth order) using a multi-surface pseudophakic eye model and a multiconfiguration approach, where the merit function jointly considers the optical quality at different object plane locations. An example of MIOL [22 diopters (D) far distance correction] was designed. For this design, the ocular modulator transfer function (MTF) at 50 cycles per millimeter remained above 0.47 for all object locations. The design provides high optical quality performance for far and intermediate distances and peak optical performance at near distances (MTF > 0.57). Additionally, the design shows good performance against pupil changes (3–5 mm pupil diameter range). Finally, when the MIOL was tested on pseudophakic eye models with corneal spherical aberrations within a typical population range, the high multifocal performance was maintained in almost 40% of potential patients (ignoring asymmetric aberrations effects).   © 2013 Optical Society of America

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Multifocal intraocular lenses (hereafter, MIOLs) have gained popularity as a treatment for cataracts, also with the aim at providing the patient with functional vision for targets located at different distances. MIOLs are based on the simultaneous vision principle; i.e., the images of objects located at different distances are superimposed on the retina. The optical and neural aspects involved in the visual processing of simultaneous images are still under debate [1]. A major goal when designing MIOLs is to provide good optical image quality for different object planes, although to date many designs (bifocal IOLs) only provide foci for far and near distances, with a drastic decrease in intermediate optical quality.

Current MIOLs are normally based on refractive or diffractive approaches or a combination of both (hybrid MIOLs). Unlike diffractive MIOLs, the optical performance of refractive MIOLs is typically sensitive to pupil changes. On the other hand, the optical quality of diffractive MIOLs is only optimized for a specific wavelength resulting in chromatic halos in polychromatic light. A major limitation of bifocal diffractive lenses (partially overcome by new trifocal diffractive designs [2]) is the poor optical quality at intermediate distances.

Typical refractive MIOLs are based on alternating concentric zones with optical powers for far and near distances. Each zone redirects light coming from near and far, and typically an aspheric transition between the zones indirectly redirects some light coming from intermediate distances onto the retina. However, such passive designs do not always ensure an optimal optical quality for intermediate vision [3].

An alternative to segmented designs is to use continuous, smooth, aspheric profiles. These designs aim at expanding the depth of focus, and therefore, at providing the patient with intermediate distance vision. Generally, the approaches for designing aspheric MIOLs involve the theoretical search of an optimal aspheric wavefront at the exit pupil [4,5], or producing a spherical aberration that optimizes the through-focus visual performance (estimated experimentally using, for example, adaptive optics [6]). The major drawbacks of these approaches include the intrinsic difficulties (and lack of uniqueness) of deriving IOL geometry from the optimal wavefront surface at the exit pupil and restricting the optimization to the modulation of a single (spherical) aberration. Minimizing the spherical aberration of patients is a widespread strategy in monofocal IOL design [7]. Applying Monte Carlo statistical analysis, Hong and Zhang [8] found that in hybrid MIOL designs, moderate negative spherical aberration (around –0.1 μm) provided optimal performance over a wide range of eye models.

In this Letter, we present a powerful strategy to the design of MIOLs, where using a multisurface pseudo-phakic eye model and a multiconfiguration approach, the IOL surface geometry parameters are directly optimized [9]. A related multiconfiguration approach had been used before to optimize monofocal IOLs across the visual field (isoplanatic lenses [10]).

The IOL surfaces are described by aspheres, thus ensuring continuous and smooth refractive sag profiles and a minimization of glare and halos. As an additional advantage, the dependence of through-focus performance with the pupil diameter is reduced.

The new MIOL is designed to optimize the overall optical performance over a range of foci. For this purpose, the target of the multifocal merit function is described by the weighted sum of a monofocal metric evaluated for different object locations. This is a relevant difference (and a more realistic approach) with respect to the conventional procedure, where the through-focus performance is evaluated moving the image plane instead of the object plane.

We found that the best results (higher optical performance over an extended plateau with well-defined peaks

of optimized quality) were obtained using eight object plane locations (defined as distances from the entrance pupil) in the optimization 5, 4, 3, 2, 1, 0.8, 0.6, and 0.4 meters, and the following weighting coefficients of the merit function for each plane: 0.31, 0.02, 0.02, 0.02, 0.09, 0.04, 0.04, and 0.44, respectively.

The metric used for optimizing each merit function was the monochromatic (546 nm) geometrical root-mean square wavefront error. Computations were performed using the ray-tracing program Zemax V.9 (Focus Software, Tucson, Arizona). The selected geometrical metric decreased by several orders of magnitude the computational time over other diffraction-based metrics and prevented a lack of convergence in the optimization [10]. For the same reasons, we did not pursue an optimization based on a polychromatic analysis. The optimization was performed on a pseudophakic eye model described elsewhere [10,11]. The corneal spherical aberration of the model eye (fourth-order Zernike coefficient) was $Z_{40} = 0.16$ µm for a 5 mm pupil diameter.

The geometry of the aspheric IOL surfaces is described by

$$z = \frac{cr^2}{1 + \sqrt{1 - (1-k)c^2 r^2}} + a_1 r^4 + a_2 r^6 + a_3 r^8 + a_4 r^{10}.$$

The inclusion of even aspherical coefficients from 4th to 10th order (a_1, a_2, a_3, a_4) in the IOL aspheric surfaces significantly improved the multifocal optical performance, as observed in the optimizations.

The design parameters were bounded by boundary conditions [10] in the central thickness, IOL vault (total maximum thickness), and limits to the surface asphericity values. Among other factors, these boundary conditions included in the merit function with specific weights prevented extreme geometries that could be difficult to manufacture. The IOL optical surface parameter optimization was performed on a 4.5 mm optical zone. An additional peripheral area connecting the optical zone to the MIOL haptics was designed using previously published equations [12] and not incorporated in the optimization. This area ensured smoothness in the transition between both zones and set the edge thickness.

The optimization procedure of the merit function followed a sequential routine. The IOL was initially set as a spherical equiconvex lens of desired paraxial power. The parameters optimized at each sequential step were (1) radii of curvature, (2) conic constant K, (3) coefficients a_1, and (4) coefficients a_2, a_3, and a_4. The optimization was executed with a classical damped least squares algorithm as implemented in Zemax.

An example of the MIOL (providing 22-D far distance correction) designed with our method is shown in Fig. 1(a). The IOL refractive index is 1.5387, the IOL central thickness is 1.216 mm, and the edge thickness is 0.25 mm.

Figure 1(b) shows the power profile (i.e., the paraxial local mean power as a function of the radial coordinate at the pupil plane) of the MIOL depicted in Fig. 1(a). The power profile is computed with the IOL in eye (using the pseudophakic-design eye model), and therefore involves the interaction between the optics of the MIOL
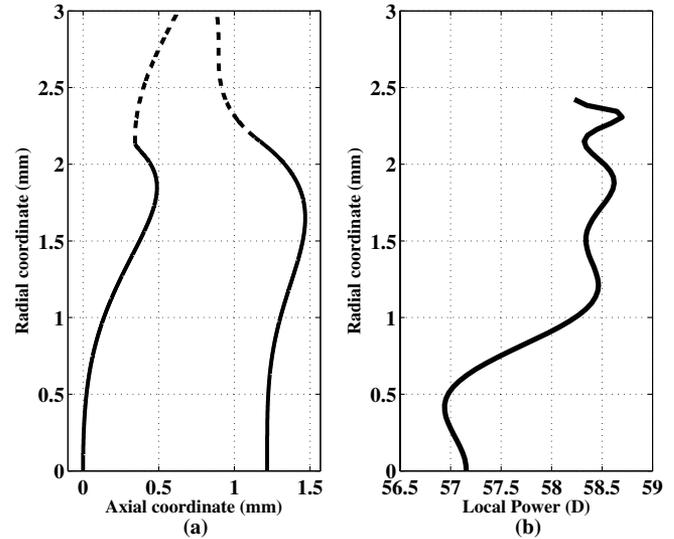

Fig. 1.   (a) Cross-section profile of a designed MIOL (22 D). Solid line: optical zone. Dashed line: peripheral area beyond the optical zone. Anterior lens surface vertex located at (0, 0) mm position. (b) Local power profile calculated in eye with the pseudophakic-design eye model and therefore considering the optical coupling between the MIOL and the eye.

and the optics of the eye. The profile with smooth transitions in the power distribution across the pupil reflects the multifocal performance of the design and represents a significant advantage over concentric MIOL with abrupt transitions. In particular, this design shows a first central inner ring of intermediate power followed by a ring of minimum power and subsequently rings of alternating power. This characteristic makes the designed MIOL to be quite robust against pupil diameter changes, which is a major concern about refractive MIOLs.

Figure 2(a) shows the monochromatic (546 nm) modulation transfer function (MTF) at 50 c/mm as a function of the object distance (5–0.4 m) for different pupil diameters (3–5 mm). The MTF remains above 0.47 for all object locations, with high modulation
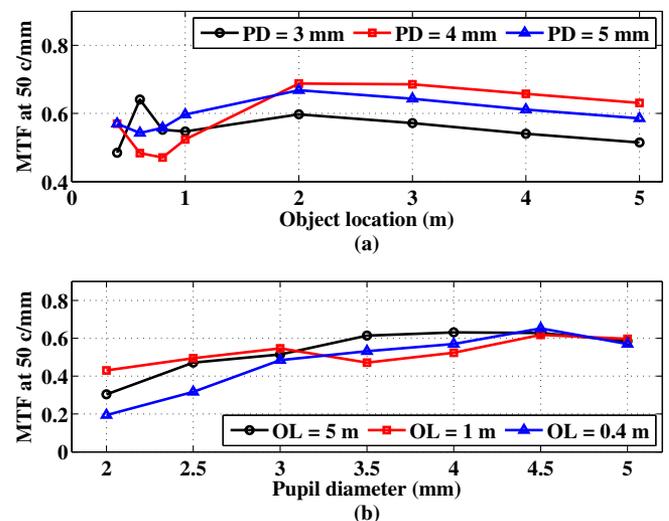

Fig. 2.   Predicted MTF at 50 c/mm of the pseudophakic-design eye model implanted with the new MIOL (22 D) as a function of (a) object location (OL) and (b) pupil diameter (PD).

(>0.57) for both near (40 cm) and far distances and for 4 and 5 mm pupils. Therefore, the design provides a large depth-of-focus, high optical quality performance for far and intermediate distances, and a peak in optical performance at near distances. The dependency of the optical performance with the pupil diameter is shown in Fig. 2(b) illustrating the relative stability of the MTF against pupil changes, at least in the 5–3 mm pupil diameter range.

Figure 3 shows the MTF (5 mm pupil diameter) for three different object planes 5, 1, and 0.4 m.

Simulations that consider the eccentric location of the fovea and IOL tilt and decentration showed that, except for specific combinations of these parameters, through-focus image quality drops off axis.

The final optical performance depends on the particular eye, specifically, the corneal model, where the IOL is implanted. Particularly, we evaluated our 22-D MIOL in different eye models. First, with corneas where the anterior corneal asphericities ranged from −0.2 to +0.2 (typical variations reported in the literature [13]) with respect to the pseudophakic-design model. The amount of spherical aberration was kept fixed (Fig. 4) by varying the interface geometry in a multilayer cornea model [10].

Second, we used eye models with different amounts of spherical aberration (Fig. 5).

Figure 4 shows that the multifocal optical performance is preserved in eyes with similar spherical aberration, regardless of the specific geometry (asphericity) of the particular cornea, at least in the absence of asymmetric aberrations.

The spherical aberration of the corneas in the pseudophakic eye model used to generate the data shown in Fig. 5 were obtained using the standard deviation of the measured corneal spherical aberration in the population of the study by Guirao et al. ($\sigma = \pm 0.054$ μm) [14]. The following corneal spherical aberrations were used in the six tested artificial eye models (for 5 mm pupil diameters): two eyes with 0.19 and 0.13 μm corneal spherical aberration (within one 0.5σ of the average, thus covering 38.3% of the potential population); two eyes with 0.21- and 0.11 μm spherical aberration (within σ of the average, thus covering 68.3% of total population); two eyes with
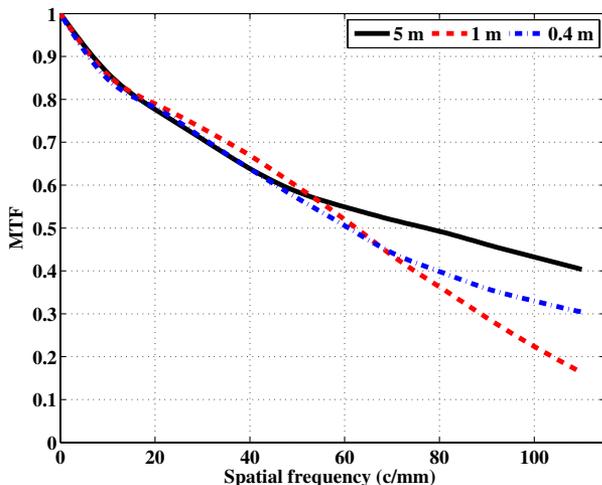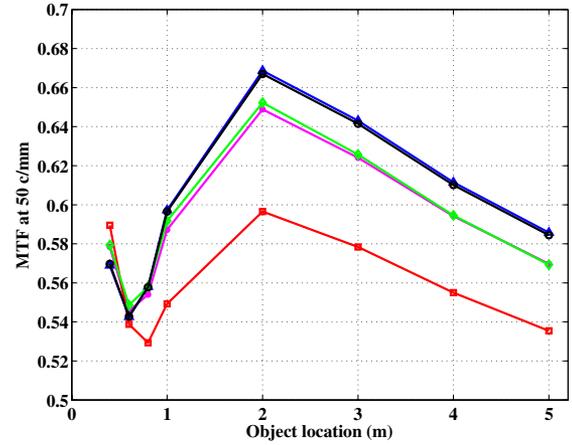

Fig. 4. Predicted MTF at 50 c/mm (5 mm pupil diameter) in four different pseudophakic eye models with different corneal geometries but the same corneal spherical aberration ($Z_{40} = 0.16$ μm, 5 mm pupil diameter) implanted with the new MIOL (22 D), as a function of the object location.

0.27- and 0.05 μm corneal spherical (within 2σ, 95.4% of total population).

Figure 5 shows the MTF at 50 c/mm as a function of the object distance for these six eye models, as well as for the design model, as a reference. The MTF remains above 0.4 for the eye models with corneal spherical aberrations within $\pm 0.5\sigma$ with respect to that of the design eye model, at all object locations. This implies that a potentially high multifocal behavior is achievable for almost 40% of the patients. For eye models with corneal spherical aberration within $\pm\sigma$ or larger, the discrepancies from the optical performance of the design model are higher, particularly for intermediate distances, although the MTF values are higher than that of other MIOL reported in the literature with comparable modulations for near and far distances [15].

An alternative approach for patients with corneal spherical aberrations far from the average population is the customization of the MIOL design allowing optimal
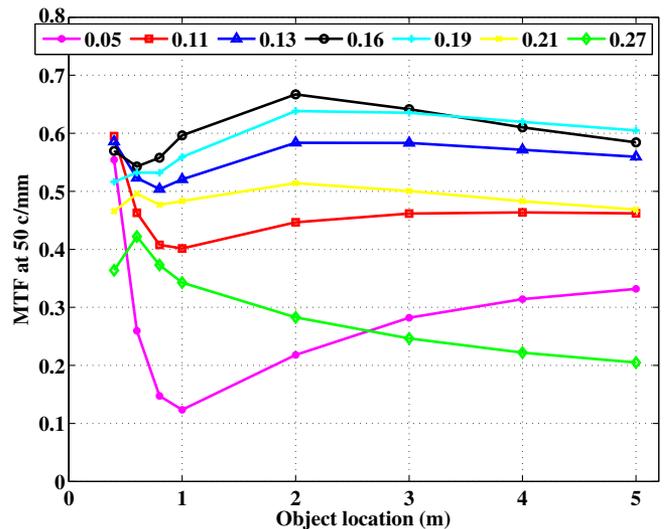

Fig. 3. MTF of the pseudophakic-design eye model implanted with the new MIOL (22 D).

Fig. 5. Predicted MTF at 50 c/mm of seven pseudophakic eye models with different amounts of corneal spherical aberration (Z_{40} in μm and 5 mm pupil diameter) implanted with the new MIOL (22 D), as a function of object location. Black circles represent the designed eye model.

performance on an individual basis. The methodology proposed in this Letter is particularly suitable for designing such customized MIOLs, as it would only require adapting the pseudophakic eye model used for the design to the anatomical parameters of the patient's eye (available clinically through ocular biometry [16]). Also, the same approach can be used to design MIOLs for a wide range of optical powers. In particular, we explored MIOL designs with far distance powers ranging from +10 to +30 D [9].

The results shown in Fig. 5 also suggest the possibility of generating MIOL catalogs using a trade-off strategy between generic and customized MIOL designs. For each power, several MIOLs could be designed using pseudophakic eye models that would uniformly cover a wide range of corneal spherical aberrations ($\pm 2\sigma$) previously mentioned. For example, a set of four designs for each power obtained from the corresponding corneal spherical aberrations models (-1.5, -0.5, 0.5, and 1.5σ with respect to the population average) would theoretically provide for any subject a MIOL, which would keep the MTF above 0.5 at all object locations.

Finally, we note that custom model eyes with real anatomical information will also allow us to evaluate the effects of IOL positioning and other surgical variables on the performance of the new MIOLs on patients [16,17].

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