Aberration-free intraocular lenses – What does this really mean?

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Abstract

Background: *So-called aberration-free intraocular lenses (IOLs) are well established in modern cataract surgery. Usually, they are designed to perfectly refract a collimated light beam onto the focal point.*

Methods: *We show how much aberration can be expected with such an IOL in a convergent light beam such as that found anterior to the human cornea. Additionally, the aberration in a collimated beam is estimated for an IOL that has no aberrations in the convergent beam. The convergent beam is modelled as the pencil of rays corresponding to the spherical wavefront resulting from a typical corneal power of 43 m^{-1}. The IOLs are modelled as infinitely thin phase plates with 20 m^{-1} optical power placed 5 mm behind the cornea. Their aberrations are reported in terms of optical path length difference and longitudinal spherical aberration (LSA) of the marginal rays, as well as nominal spherical aberration (SA) calculated based on a Zernike representation of the wavefront-error at the corneal plane within a 6 mm aperture.*

Results: *The IOL designed to have no aberrations in a collimated light beam has an optical path length difference of −1.8 μm, and LSA of 0.15 m^{-1} in the convergent beam of a typical eye. The corresponding nominal SA is 0.065 μm. The IOL designed to have no aberrations in a convergent light beam has an optical path length difference of 1.8 μm, and LSA of −0.15 m^{-1} in the collimated beam.*

Aberrationsfreie Intraokularlinsen für die Kataraktchirurgie – Was ist damit gemeint?

Zusammenfassung

Hintergrund und Zielsetzung: *Sogenannte aberrationsfreie Intraokularlinsen (IOL) sind in der modernen Kataraktchirurgie weit verbreitet. In der Regel sind sie so gestaltet, dass sie einen kollimierten Lichtstrahl perfekt auf den Fokus-Punkt brechen.*

Methoden: *Wir zeigen wie viel Aberration mit einer solchen IOL in einem konvergenten Strahlengang, wie er hinter der menschlichen Hornhaut vorkommt, erwartet werden kann. Darüber hinaus, wird die Aberration im kollimierten Strahlengang abgeschätzt, die eine IOL, die im konvergenten Strahlengang keine Aberration induziert, induziert. Der Konvergente Strahlengang ist durch die sphärische Wellenfront modelliert, die mit einer typischen Hornhautbrechkraft von 43 m^{-1} erwartet werden kann. Die IOL sind als dünne Phasenplatten mit 20 m^{-1} Brechkraft modelliert und befinden sich 5 mm hinter der Hornhaut. Ihre Aberration wird als optische Weglängendifferenz und longitudinale Aberration (LSA) der Randstrahlen, sowie als nominelle sphärische Aberration (SA) basierend auf einer Zernike-Darstellung des Wellenfront-Fehlers auf Hornhautebene innerhalb einer 6 mm Apertur angegeben.*

Ergebnisse: *Die IOL ohne Aberration im kollimierten Strahlengang liefert eine optische Weglängendifferenz von −1.8 μm und LSA von 0.15 m^{-1} im konvergenten Strahlengang. Die zugehörige nominelle SA ist 0.065 μm. Die IOL ohne Aberration im konvergenten*

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Conclusions: *An IOL designed to have no aberrations in a collimated light beam will increase the SA of a patient's eye after implantation.*

Keywords: IOL concepts, Optical simulation, Aspheric IOL, Optical design, Aberration neutral IOL, Corneal aberration

Strahlengang liefert eine optische Weglängendifferenz von 1,8 μm und LSA von -0.15 m^{-1} im kollimierten Strahlengang.

Schlussfolgerung: *Wenn eine IOL so ausgelegt ist, dass sie im kollimierten Strahlengang keine Aberration aufweist, dann erhöht sie die SA des Patientenauges nach der Implantation.*

Schlüsselwörter: IOL Konzepte, Optische Simulation, Asphärische IOL, Optisches Design, Aberrationsneutrale IOL, Korneale Aberration

Background

In the last 2 decades many different intraocular lens (IOL) concepts have been developed, including toric lenses, bi- or multifocal lenses [3], blue light filtering lenses, and aspherical designs. Aspheric lenses are often subdivided into aberration correcting lenses which aim to correct, for instance, the average spherical aberration (SA) of the cornea, and aberration-free lenses which are expected to act neutrally in terms of SA [3,10]. In other words, these aberration-free lenses are assumed neither to add any SA (such as occurs with spherical IOLs), nor to correct SA of the cornea.

The influence of an IOL on the total ocular SA is often quantified by the nominal SA, which many IOL manufacturers provide for their aspherical IOLs. It refers to the difference of the Zernike coefficient of primary SA calculated from the Zernike-decomposition of the wavefront error at the corneal plane with and without the IOL, based on a standard schematic model eye (e.g. the Liou Brennan eye [5,6] or the Navarro model eye [9]). The nominal SA allows surgeons to select appropriate aspherical IOLs based on the corneal topography or tomography of a given patient's eye.

In several patents aberration-free IOLs are described to have no aberration in a setup with a collimated light beam [4]. Their aberration-free property can easily be verified in an optical setup with a collimated light beam and a variable aperture size: the position of best focus must be identical for all aperture diameters [7].

The purpose of this article is to show how much aberration may be expected with such an IOL in a convergent light beam such as that found behind the human cornea. Additionally, the aberration in a collimated light beam is estimated for an IOL that has no aberrations in the convergent beam.

Methods

The IOLs are modelled as thin phase plates. They are optimized and tested in two different settings: Setting 1: a plano wavefront (collimated light beam impinging the IOL) which is focused by the IOL of power P at focal distance $f = 1/P$ behind the IOL, Setting 2: a spherical wavefront which is focused by the IOL to an image distance $b = (1/b + 1/R)^{-1}$ behind the IOL. The radius of curvature R of the wave front is given by

$$R = \frac{1.3375}{K_C} - (ELP + 0.06\text{mm}), \tag{1}$$

where $K_C = 43\,\text{m}^{-1}$ refers to the refractive power of the cornea, and $ELP = 5$ mm to the predicted IOL position (effective lens position) measured from the anterior corneal center to the lens-plane.

First, we calculate the phase plate $\vartheta_=(r)$ (radial coordinate r) that will have no aberrations in Setting 1. The optical path length from the lens plane to the focal point is

$$\varphi_=(r) = n\sqrt{r^2 + f^2}. \tag{2}$$

The refractive index of the surrounding medium is $n = 1.336$ [6]. All optical path lengths are set to the reference path length $\varphi_=(0)$ resulting in

$$\vartheta_=(r) = nf - \varphi_=(r). \tag{3}$$

Then, we calculate the phase plate $\vartheta_>(r)$ that will have no aberrations in Setting 2. To get the optical path length $\varphi_>(r)$ from the lens plane to the image point, the focal length f in Eq. (2) must be replaced by the image distance b. The corneal phase function

$$\varphi_C(r) = n(R - \sqrt{r^2 + R^2}) \tag{4}$$

represents the optical path length offset of the incoming spherical wavefront at the IOL's position. All optical path lengths are set to the reference path length $\varphi_>(0)$ resulting in

$$\vartheta_>(r) = nb - \varphi_C(r) - \varphi_>(r). \tag{5}$$

Finally, phase plate $\vartheta_=(r)$ (Eq. (3)) is tested in setting 2 and phase plate $\vartheta_>(r)$ (Eq. (5)) in setting 1. Optical path length