Chapter

Aberration Correction with Aspheric Intraocular Lenses

Timo Eppig, Jens Schrecker, Arthur Messner and Achim Langenbucher

Abstract

The shape of the normal human cornea induces positive spherical aberration (SA) which causes image blur. In the young phakic eye, the crystalline lens compensates for a certain amount of this corneal aberration. However, the compensation slowly decreases with the aging lens and is fully lost after cataract extraction and implantation of a standard intraocular lens (IOL). Conventional spherical IOLs add their intrinsic positive SA to the positive SA of the cornea increasing the image blur. As a useful side effect, this also increases the depth of focus—often referred to as pseudo-accommodation. Aspheric intraocular lenses have been introduced to be either neutral to SA or to compensate for a certain amount of corneal SA. A customized correction for the individual eye seems to be the most promising solution for tailored correction of SA. In this chapter we will provide detailed information on the various concepts of aspheric intraocular lenses to elucidate that the term "aspheric intraocular lens" is being used for a large amount of different lens designs.

Keywords: spherical aberration, aspheric surface, customized intraocular lens, decentration, tilt

1. Introduction

The disease pattern of cataract comprises pathologic conditions of the human eye resulting from an opacification of the crystalline lens. The most frequent causes for the development of cataract are age-related transformation processes. Although research on pharmacologic treatment of cataract has been in focus for many years, the surgical extraction of the cloudy crystalline lens and implantation of an artificial intraocular lens (IOL)—referred to as cataract surgery—represent the only available treatment. Cataract surgery is one of the most frequently performed surgical procedures with several million surgeries being performed worldwide each year.

First IOL developments were primarily targeted on biocompatible materials and new fixation techniques rather than on correction of ocular aberrations other than defocus and astigmatism. First lens implants were made from polymethyl methacrylate, therefore being rigid and requiring large incisions for implantation. Furthermore, the optimum site of implantation (anterior chamber, iris, ciliary sulcus, or capsular bag) still had to be found, and adequate haptics for proper fixation had to be developed. Surgical results were therefore less predictable [1, 2].

In the early 1980s, foldable silicone materials and later acrylic materials allowed implantation through smaller ports and therefore caused less damage to the corneal structure allowing a faster rehabilitation. This finally facilitated ambulant cataract

surgery. In the following years, the capsular bag was identified as the optimum position for an IOLs, and the development of new lens power calculation formulas dramatically increased the predictability of the refractive outcome [1].

2. Aspheric lenses

With the improvement in IOL power calculation, the goal of cataract surgery became predictable; the focus of cataract surgery shifted from "restoration of vision" to "refractive surgery." Manufacturers started optimizing the IOL optic from an equiconvex spherical lens design to different aspheric surface profiles and finally multifocal and free-form surface designs. The buzzword of those days was "spherical aberration" (SA) which should be eliminated to improve contrast sensitivity and visual acuity. Spherical aberration is one of the monochromatic aberrations that is caused by the difference in focal length (or optical power) for varying aperture diameter of a lens. For positive spherical aberration, the optical power increases from the lens center to the periphery, and rays far from the optical axis will intersect the optical axis in front of the paraxial focus (**Figure 1**).

Any spherical optical surface causes SA. To achieve an equal distribution of optical power across the lens diameter, the optical surfaces have to be tailored accordingly. SA can only be reduced by varying the spherical radii of curvature of anterior and posterior surface yielding a so called best-form lens, but it cannot be eliminated. This can be achieved by implementing aspheric surfaces. There are basically two types of aspheric surfaces that have been described in the literature, the first one is referred to as "continuous asphere" and can be described by the formula

$$z = \frac{\frac{1}{r} \cdot \rho^2}{1 + \sqrt{1 - (1 - Q) \cdot \frac{1}{r^2} \rho^2}} + \sum_{n=1}^{n=8} a_{2n} \cdot \rho^{2n} + X \qquad (1)$$

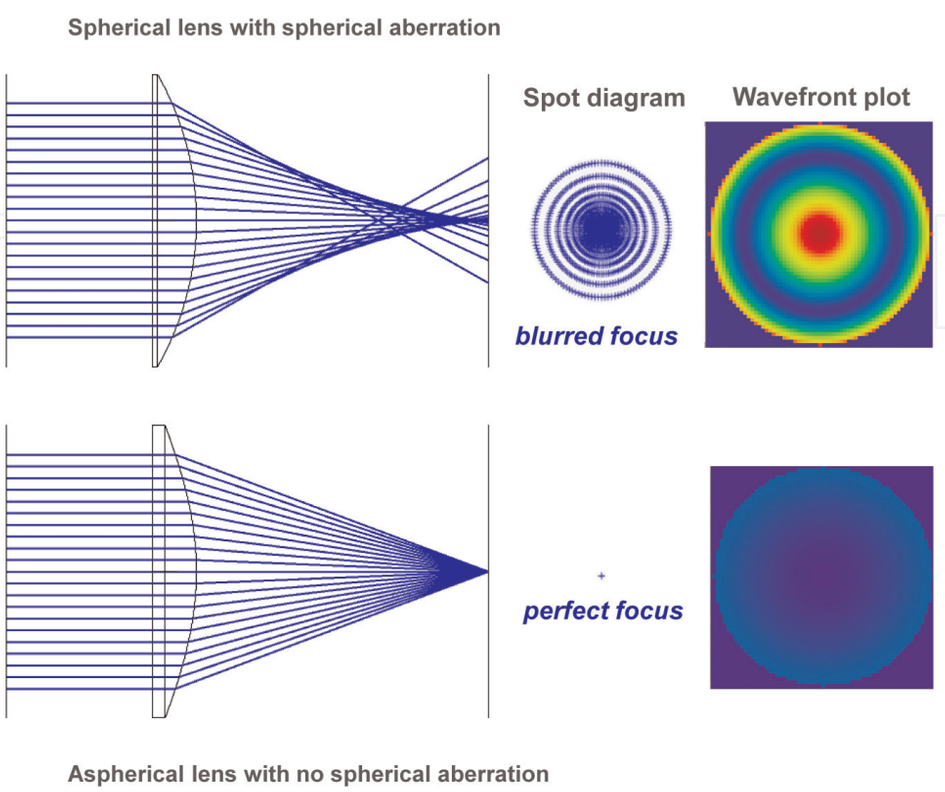

Figure 1.
Rays focused by a lens with positive spherical aberration (top) compared to a lens without spherical aberration (bottom) [4].

where z is the height of the surface from the apex (= 0 mm), r is the radius of curvature, and ρ is the radial coordinate from the center to the periphery. Q is called "asphericity" [3], and a_{2n} are higher-order aspheric coefficients. X is a placeholder for additional polynomials, such as Zernike polynomials, which can be used to define additional surface shapes. From this equation numerous aspheric surface profiles can be generated (**Figure 2**), and most of current aspheric intraocular lens designs are based on the formula above. Equation (1) can be expanded to represent toric and biconic surfaces as well. The asphericity Q is identical to the conic constant κ (often used in optical design software) and can be transformed from other shape definitions for the aspheric surface such as the eccentricity e or the index of eccentricity e^2 [3]:

$$Q = -e^2 \tag{2}$$

The second type of aspherical surfaces, called "zonal asphere," is constructed from a set of annular rings with varying radius of curvature and asphericity. For a detailed description of these surfaces, please refer to the literature [5, 6].

By modulating radius of curvature, asphericity, and aspheric coefficients, the SA induced by the surface can be customized. Additional polynomials can be added on top to create non-rotationally symmetric aspheric surfaces to compensate for higher-order errors such as coma or trefoil. For example, one alternate way to compensate for spherical aberration would be to modulate the aspherical surface with a linear combination of Zernike polynomials representing various orders of spherical aberration:

$$X = C_{11} \cdot Z_4^0 + C_{22} \cdot Z_6^0 + C_{37} \cdot Z_8^0 + \cdots \tag{3}$$

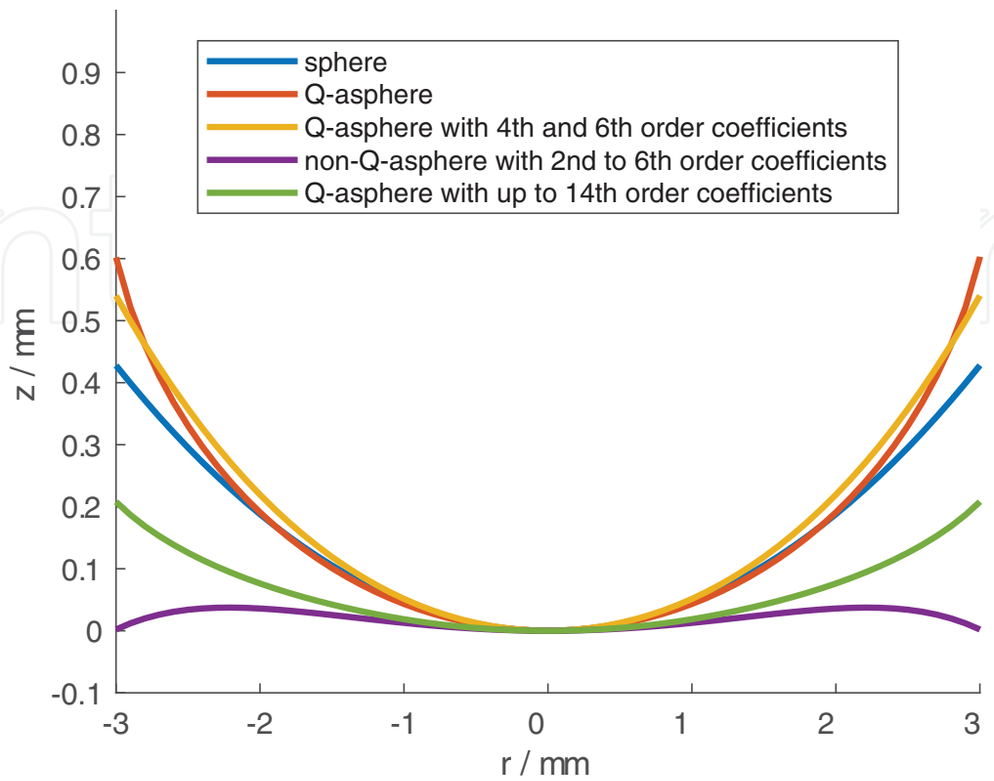

Figure 2.
Variation of optical surface section with increasing number of coefficients. z is the elevation relative to the surface apex. All curves are derived from intraocular lens designs for an average power (20 to 22 D) lens.

3. Corneal spherical aberration

As mentioned above, the average human cornea induces a significant portion of positive SA, which is typically being described by the Zernike coefficient Z_4^0 (spherical aberration) on a diameter of 6.0 mm at corneal plane. The amount of SA can be calculated from the corneal surface shape by optical ray tracing. A method to do so was described by Norrby et al. providing a reference value for the Liou-Brennan model eye [7, 8]. Calossi provided an overview of SA values for a limited set of variables [3].

Depending on the underlying database, various authors reported different values for the average corneal SA. Holladay et al. reported that the average SA of the human cornea is about +0.27 ± 0.20 μm (value misprinted in the original publication [9] and corrected by Norrby et al. [7]). Similar values were found by Beiko and Haigis (+0.274 ± 0.089 μm) [10]. The widely spread Liou-Brennan model eye provides about +0.258 μm of spherical aberration being close to the reported average clinical values [7, 8]. De Sanctis et al. found higher values in their patients (+0.328 ± 0.132 μm) [11], while Shimozono et al. found lower values (0.203 ± 0.100 μm) [12].

4. Correction of spherical aberration with IOLs

Aberration correction could be best described as a superposition of wave fronts as outlined in **Figure 3**.

During cataract surgery the corneal SA is typically increased by the likewise positive spherical aberration of a spherical IOL. Therefore, lens designers at first created the "aberration-free" or "aberration-neutral" lens concept, a lens design that was meant to eliminate its intrinsic spherical aberration and thus being neutral to the eye's overall SA [13]. However, the amount of SA is highly depending on the vergence of the incident rays. Therefore, there are differences in the design of "aberration-neutral" lenses: some of them are designed to be neutral to SA in a collimated beam, e.g., a beam as such could be used in measurement instrumentation. Others are designed to be neutral to SA behind some generic model cornea (in a converging beam). Both of them will exhibit a considerable amount of SA when implanted in a real eye; the first will provide a small correction for SA, while the latter may provide

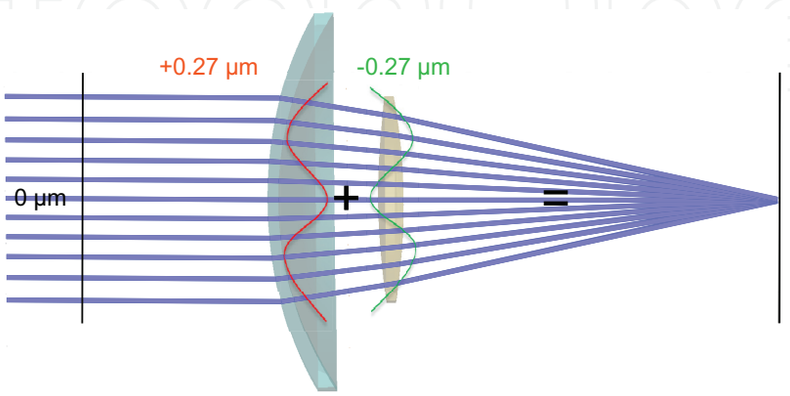

Figure 3.
Simplified sketch of the principle of aberration correction: An impinging plane wave front (collimated beam) is refracted by the cornea and affected by spherical aberration (red); the intraocular lens (yellow) compensates for the same amount of spherical aberration (green) resulting in a perfect wave front at the focus plane. Note: The plotted wave fronts do not account for the defocus.

Manufacturer	Product	SA correction
Johnson & Johnson Vision, Groningen, The Netherlands	TECNIS	−0.27 μm [9]
HOYA, Nagoya, Japan	Vivinex XC1	−0.18 μm [17, 18]
Carl Zeiss Meditec, Berlin, Germany	CT ASPHINA 509MP	−0.18 μm [18]
Alcon Laboratories, Forth Worth, TX, USA	AcrySof IQ SN60WF	−0.17 μm [17]
Bausch + Lomb, Rochester, NY, USA	EyeCee One	−0.14 μm [18]
	Quatrix Evolutive	−0.1 μm [18]
PhysIOL, Liege, Belgium	PODeye	−0.11 μm [18]
Kowa Pharmaceuticals, Düsseldorf, Germany	AvanSee	−0.04 [18]

Table 1.
List of selected intraocular lens models providing correction of spherical aberration.

negligible change to the corneal SA. When being analyzed on an optical bench (in a collimated beam), both lenses will show the opposite characteristics [4].

Aberration-correcting designs evolved subsequently, providing compensation to a fixed amount of corneal SA. One of the first aberration-correcting lenses was presented by Holladay et al. providing a correction of −0.27 μm and thus targeting on the average SA found in human eyes [9].

Today, surgeons may choose from a variety of aspheric IOLs with different amount of compensation for SA (**Table 1**). Theoretically, one could choose the IOL providing the optimum correction for an eye. This would require preoperative examination of corneal topography and analysis of corneal aberrations. Diagnostic instrumentation for the anterior segment such as the Pentacam (Oculus Optikgeräte GmbH, Wetzlar, Germany) or the CASIA2 (Tomey Corp., Nagoya, Japan) allow direct readout of the SA amount over 6 mm diameter. The SA value calculated from corneal tomographic data could then be used to select an IOL model that provides best correction. Still, since the range of IOLs with different SA corrections is limited, not every eye could be supplied with optimum correction. Clinical results with this "selection method" are controversial but indicate the potential for improvement [14–16]. Piers et al. found that contrast sensitivity peaks with 0 μm of SA [17]. On the contrary, other investigators found that a residual SA of about +0.1 μm may be beneficial for visual performance [18–20]. Manzanera and Artal argued that changes in SA between −0.17 and + 0.2 μm are merely noticeable by patients [21]. This may be an explanation why the differences in visual performance between aberration-free and aberration-correcting lenses are usually small.

The next logical step is a compensation procedure based on the true individual SA, rather than on average values. Wang et al. found that not only SA should be considered but the full spectrum of corneal aberrations [22–24]. Especially eyes with high amounts of spherical aberration such as eyes after laser refractive surgery or eyes with forme fruste keratoconus could benefit more from customized correction of SA [22, 23, 25] than normal eyes, if centration of the implant can be kept within strict limits. Therefore, an optimum solution could be the customization of intraocular lenses [26, 27]. Several researchers provided theoretical basics and theoretical results showing the potential of customized intraocular lenses [28–31]. The design process of such IOLs requires the implementation of customized model eyes based on biometric data and the use of ray tracing technology [28, 32–36]. The first clinical results with this method have recently been published showing promising results [37].

5. Limitations of aberration-correcting lenses

A major limitation for the selection of the appropriate IOL is the accuracy and repeatability of the preoperative corneal topography. The calculation of corneal SA requires highest precision of corneal topography in the periphery, since the difference in elevation between an aspheric corneal surface and a spherical surface is only some microns (**Figure 4**). Schröder et al. investigated the measurement repeatability and precision of several corneal topographers and tomographers and found that the repeatability of these devices is decreasing from the center to the periphery and may not be sufficient to detect small changes in corneal asphericity [38].

Another limitation arises from the concept of aberration correction itself. As outlined in **Figure 3**, the method requires the alignment of the IOL in relation to the cornea to be as perfect as possible. But even if an ideal positioning of the IOL is achieved intraoperatively, the risk of decentration or tilt remains in the postoperative course.

Altmann et al., Eppig et al., and others analyzed the effects of decentration and tilt of spherical and aspherical IOLs on the image quality and found that it is more affected by decentration than by tilt and that the susceptibility of lens misalignment increases with the amount of SA to be corrected [9, 39–46]. Some authors defined that a range of decentration within a SA-correcting IOL would perform better or equal than a standard spherical IOL. This range was reported to be between 0.0 and 0.3–0.8 mm, depending on the design of the lens and simulation conditions [9, 40–42]. In a previous publication, we summarized the data on the IOL decentration from various sources and found that the clinically observed decentration is between 0 and 1 mm but most frequently about 0.3 mm [33, 40, 47–56]. Others showed that there is a tendency for IOLs decentering and tilting into nasal direction with mirror symmetry between both eyes [51].

Gillner et al. showed in a previous publication that IOL designs with a more conservative correction of SA may provide a larger range of tolerance to decentration [41]. Examples thereof are the ZO/ASPHINA design (Carl Zeiss Meditec AG, Berlin, Germany) and the Aspheric Balanced Curve Design (ABCD) (Hoya Corporation, Tokyo, Japan). Both designs are based on higher-order

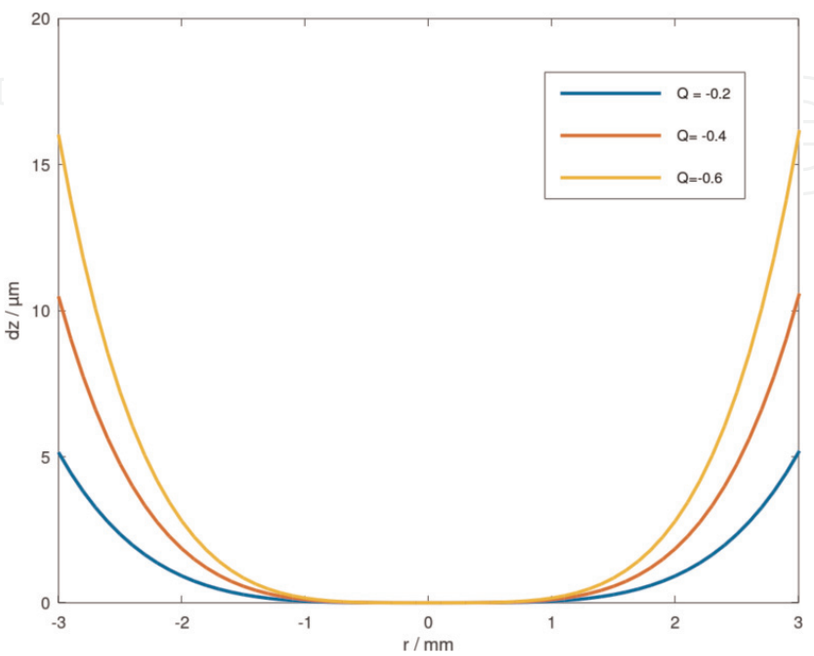

Figure 4.
Difference in corneal elevation for three surfaces with R = 7.77 mm radius of curvature and several values of Q compared to a sphere.

aspherics including coefficients a_4 and higher (see Eq. 1) and were specifically designed considering some reasonable amount of IOL decentration. The effect of decentration on image performance of some selected IOL designs is shown in **Figures 5** and **6**. The graphs exhibit a drop of the image quality with aspheric lenses below the image quality of a spherical IOL when decentration exceeds 0.4 and 0.3 mm, respectively.

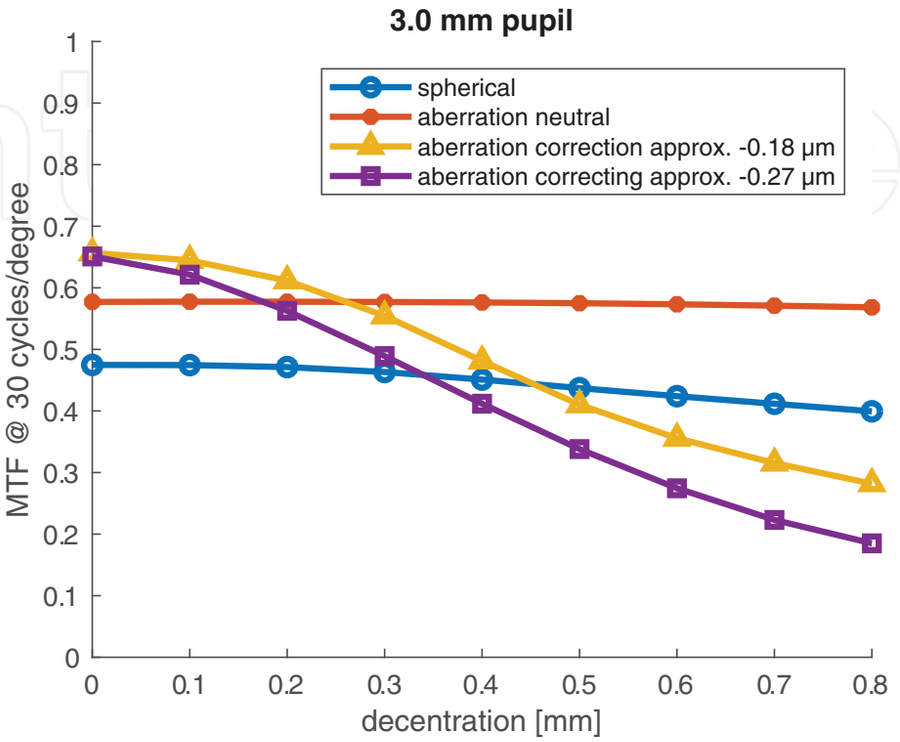

Figure 5.
Simulation of modulation transfer function at 30 cycles per degree for four different intraocular lenses and a pupil diameter of 3.0 mm in the Liou-Brennan model eye as a function of decentration [40, 41, 57].

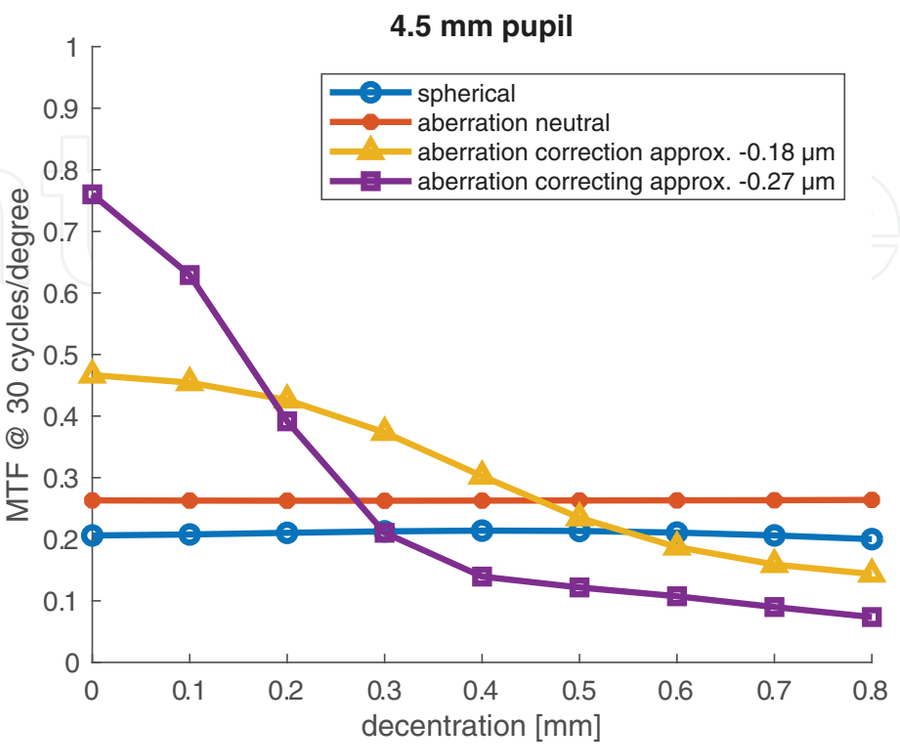

Figure 6.
Simulation of modulation transfer function at 30 cycles per degree for four different intraocular lenses and a pupil diameter of 4.5 mm in the Liou-Brennan model eye as a function of decentration [40, 41].

6. Conclusions

Correcting the spherical aberration of the cornea by intraocular lenses may improve the visual outcome compared to standard spherical lenses. Especially patients with high aberrations after corneal refractive surgery may benefit from a reduction of the overall aberrations. However, the prospects for a 100% correction of SA or aiming to a residual SA of +0.1 μm are limited with respect to an ideal and stable IOL. Therefore, any generic or customized IOL concept pursuing an aberration correction of aberrations, such as astigmatism, spherical aberration, coma, etc. must be designed with a tolerance according to the average expected misalignment in normal eyes (approximately 0–0.3 mm decentration and 0–3 degrees of tilt) [40, 57]. Consequently, this likewise limits the correctability of some higher-order aberrations. Eyes after corneal refractive surgery usually show very high values of SA and require special attention in the planning of cataract surgery. While eyes after myopic refractive procedures might benefit from a negative SA IOL [22], eyes after hyperopic refractive procedures often show high-negative SA and would require an IOL with positive SA for compensation [23]. Due to the high variability of SA in cataract patients, the "one-size-fits-all" approach may only provide optimum correction for a small amount of patients. Therefore, customized intraocular lenses tailored to correct for the individual spherical aberration may provide a better solution for a wide range of patients.

Author details

Timo Eppig[1,2*], Jens Schrecker[3], Arthur Messner[1] and Achim Langenbucher[2]

1 AMIPLANT GmbH, Schnaittach, Germany

2 Institute of Experimental Ophthalmology, Saarland University, Homburg, Germany

3 Department of Ophthalmology, Rudolf-Virchow-Klinikum, Glauchau, Germany

*Address all correspondence to: timo.eppig@uks.eu

References

[1] Auffarth GU, Apple DJ. Zur Entwicklungsgeschichte der Intraokularlinsen. Der Ophthalmologe. 2001;**98**(11):1017-1028

[2] Apple DJ. Sir Harold Ridley and his Fight for Sight: He Changed the World so that we May Better See it. 10th ed. Thorofare, NJ, USA: Slack Inc.; 2006

[3] Calossi A. Corneal asphericity and spherical aberration. Journal of Refractive Surgery. 2007;**23**(5):505-514

[4] Eppig T, Schröder S, Schrecker J, et al. Do aberration neutral intraocular lens designs effectively induce no spherical aberration? In: 35th Congress of the European Society of Cataract and Refractive Surgery. Lisbon 2017. Available from: https://www.escrs.org/abstracts/details.asp?confid=24&sessid=1078&type=poster&paperid=28779 [Accessed: 09 August 2019]

[5] Smith G, Atchison DA. Construction, specification, and mathematical description of aspheric surfaces. American Journal of Optometry and Physiological Optics. 1983;**60**(3):216-223

[6] Atchison DA. Design of aspheric intraocular lenses. Ophthalmic and Physiological Optics. 1991;**11**(2):137-146

[7] Norrby S, Piers P, Campbell C, et al. Model eyes for evaluation of intraocular lenses. Applied Optics. 2007;**46**(26):6595-6605

[8] Liou H-L, Brennan NA. Anatomically accurate, finite model eye for optical modeling. Journal of the Optical Society of America. A. 1997;**14**(8):1684-1695

[9] Holladay JT, Piers PA, Koranyi G, et al. A new intraocular lens design to reduce spherical aberration of pseudophakic eyes. Journal of Refractive Surgery. 2002;**18**(6):683-691

[10] Beiko GHH, Haigis W, Steinmueller A. Distribution of corneal spherical aberration in a comprehensive ophthalmology practice and whether keratometry can predict aberration values. Journal of Cataract and Refractive Surgery. 2007;**33**(5):848-858

[11] de Sanctis U, Vinai L, Bartoli E, et al. Total spherical aberration of the cornea in patients with cataract. Optometry and Vision Science. 2014;**91**(10):1251-1258

[12] Shimozono M, Uemura A, Hirami Y, et al. Corneal spherical aberration of eyes with cataract in a Japanese population. Journal of Refractive Surgery. 2010;**26**(6):457-459

[13] Langenbucher A, Schröder S, Cayless A, et al. Aberration-free intraocular lenses—what does this really mean? Zeitschrift für Medizinische Physik. 2017;**27**(3):255-259

[14] Nochez Y, Favard A, Majzoub S, et al. Measurement of corneal aberrations for customisation of intraocular lens asphericity: Impact on quality of vision after micro-incision cataract surgery. The British Journal of Ophthalmology. 2010;**94**(4):440-444

[15] Tan Q-Q, Lin J, Tian J, et al. Objective optical quality in eyes with customized selection of aspheric intraocular lens implantation. BMC Ophthalmology. 2019;**19**(1):152

[16] Jia L-X, Li Z-H. Clinical study of customized aspherical intraocular lens implants. International Journal of Ophthalmology. 2014;7(5):816-821

[17] Piers PA, Manzanera S, Prieto PM, et al. Use of adaptive optics to determine the optimal ocular spherical aberration. Journal of Cataract and Refractive Surgery. 2007;**33**(10):1721-1726

[18] Nochez Y, Majzoub S, Pisella P-J. Effect of residual ocular spherical aberration on objective and subjective quality of vision in pseudophakic eyes. Journal of Cataract and Refractive Surgery. 2011;**37**(6):1076-1081

[19] Werner JS, Elliott SL, Choi SS, et al. Spherical aberration yielding optimum visual performance: Evaluation of intraocular lenses using adaptive optics simulation. Journal of Cataract and Refractive Surgery. 2009;**35**(7): 1229-1233

[20] Ferrer-Blasco T. Effect of partial and full correction of corneal spherical aberration on visual acuity and contrast sensitivity. Journal of Cataract and Refractive Surgery. 2009;**35**(5):949-951

[21] Manzanera S, Artal P. Minimum change in spherical aberration that can be perceived. Biomedical Optics Express. 2016;**7**(9):3471-3477

[22] Wang L, Pitcher JD, Weikert MP, et al. Custom selection of aspheric intraocular lenses after wavefront-guided myopic photorefractive keratectomy. Journal of Cataract and Refractive Surgery. 2010;**36**(1):73-81

[23] Wang L, Shoukfeh O, Koch DD. Custom selection of aspheric intraocular lens in eyes with previous hyperopic corneal surgery. Journal of Cataract and Refractive Surgery. 2015;**41**(12): 2652-2663

[24] Koch DD, Wang L. Custom optimization of intraocular lens asphericity. Transactions of the American Ophthalmological Society. 2007;**105**:36-41; discussion 41-42

[25] Schröder S, Eppig T, Liu W, et al. Keratoconic eyes with stable corneal tomography could benefit more from custom intraocular lens design than normal eyes. Scientific Reports. 2019; **9**(1):3479

[26] Altmann GE. Wavefront-customized intraocular lenses. Current Opinion in Ophthalmology. 2004;**15**(4): 358-364

[27] Beiko GHH. Personalized correction of spherical aberration in cataract surgery. Journal of Cataract and Refractive Surgery. 2007;**33**(8): 1455-1460

[28] Einighammer J, Oltrup T, Feudner E, et al. Customized aspheric intraocular lenses calculated with real ray tracing. Journal of Cataract and Refractive Surgery. 2009;**35**(11): 1984-1994

[29] Langenbucher A, Eppig T, Seitz B, et al. Customized aspheric IOL design by raytracing through the eye containing quadric surfaces. Current Eye Research. 2011;**36**(7):637-646

[30] Langenbucher A, Janunts E, Seitz B, et al. Theoretical image performance with customized aspheric and spherical IOLs - when do we get a benefit from customized aspheric design? Zeitschrift für Medizinische Physik. 2014;**24**(2): 94-103

[31] Piers PA, Weeber HA, Artal P, et al. Theoretical comparison of aberration-correcting customized and aspheric intraocular lenses. Journal of Refractive Surgery. 2007;**23**(4):374-384

[32] Zhu Z, Janunts E, Eppig T, et al. Tomography-based customized IOL calculation model. Current Eye Research. 2011;**36**(6):579-589

[33] Rosales P, Marcos S. Customized computer models of eyes with intraocular lenses. Optics Express. 2007; **15**(5):2204-2218

[34] Ortiz S, Pérez-Merino P, Durán S, et al. Full OCT anterior segment biometry: An application in cataract surgery. Biomedical Optics Express. 2013;**4**(3):387-396

[35] Sun M, Pérez-Merino P, Martinez-Enriquez E, et al. Full 3-D OCT-based pseudophakic custom computer eye model. Biomedical Optics Express. 2016; **7**(3):1074-1088

[36] Preussner P-R, Wahl J, Lahdo H, et al. Ray tracing for intraocular lens calculation. Journal of Cataract and Refractive Surgery. 2002;**28**(8): 1412-1419

[37] Schrecker J, Langenbucher A, Seitz B, et al. First results with a new intraocular lens design for the individual correction of spherical aberration. Journal of Cataract and Refractive Surgery. 2018;**44**(10):1211-1219

[38] Schröder S, Mäurer S, Eppig T, et al. Comparison of corneal tomography: Repeatability, precision, misalignment, mean elevation, and mean pachymetry. Current Eye Research. 2018;**43**(6): 709-716

[39] Altmann GE, Nichamin LD, Lane SS, et al. Optical performance of 3 intraocular lens designs in the presence of decentration. Journal of Cataract and Refractive Surgery. 2005;**31**(3):574-585

[40] Eppig T, Scholz K, Löffler A, et al. Effect of decentration and tilt on the image quality of aspheric intraocular lens designs in a model eye. Journal of Cataract and Refractive Surgery. 2009; **35**(6):1091-1100

[41] Gillner M, Langenbucher A, Eppig T. Untersuchung der theoretischen Abbildungsqualität asphärischer Intraokularlinsen bei Dezentrierung. Hoya AF-1 iMics1 und Zeiss ASPHINA(TM) (Invent ZO). Der Ophthalmologe. 2012;**109**(3):263-270

[42] Pieh S, Fiala W, Malz A, et al. In vitro strehl ratios with spherical, aberration-free, average, and customized spherical aberration-correcting intraocular lenses. Investigative Ophthalmology and Visual Science. 2009;**50**(3):1264-1270

[43] Ortiz C, Esteve-Taboada JJ, Belda-Salmerón L, et al. Effect of decentration on the optical quality of two intraocular lenses. Optometry and Vision Science. 2016;**93**(12):1552-1559

[44] Dietze HH, Cox MJ. Limitations of correcting spherical aberration with aspheric intraocular lenses. Journal of Refractive Surgery. 2005;**21**(5):S541-S546

[45] Turuwhenua J. A theoretical study of intraocular lens tilt and decentration on perceptual image quality. Ophthalmic and Physiological Optics. 2005;**25**(6):556-567

[46] Pérez-Merino P, Marcos S. Effect of intraocular lens decentration on image quality tested in a custom model eye. Journal of Cataract and Refractive Surgery. 2018;**44**(7):889-896

[47] Kim JS, Shyn KH. Biometry of 3 types of intraocular lenses using Scheimpflug photography. Journal of Cataract and Refractive Surgery. 2001; **27**(4):533-536

[48] Taketani F, Matuura T, Yukawa E, et al. Influence of intraocular lens tilt and decentration on wavefront aberrations. Journal of Cataract and Refractive Surgery. 2004;**30**(10): 2158-2162

[49] Baumeister M, Neidhardt B, Strobel J, et al. Tilt and decentration of three-piece foldable high-refractive silicone and hydrophobic acrylic intraocular lenses with 6-mm optics in an intraindividual comparison. American Journal of Ophthalmology. 2005;**140**(6):1051-1058

[50] Mutlu FM, Erdurman C, Sobaci G, et al. Comparison of tilt and decentration of 1-piece and 3-piece hydrophobic acrylic intraocular lenses.

Journal of Cataract and Refractive Surgery. 2005;**31**(2):343-347

[51] de Castro A, Rosales P, Marcos S. Tilt and decentration of intraocular lenses in vivo from Purkinje and Scheimpflug imaging. Validation study. Journal of Cataract and Refractive Surgery. 2007;**33**(3):418-429

[52] Mester U, Heinen S, Kaymak H. Klinische Ergebnisse unter besonderer Berücksichtigung von Dezentrierung und Verkippung der asphärischen Intraokularlinse FY-60AD. Der Ophthalmologe. 2010;**107**(9):831-836

[53] Choi SK, Kim JH, Lee D, et al. IOL tilt and decentration. Ophthalmology. 2010;**117**(9):1862, 1862.e1-1862, 1862.e4

[54] Sauer T, Mester U. Tilt and decentration of an intraocular lens implanted in the ciliary sulcus after capsular bag defect during cataract surgery. Graefe's Archive for Clinical and Experimental Ophthalmology. 2013;**251**(1):89-93

[55] Wang X, Dong J, Wang X, et al. IOL tilt and decentration estimation from 3 dimensional reconstruction of OCT image. PLoS One. 2013;**8**(3):e59109

[56] Findl O, Hirnschall N, Nishi Y, et al. Capsular bag performance of a hydrophobic acrylic 1-piece intraocular lens. Journal of Cataract and Refractive Surgery. 2015;**41**(1):90-97

[57] Ale JB. Intraocular lens tilt and decentration: A concern for contemporary IOL designs. Nepalese Journal of Ophthalmology. 2011;**3**(1): 68-77