

Retinal images in optomechanical eye model with monofocal intraocular lens

AGNIESZKA JÓŻWIK*, JERZY NOWAK, DAMIAN SIEDLECKI, MAREK ZAJĄC, JÓZEF ZARÓWNY

Institute of Physics, Wrocław University of Technology,
Wybrzeże Wyspiańskiego 27, 50-370 Wrocław, Poland

*Corresponding author: agnieszka.jozwik@pwr.wroc.pl

Intraocular lens (IOL) is an artificial lens implanted into the eye. It usually replaces the existing crystalline lens, which is clouded over due to a cataract. In order to evaluate the optical performance of different IOLs an optomechanical model of human eye was developed. This model closely reproduces anatomical and optical properties of the average human eye. This makes it possible to measure the optical performance of different types of intraocular lenses and to estimate the influence of their location in eye on quality of vision. Four monofocal intraocular lenses were taken for analysis. The analysis of the quality of retinal images was carried out by means of either qualitative image comparison or physical quantities estimation. The analysis of LSF and MTF shows that the performance of the lenses tested changes slightly with differences in their design and/or material.

Keywords: intraocular lens, artificial eye model, imaging quality, cataract.

1. Introduction

Cataract means an opacification of the crystalline lens which leads to a significant retinal image degradation and therefore to substantial decrease of patient's quality of vision. It is still one of the most frequent causes of blindness [1, 2]. Up to now the most effective method of cataract treatment is based on extraction of the opaque crystalline lens and replacing it with an artificial implant (intraocular lens, IOL). The surgery of opaque crystalline lens removal has been known since ancient times [3–6].

First artificial intraocular lens was developed by Sir Harold Ridley in the mid-20 century [7, 8]. First IOLs were made of PMMA and relatively large incision of the eye balls was necessary for their implantation. Since this time new materials for IOL manufacturing were developed ensuring high biocompatibility and flexibility [9–11]. Obviously, the IOLs themselves have been changed with modern materials minimizing the risk of complications, and sophisticated designs enabling easy and unfailling implantation procedure (foldable lens), reducing the incision size and therefore the invasiveness of the whole procedure [12, 13]. The technique of cataract extraction and

subsequent IOL implantation has evolved as well and now it is a relatively low invasive, safe and effective procedure [14]. For the last few decades it has become one of the most successful surgeries among all implantable medical procedures [1].

A considerable advancement in IOL design can be observed as well. Except the basic monofocal spherical lenses there exists a huge variety of designs of commercially available IOL, including more advanced multifocal, pseudoaccommodative and accommodative IOLs [15–18]. All these improvements have been made in order to improve the patient's quality of near and far vision in low and high illumination levels.

From the optical point of view, the most important condition to improve patient's visual comfort is to ensure high quality of the retinal image. Therefore a lot of effort and energy has been taken in designing the IOL of the shape which would ensure as good optical performance as possible. Modern IOLs have aspheric surfaces ensuring good correction of aberrations, especially spherical aberration [19, 20].

The optical performance of the pseudophakic eye depends on the parameters and features of the implanted IOL. Therefore, it is necessary for the ophthalmic surgeon to have an access to precise, controlled and quantitative information on the optical properties of the IOLs, and, in particular, on the quality of retinal image in the aphakic eye with implanted IOL. There are a lot of clinical studies describing visual outcome of patients after crystalline lens extraction and IOL implantation, mainly expressed in terms of visual acuity (VA) and contrast sensitivity [15, 16, 21–26].

However, these clinical studies which evaluate and compare the visual outcomes in large patient populations have a serious drawback since it is difficult to separate the effect of IOL quality from the influence of the other, possibly existing, eye abnormalities. This kind of studies cannot be treated as fully authoritative. The most objective way of comparing visual outcome of IOL implantation is to perform the visual tests of the same person before and after IOL implantation. Patients after cataract treatment always have better visual performance than before such procedure, so they cannot objectively assess implanted lens quality. The same doubt concerns the studies of comparison of different types and designs of intraocular lenses. It is not possible to have comparable conditions of visual quality measurements. There is also doubt whether it is possible to implant different IOL types to one patient. Quantitative data come only from manufacturers, who sometimes insert it in the IOL technical data sheet, certainly without disclosing the conditions of the test. This indicates the need for a new method of evaluating the retinal image quality in eyes with IOLs under conditions that closely resemble clinical cases.

One of the solutions to this problem is computer simulation. Numerical ray tracing through model eye with IOL “implanted” enables estimations of the quality of the image created on the retina. Retinal images of an object in the form of Landolt “C” simulated numerically were analysed by KORYNTA *et al.* [27]. Gullstrand eye model was a base for modulation transfer function (MTF) calculation performed with WinSigma software by NORRBY [28]. FRANCHINI *et al.* [29] considered LeGrand eye model and typical ray-tracing programme to calculate spot diagram on the retinal

surface. TURUWHENUA [30] has calculated line spread function (LSF) and modulation transfer function (MTF) using Navarro eye model and Zemax software. The MTF function for different IOL types and pupil diameters has been calculated using CodeV programme by HUNTER *et al.* [31] using modified Dubbelman eye model. SIEDLECKI *et al.* [32] considered numerically classic (refractive) and hybrid (refractive-diffractive) IOLs.

One more possibility of IOL evaluation is to measure its optical quality in a laboratory set-up with the use of a physical model of the eye. There are a number of examples of such studies in the literature. TOGNETTO *et al.* [33] used specially designed optical bench. However, testing the IOL in air environment causes differences in its performance with respect to those obtained in real one. This indicates that such measurements should be performed with an enormous care in order to ensure that conditions are as close as possible to those applied when the IOL is implanted in the living eye [34]. In order to correct these differences the IOL under investigation has to be located in the wet cell filled with immersive liquid miming the aqueous humour [35, 36]. The other reason of using wet-cell model is that one of the materials used for IOL fabrication is a hydrophilic substance (*i.e.*, hydrogels). PELI and LANG [37] have determined experimentally MTF based on the measured spread function given by multifocal IOL's located in a wet cell.

So far, the best method to determine the optical performance of IOL in conditions close to natural ones is to construct a model of eye substituting the real one. Physical eye model makes it possible to objectively compare different IOL types. NEGISHI *et al.* [38] constructed a special visual simulation system, which was used to evaluate the effect of decentration of a monofocal intraocular lens (IOL) and a refractive multifocal IOL on retinal image quality. GOBBI *et al.* [39, 40] proposed optomechanical eye model, which should imitate as close as possible the real human eye condition with its mechanical and optical parameters in order to simulate *in vivo* testing of IOLs. The other version of artificial eye developed by CASTRO *et al.* [41] consists of PMMA water-cell with PMMA rigid contact lens simulating the cornea. Their measurements are based on tilt and decentration of IOL with the use of a commercial Scheimpflug system, custom algorithms, and a custom-built Purkinje imaging apparatus. BAKARAJU *et al.* [42] developed a physical model eye to measure the optical performance of corrective lens designs, like spectacles, contact lenses, and intraocular lenses (IOL). They modelled three adult human eyes with different accommodation levels and pupil sizes.

The aim of the present study is to develop an optomechanical model of human eye that might be used for investigating the optical performance of different intraocular lens types and which would allow taking into account shift (longitudinal and transversal) and/or inclination (tilt) of the implant considering different field angles of the incoming beam in order to simulate the off-axis optical performance and peripheral optical quality; as well as to develop quantitative and qualitative estimators of retinal image quality.

2. Optomechanical eye model

Optomechanical model of the human eye is designed for testing the optical performance of different intraocular lenses. This model is presented as draft in Fig. 1a and as a picture in Fig. 1b. It is based on a simplified numerical Liou–Brennan model eye [43] and it was created to render real eye conditions. Some simplification was allowed with respect to the cornea shape.

The model consists of:

a) *Cornea* made of PMMA of refractive index $n = 1.491$ for $\lambda = 589$ nm in the form of convex-concave meniscus of outer radius $r_1 = 7.77$ mm and inner radius $r_2 = 6.40$ mm, and central thickness $d = 0.50$ mm. Focusing power of cornea is 39.38 D. This cornea can be replaced by the aspherical one of the shape more adequate to that of real eye, if necessary.

b) *Chamber* (wet cell) to be filled with immersion liquid. The IOL being tested must be hosted in a liquid environment, resembling the aqueous humour by its refractive index. The wet cell can be filled in and emptied with a syringe in order to avoid

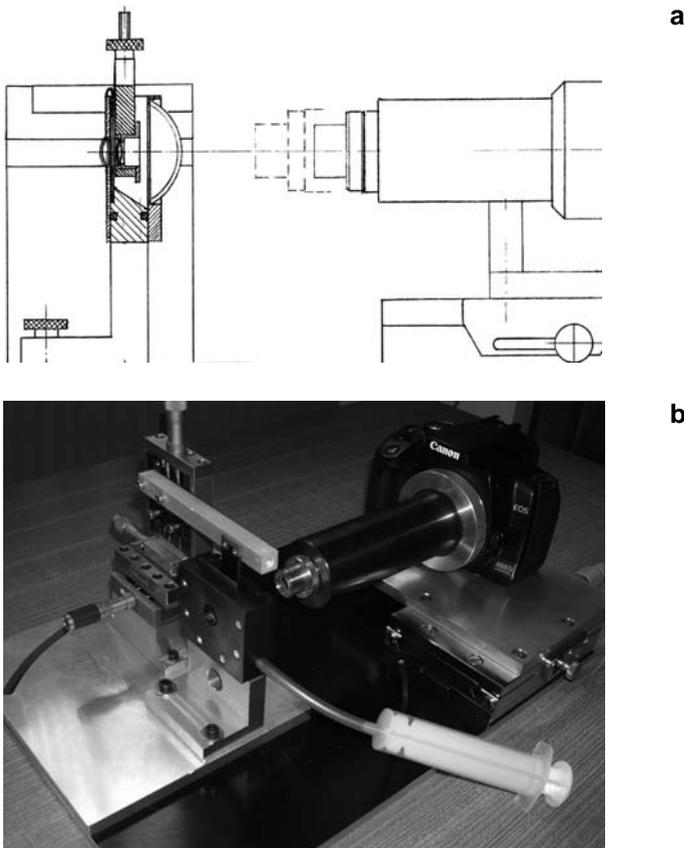


Fig. 1. Optomechanical model of human eye: draft (a), outer appearance (b).

creation of air bubbles that might have significant destructive influence on the optical performance of the model. As the immersion liquid simulating aqueous and vitreous humour we used distilled water in regard of refraction index similarity.

c) *Rear window* made of crown-type glass of refractive index $n = 1.516$. Outer radius is equal to $r_1 = 16.50$ mm and inner radius to $r_2 = 18.90$ mm, and central thickness was $d = 2.40$ mm. The aerial image of interest given by the whole model eye is formed just behind the rear window and the additional aberrations introduced by this window are small in comparison to the aberrations introduced by the IOL and are neglected.

d) *Exchangeable diaphragm* simulating varied eye pupil sizes.

e) *Specific IOL holder* with shift and rotary functions facilitates the simulation of different errors in the IOL location. The “zero” position of the IOL corresponds to the distance from artificial cornea equal to that of healthy eye, *i.e.*, equal to typical anterior chamber depth. The possibility of getting an individually measured tilt and decentration in 3-dimensions is important to assess the influence of the IOL position on the optical outcome. A micrometer screw makes it possible to change position of intraocular lenses in vertical and horizontal directions and along optical axis. Axial position change can compensate differences in IOL focusing power and allows accurate focusing of the retinal image. Rotation of intraocular lenses progresses along lens diameter in one degree steps.

In this eye model, the length of the chamber is slightly longer than in equivalent emmetropic eye, so the “retinal image” is formed as aerial image in the space in front of the rear window. Such stratagem was applied in order to avoid deformations of the image by possible imperfections of the rear window.

This aerial transferred is imaged with a microscopic objective (f) with linear magnification of $p = 6.6$ times and numerical aperture $NA = 0.12$ on the CCD detector being a part of typical photographic camera (EOS 400D, CANON). The detector consists of 10 megapixel of dimensions $6.6 \times 6.6 \mu\text{m}$. The effective pixel size in the aerial image plane is $1 \times 1 \mu\text{m}$, which is comparable to the cone diameter. Such a combination of the microscopic objective and pixel size in the CCD array assures that the angular resolution of the optomechanical model is similar to the angular resolution of a healthy eye. The images formed by the lens can be detected by the CCD camera and observed on the monitor of a personal computer.

Spectral sensitivity of the CCD detector is similar to the spectral sensitivity of human eye. The image is captured in the RAW format.

The spherical rear window has its centre at the point which corresponds to the centre of rotation of the simulated eye ball. The part of the model responsible for image capturing (microscope objective and camera) is mounted on a movable arm with the axis of rotation corresponding to the nodal point of the eye to be simulated. This makes it possible to test the optical performance for different field angles of the incoming beam in order to estimate the peripheral quality of vision. To simulate correctly the off-axis imaging properties of the eye it is necessary to replace the spherical cornea by aspherical one.

Four monofocal intraocular lenses were taken for analysis [44]: SK21RU (Alcon), CZ70BD (Alcon), SA60AT (Alcon) and SN60AT (Alcon). The CZ70BD is a one-piece biconvex polymethylmethacrylate IOL with a 7.0 mm optic diameter. Its nominal power is 21.5 D. The SA60AT is a one-piece biconvex aspheric acrylic IOL with a 7.0 mm optic diameter with UV filter. Its nominal power is 22.0 D. The SK21RU is a one-piece biconvex polymethylmethacrylate IOL with a 6.0 mm optic diameter. Its nominal power is 18.5 D. The SN60AT is a one-piece biconvex acrylic IOL with a 6.0 mm optic diameter with UV filter and blue light filter. Its nominal power is 26.5 D.

The experiments were performed with white light. Images of the test were converted to grey scale. A pupil of 4 mm in diameter was used in this research.

3. Experiments

For qualitative analysis, a Siemens star test was used. The test was printed on a white paper and had 50 black and white sectors. The lowest spatial frequency was equal to 0.1 c/mm. The highest frequency – in the middle of the test – was about 1.3 c/mm. The distance from the test to the model eye was equal to 5.5 m, so that this experiment could be treated as a simulation of typical distant vision test. For this distance spatial frequency of the test varied in the range 7.9–102.4 c/deg. Since the goal of the first

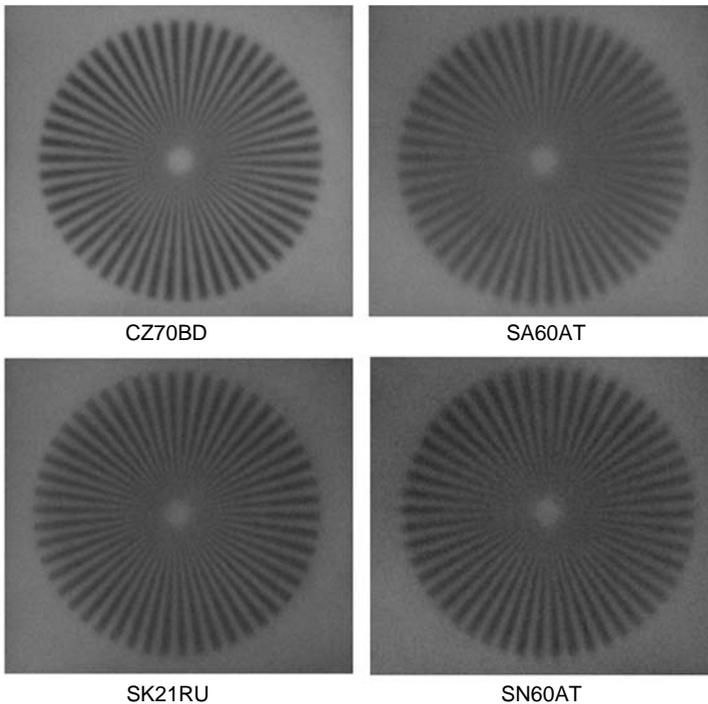


Fig. 2. Image of Siemens star test.

can be treated as a proof that this eye model correctly emulates optical properties of the real eye in the best way possible.

As quantitative measures of the retinal image quality, line spread function (LSF) and modulation transfer function (MTF) were used. The first one was obtained as the derivative of the image of an edge. Appropriate object (edge) was simulated on a computer screen and the recorded image of this object was then numerically differentiated along the direction perpendicular to the edge. The obtained LSFs are presented in Fig. 4.

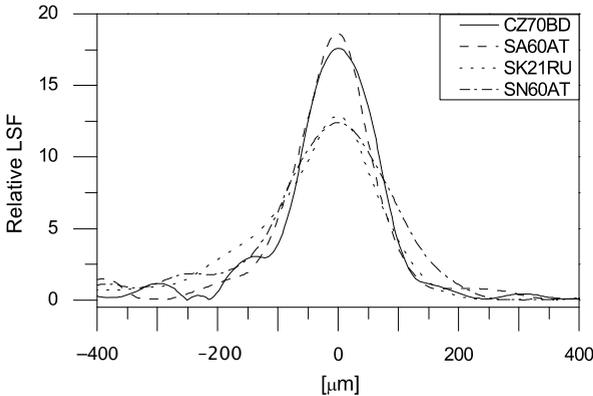


Fig. 4. Line spread function for monofocal intraocular lenses investigated.

It is worth emphasizing that the shapes of all LSFs are nearly symmetrical. Maximum intensity and half-width were calculated as numerical parameters characterizing the measured LSFs. Differences between the images captured for all IOLs are small, which is confirmed by the values of the parameters (as measured in the camera plane) presented in Tab. 2 (rows 1 and 2).

T a b l e 2. Numerical parameters characterizing LSF and MTF.

	Intraocular lens (IOL)			
	CZ70BD	SA60AT	SK21RU	SN60AT
Maximum LSF	17.6	18.6	12.9	12.4
Half-width LSF [\$\mu\$m]	70	66	86	82
MTF50 [cpd]	7.0	6.6	6.8	5.5

Estimation of the MTF gives very important information on the quality of the retinal image. This function can be defined as the ratio of Michelson contrast in the image of sinusoidal luminance distribution to the contrast in the object luminance distribution itself [45]. From this definition a simple method of its measurement follows. A sinusoidal test pattern of a given spatial frequency and contrast was generated on a computer screen and its image was captured. Contrast in the image was

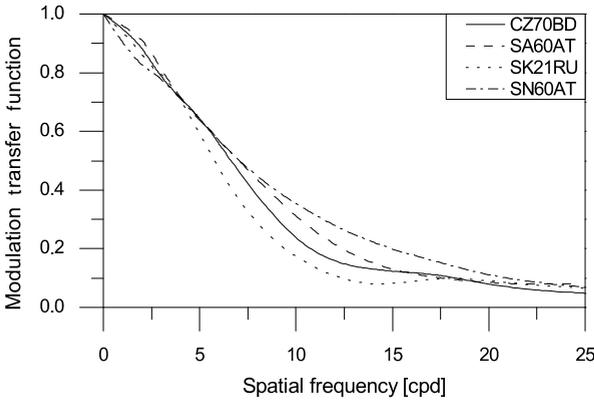


Fig. 5. Modulation transfer function measured with 100% contrast of initial test pattern.

then calculated from the numerical data. The image was calibrated using additional black-and-white test object. Several sinusoidal tests of spatial frequency varying within the range of 0.1–3 c/mm presented from the distance equal to 5.5 m (which is equivalent to the angular spatial frequency varying from 0.79 to 60 c/deg) were used. The MTF curves estimated in such a way for all the IOLs investigated are presented in Fig. 5.

It is worth noting that the shape of the curves obtained corresponds well to the MTF curves obtained either numerically [31] or experimentally with the use of model eye [46] by other authors.

In order to describe the MTF slope in a simple way the parameter MTF50 was used which is defined as a spatial frequency for which the modulation transfer function falls down to the value of 0.5. This parameter seems to describe the characteristic of the MTF in a better way than the cut-off frequency since the cut-off frequency is highly influenced by noise. Row 3 of Tab. 2 presents values of this parameter for four monofocal lenses. It is obvious that MTF50 for all lenses has similar values. Although

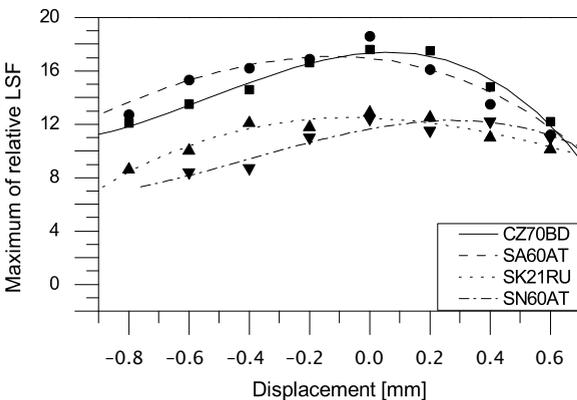


Fig. 6. Dependence of the LSF maximum value on the IOL longitudinal displacement.

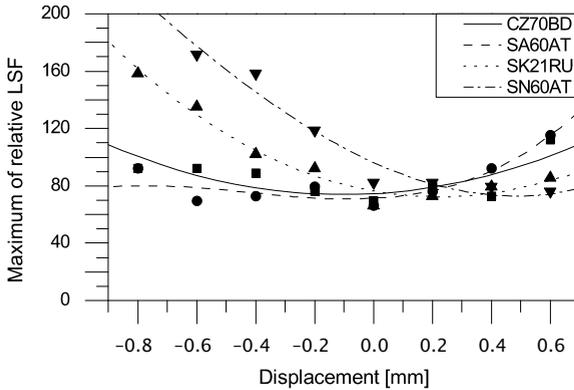


Fig. 7. Dependence of the LSF half-width on the IOL longitudinal displacement.

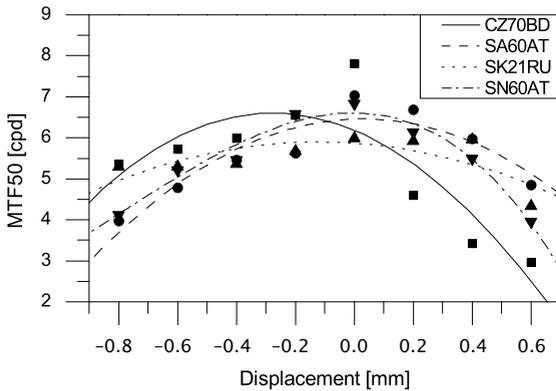


Fig. 8. Dependence of MTF50 parameter on the IOL longitudinal displacement.

the MTF50 parameter values are similar, the optical performance of all the implants are slightly different.

In this research the influence of longitudinal dislocation of IOL on the retinal image quality was measured. IOL was shifted horizontally along optical axis in 0.2 mm steps in cornea and retina directions. The changes of parameters describing LSF and MTF were compared. Figures 6–8 present characteristics of changes maximum and half-width of LSF and MTF50 parameter with the longitudinal deposition of different IOLs. Zero on the displacement scale is reference position. The influence of the IOL dislocation on retinal image quality is relatively small. Changes of horizontal location of about 0.3 mm practically do not affect the retinal image. It is important to notice that all the lenses under investigation are similar in shape.

4. Conclusions

Optomechanical models of eye enable objective assessment of IOLs quality using physical quantities such as line spread function (LSF) and modulation transfer func-

tion (MTF) and qualitative representation which may be potentially useful for characterization of optical performance of different types of IOLs. Such models can be successfully used in prediction of quality of vision of pseudophakic eyes as well as refractive/diffractive IOL design optimization.

In this study, the retinal images in eyes with selected monofocal IOLs and a refractive multifocal IOL were investigated using specially designed optomechanical eye model. This model consists of a chamber filled with a liquid resembling the aqueous humour with its refractive index and Abbe number. The front window of this chamber simulates cornea being a meniscus lens of the same focusing power as real cornea. The IOL is placed in this chamber in the manner which allows adjustment of its location (distance from the front window) as well as decentration and tilt. A diaphragm serving as the pupil of the eye is located in the anterior part of the artificial eye chamber. The overall length is slightly larger than the corresponding length of emmetropic eye since the retinal image is assumed by the authors to form an aerial image inside the model which can be registered with the use of microscopic objective and a digital reflex camera with satisfying quality. The magnification of the microscopic objective was chosen in order to match the angular resolution of human eye, taking into account the resolution of the CCD element used in the camera.

A very unique feature of this optomechanical model is the possibility of registering off-axis images, due to rotation of the image-capturing part of the system (microscopic objective, photo camera with CCD element) around the assumed axis of rotation of the eye. This feature would enable estimation of the influence accuracy of the IOL alignment inside the eye on the peripheral vision. This may form the basis for the future research concerning the model presented in the present paper, as well as the usefulness of the model in testing optical performance of multifocal intraocular lenses, in which the incoming light is smoothly transitioned between the distance, intermediate and near focal points [47, 48].

Acknowledgements – Preliminary version of this work was presented at the 1st Polish Optical Conference, Bedlewo, Poland, June 27–July 01, 2009, and its final form was prepared as a Research Project N N518 414 138 financed by the Polish Ministry of Science and Higher Education.

References

- [1] *Facts About Cataract*, National Eye Institute, National Institutes of Health, Department of Health and Human Services, 2004.
- [2] HESS R., WOO G., *Vision through cataracts*, Investigative Ophthalmology and Visual Science **17**(5), 1978, pp. 428–435.
- [3] AZAR D.T., *Intraocular Lenses in Cataract and Refractive Surgery*, Saunders, 2001.
- [4] KA WAI FAN, *Couching for cataract and Sino-Indian medical exchange from the sixth to the twelfth century AD*, Clinical and Experimental Ophthalmology **33**(2), 2005, pp. 188–190.
- [5] KWITKO M.L., KELMAN C.D., *The History of Modern Cataract Surgery*, Kugler Publications, 1998.
- [6] ROSEN E., HAINING W.M., ARNOTT E.J., *Intraocular Lens Implantation*, Mosby-Year Book, 1983.
- [7] ALLARAKHIA L., LINDSTROM R.L., *Soft intraocular lenses*, International Ophthalmology **12**(3), 1988, pp. 185–191.

- [8] HAMILTON R.C., *Sir Harold Ridley, MD, FRCS, FRS; Inventor of the intraocular lens implant*, *Current Anaesthesia and Critical Care* **11**(6), 2000, pp. 314–319.
- [9] AMON M., *Biocompatibility of intraocular lenses*, *Journal of Cataract and Refractive Surgery* **27**(2), 2001, pp. 178–179.
- [10] MAMALIS N., *Intraocular lens biocompatibility*, *Journal of Cataract and Refractive Surgery* **28**(1), 2002, pp. 1–2.
- [11] WERNER L., MAMALIS N., ROMANIV N., HAYMORE J., HAUGEN B., HUNTER B., STEVENS S., *New photochromic foldable intraocular lens: Preliminary study of feasibility and biocompatibility*, *Journal of Cataract and Refractive Surgery* **32**(7), 2006, pp. 1214–1221.
- [12] OLSON R.J., MAMALIS N., WERNER L., APPLE D.J., *Cataract treatment in the beginning of the 21st century*, *American Journal of Ophthalmology* **136**(1), 2003, pp. 146–154.
- [13] WERNER L., MAMALIS N., *Foldable Intraocular Lenses. Cataract and Refractive Surgery*, Springer, 2005.
- [14] *Cataract Surgery Guidelines*, The Royal College of Ophthalmologists, London, 2004.
- [15] BELLUCCI R., *Multifocal intraocular lenses*, *Current Opinion in Ophthalmology* **16**(1), 2005, pp. 33–37.
- [16] BELLUCCI R., SCIALDONE A., BURATTO L., MORSELLI S., CHIEREGO C., CRISCUOLI A., MORETTI G., PIERS P., *Visual acuity and contrast sensitivity comparison between Tecnis and AcrySof SA60AT intraocular lenses: A multicenter randomized study*, *Journal of Cataract and Refractive Surgery* **31**(4), 2005, pp. 712–717.
- [17] DICK H.B., *Accommodative intraocular lenses: Current status*, *Current Opinion in Ophthalmology* **16**(1), 2005, pp. 8–26.
- [18] DOANE J.F., JACKSON R.T., *Accommodative intraocular lenses: Considerations on use, function and design*, *Current Opinion in Ophthalmology* **18**(4), 2007, pp. 318–324.
- [19] MONTES-MICO R., FERRER-BLASCO T., *Aspheric intraocular lenses enhance contrast sensitivity*, *Expert Review of Ophthalmology* **2**(5), 2007, pp. 723–726.
- [20] SZURMAN P., PETEREMEIER K., *Aspheric IOLs benefit quality of vision*, *Cataract and Refractive Surgery Today Europe*, January 2009, pp. 17–18.
- [21] BHATTACHARJEE H., BHATTACHARJEE K., MEHDI J., *Visual performance: Comparison of foldable intraocular lenses*, *Journal of Cataract and Refractive Surgery* **32**(3), 2006, pp. 451–455.
- [22] HAYASHI K., HAYASHI H., NAKAO F., HAYASHI F., *Influence of astigmatism on multifocal and monofocal intraocular lenses*, *American Journal of Ophthalmology* **130**(4), 2000, pp. 477–482.
- [23] LOMBARDO A.J., HARDTEN D.R., MCCULLOCH A.G., DEMARCHI J.L., DAVIS E.A., LINDSTROM R.L., *Changes in contrast sensitivity after Artisan lens implantation for high myopia*, *Ophthalmology* **112**(2), 2005, pp. 278–285.
- [24] MESTER U., DILLINGER P., ANTERIST N., *Impact of a modified optical design on visual function: Clinical comparative study*, *Journal of Cataract and Refractive Surgery* **29**(4), 2003, pp. 652–660.
- [25] NIO Y.K., JANSONIUS N.M., GERAGHTY E., NORRBY S., KOOLIJMAN A.C., *Effect of intraocular lens implantation on visual acuity, contrast sensitivity and depth of focus*, *Journal of Cataract and Refractive Surgery* **29**(11), 2003, pp. 2073–2081.
- [26] STEINERT R.F., POST C.T. JR, BRINT S.F., FRITCH C.D., HALL D.L., WILDER L.W., FINE I.H., LICHTENSTEIN S.B., MASKET S., CASEBEER C., *A prospective, randomized, double-masked comparison of a zonal-progressive multifocal intraocular lens and a monofocal intraocular lens*, *Ophthalmology* **99**(6), 1992, pp. 853–860.
- [27] KORYNTA J., BOK J., CENDELIN J., MICHALOVA K., *Computer modeling of visual impairment caused by intraocular lens misalignment*, *Journal of Cataract and Refractive Surgery* **25**(1), 1999, pp. 100–105.
- [28] NORRBY S., *Standardized methods for assessing the imaging quality of intraocular lenses*, *Applied Optics* **34**(31), 1995, pp. 7327–7333.
- [29] FRANCHINI A., GALLARATI B.Z., VACCARI E., *Computerized analysis of the effects of intraocular lens edge design on the quality of vision in pseudophakic patients*, *Journal of Cataract and Refractive Surgery* **29**(2), 2003, pp. 342–347.

- [30] TURUWHENUA J., *A theoretical study of intraocular lens tilt and decentration on perceptual image quality*, *Ophthalmic and Physiological Optics* **25**(6), 2005, pp. 556–567.
- [31] HUNTER J.J., CAMPBELL M.C.W., GERAGHTY E., *Optical analysis of an accommodating intraocular lens*, *Journal of Cataract and Refractive Surgery* **32**(2), 2006, pp. 269–278.
- [32] SIEDLECKI D., ZAJĄC M., NOWAK J., *Retinal images in the model of pseudophakic eye with classic and hybrid intraocular lenses*, *Journal of Modern Optics* **55**(4–5), 2008, pp. 653–669.
- [33] TOGNETTO D., SANGUINETTI G., SIROTTI P., CECCHINI P., MARCUCCI L., BALLONE E., RAVALICO G., *Analysis of the optical quality of intraocular lenses*, *Investigative Ophthalmology and Visual Science* **45**(8), 2004, pp. 2682–2690.
- [34] HICKLING I.N., Response to article: TOGNETTO D., *et al.*, *Analysis of the optical quality of intraocular lenses*, *Invest. Ophthalmol. Vis. Sci.* **45**(8), 2004, pp. 2682–2690, Published January 3, 2005.
- [35] BARBERO S., MARCOS S., JIMENEZ-ALFARO I., *Optical aberrations of intraocular lenses measured in vivo and in vitro*, *Journal of the Optical Society of America A* **20**(10), 2003, pp. 1841–1851.
- [36] FAALAND R.W., GROSSMAN L.W., *Design and evaluation of a null lens for testing the optical performance of silicone intraocular lenses*, *Applied Optics* **39**(16), 2000, pp. 2678–2682.
- [37] PELI E., LANG A., *Appearance of images through a multifocal intraocular lens*, *Journal of the Optical Society of America A* **18**(2), 2001, pp. 302–309.
- [38] NEGISHI K., OHNUMA K., IKEDA T., NODA T., *Visual simulation of retinal images through a decentered monofocal and a refractive multifocal intraocular lens*, *Japanese Journal of Ophthalmology* **49**(4), 2005, pp. 281–286.
- [39] GOBBI P.G., FASCE F., BOZZA S., BRANCATO R., *Optomechanical eye model with imaging capabilities for objective evaluation of intraocular lenses*, *Journal of Cataract and Refractive Surgery* **32**(4), 2006, pp. 643–651.
- [40] GOBBI P.G., FASCE F., BOZZA S., CALORI G., BRANCATO R., *Far and near visual acuity with multifocal intraocular lenses in an optomechanical eye model with imaging capability*, *Journal of Cataract and Refractive Surgery* **33**(6), 2007, pp. 1082–1094.
- [41] 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* **33**(3), 2007, pp. 418–429.
- [42] BAKARAJU R.C., EHRMANN K., FALK D., PAPAS E.B., HO A., *Working sketch of an anatomically and optically equivalent physical model eye*, *Proceedings of SPIE* **7163**, 2009, p. 716316.
- [43] LIU H.L., BRENNAN N.A., *Anatomically accurate, finite model eye for optical modeling*, *Journal of the Optical Society of America A* **14**(8), 1997, pp. 1684–1695.
- [44] HOLLADAY J.T., *International intraocular lens and implant registry*, *Journal of Cataract and Refractive Surgery* **30**(1), 2004, pp. 207–229.
- [45] ARTAL P., NAVARRO R., *Monochromatic modulation transfer function of the human eye for different pupil diameters: An analytical expression*, *Journal of the Optical Society of America A* **11**(1), 1994, pp. 246–249.
- [46] NORRBY S., PIERS P., CAMPBELL C., VAN DER MOOREN M., *Model eyes for evaluation of intraocular lenses*, *Applied Optics* **46**(26), 2007, pp. 6595–6605.
- [47] MONTES-MICO R., ALIO J.L., *Distance and near contrast sensitivity function after multifocal intraocular lens implantation*, *Journal of Cataract and Refractive Surgery* **29**(4), 2003, pp. 703–711.
- [48] SOUZA C.E., MUCCIOLI C., SORIANO E.S., CHALITA M.R., OLIVEIRA F., FREITAS L.L., MEIRE L.P., TAMAKI C., BELFORT R. JR., *Visual performance of AcrySof ReSTOR apodized diffractive IOL: A prospective comparative trial*, *American Journal of Ophthalmology* **141**(5), 2006, pp. 827–832.