OCULAR MAGNIFICATION IN PHAKIC AND PSEUDOPAKIC EYES AND IN EYES WITH KERATOPROSTHESES

Ph.D thesis

Dr. Achim Langenbucher

Clinical Medicine Doctoral School

Semmelweis University

Supervisor: Nóra Szentmáry, MD, Ph.D

Official reviewers: György Barcsay, MD, Ph.D

Péter Vámosi, MD, Ph.D

Head of the Complex Examination Committee:

László Schmeller, MD, D.Sc.

Members of the Complex Examination Committee:

Ágnes Kerényi, MD, Ph.D

Miklós Resch, MD, Ph.D

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1. Introduction

Visual acuity is not the only quality criterion for visual performance. There are several parameters such as contrast transfer, blended vision, defocus properties or the state of stereopsis, which affect visual performance.

From the definition, optical magnification in general refers to the ratio of image to object size. Lateral magnification in the eye is based on two different definitions, one for objects at infinity and one for objects at finite distances. For infinite object distances, object size is not defined and therefore, magnification refers to the ratio of retinal image size to the visual angle of an object in radians. For objects at finite distances, the classical definition of magnification as the ratio of retinal image size to object size is valid. If we restrict to an eye as a centred optical system with rotational symmetric surfaces we call it *stigmatic*. If the optical system is not centred or there is at least one element with some variation of curvature for different meridians we call it *astigmatic*. In the stigmatic case, lateral magnification is isometric, which means that for all meridians the object to image magnification is the same. For an astigmatic eye, lateral magnification varies and the object to image transfer is no longer isometric, we have some image distortion.

From the classical definition, aniseikonia refers to the binocular refraction status, where the lateral magnification of both eyes shows some disparity. In contrast to anisometropia, aniseikonia refers to the lateral magnification disparity. In ophthalmology, the classical understanding of aniseikonia in general is related to a difference in the overall object to image magnification, comparing both eyes of one individual, which is also described as binocular aniseikonia. If we have any astigmatic optical element in the eye, lateral magnification varies in different meridians. If astigmatism remains uncorrected, we notice some blur in the image, and if astigmatism is fully corrected (e.g. with spectacle glasses), we get a sharp image, but some image distortion. Such an image distortion due to a variation of ocular magnification in different meridians is called meridional aniseikonia.

A circular object traced through the optical system yields an elliptical image, defined by a long (with the highest magnification) and the short axis (with the lowest magnification), alongside with the 2 cardinal meridians (meridian of magnification and axis of magnification.

Meridional magnification refers to the ratio of the long to short axis. Each point at the circle (at object plane) corresponds to a point at the ellipse (at image plane). Horizontal and vertical lines are inclined as referred with the horizontal and vertical declination error. Meridional aniseikonia could take place isolated, if the overall magnification of both eyes is identical, or in combination with binocular aniseikonia, if the overall magnification of both eyes does not match. Eyes are called eikonic if the overall magnification of both eyes is identical and we do not have variations on meridional magnification. Aniseikonia is always a consequence of anisometropia, but not all cases of anisometropia cause aniseikonia. In some cases, differences in biometric measures could counterbalance each other so, that the resulting binocular or meridional lateral magnification is identical.

The incidence of aniseikonia is mostly underestimated or even ignored in clinical routine, as in most cases, symptoms are not obvious or measureable. In the normal adult population with an age more than 20 years, prevalence of aniseikonia due to an anisometropia of 1 diopter (dpt) or more is estimated to 10%. In contrast, especially after cataract surgery with implantation of an artificial lens implant (IOL), after corneorefractive surgery such as PRK or LASIK or other types of corneal (e.g. penetrating keratoplasty) or posterior eye segment (e.g. cerclage) procedures, prevalence of aniseikonia seems to be significantly increased up to 40%. However, many cases of aniseikonia remain undiagnosed in clinical routine and its high prevalence should sensitize ophthalmologists to the general problems of ocular magnification and aniseikonia

Sensitivity to magnification disparity shows a large variation in the population. Some patients are already impaired with an overall magnification difference of around 1% between the left and the right eye, and others tolerate magnification differences between both eyes of 3 or 4 % without any interference of vision. In contrast to binocular aniseikonia, the tolerance or acceptance to meridional aniseikonia is not studied systematically in the literature. Some researchers report, that if disparity in overall magnification is properly corrected, a variation in meridional magnification is tolerated. Others report, that especially meridional variation of magnification is less tolerated due to image distortion and causes in some cases severe complains to the patients such as headaches, fusion problems or asthenopic complains.

Spectacle glasses show the largest effect on ocular magnification. Due to the large distance from the eye's image-sided principal plane, a spectacle correction for ametropia always affects ocular magnification much more than e.g. a contact lens correction. Minus corrections for myopic eyes minify the retinal image size, whereas plus corrections magnify the retinal image size. That also has to be taken into consideration if we measure the visual performance of the eye in terms of visual acuity. With acuity tests, letters are projected with standard sizes (e.g. Landolt ring), with an opening of 1 arc second for testing for visual acuity of 1.0), and with myopic / hyperopic spectacles the visual field angle of the letter is smaller / larger which implies a reduced / increased visual acuity by artefact.

2. Objectives

The purpose of this PhD thesis is

- to present mathematical strategies for determination of ocular magnification in the (spectacle-)corrected and uncorrected eye before and after cataract surgery with implantation of standard lenses and toric implants,
- to show how ocular magnification is changed in different clinical situations such as corneal surgery (e.g. LASIK, LASEK, PRK or keratoplasty), cataract surgery with implantation of a standard or toric capsular bag lens,
- to show how the optics part of keratoprostheses can be designed to realize intended magnification, visual field angle, and refraction, and
- to give ideas how aniseikonia as a disparity between ocular magnification between both eyes or magnification between different meridians could be addressed in clinical routine to get an eikonic imaging.

3. Methods

Evaluation of the retinal image size requires knowledge on the entire optical system, which includes shape of all refractive surfaces, all distances in the eye, as well as all refractive indices. We have to differentiate between a corrected optical system and an uncorrected optical system. In the corrected optical system, all rays initiated from an object point meet in the corresponding image point (conjugate point), and in an uncorrected system we have some blur, which means that depending on the intersection of a ray through the entrance pupil it will hit the retina at a different position. For uncorrected optical systems the central ray is used as reference, which passes through the centre of the entrance pupil.

Calculation of ocular magnification in this thesis was performed using matrix calculation strategy. That implies a restriction to centred optical elements in the optical system and to linear Gaussian optics. With these restrictions, any optical system can be described with refraction and translation matrices, where the refraction matrices represent refracting surfaces and the translation matrices the homogeneous interspace between refractive surfaces. An optical system is represented by a system matrix, which is the product of all the refraction and translation matrices factored in an inverse order (from image to object). In case of a stigmatic optical system we could deal with 2x2 matrices and in case of astigmatic systems we consider 4x4 matrices.

In case of a corrected optical system, one element of the system matrix directly specifies ocular magnification, in case of an uncorrected optical system, the system matrix has to be split into a portion describing the anterior part of the system up to the entrance pupil and a second portion describing the posterior part, and the ray passing through the centre of the entrance pupil is selected as reference.

In a first step, ocular (overall or meridional) magnification is analysed for baseline situation for both eyes. In a second step, we predict the changes in the optical system due to cataract surgery with a standard or toric replacement lens, due to corneal surgery, or due to keratoprosthesis surgery. If comparing both eyes at baseline yields the preoperative situation for overall or meridional magnification disparities, if comparing the magnifications for the predicted situation after surgery yields the postoperative overall or meridional magnification disparities, and if comparing the predicted postoperative situation to the respective preoperative situation for the left or the right eye gives us some insight into the change (gain or loss) in ocular magnification.

In the framework of this thesis, we analysed baseline overall and meridional magnification, in a large cataract population prior to and after cataract surgery with implantation of a standard replacement lens as well as in a sub-population after implantation of a toric lens. This study was based on a dataset of N=8998 examinations before and after cataract surgery and includes biometric measurements (IOLMaster 700, Carl-Zeiss-Meditec, Jena, Germany) alongside with the refraction data. For evaluation of overall ocular magnification (changes) in standard cataract surgery we used all data, for evaluation of overall and meridional ocular magnification (changes) we selected those patients who underwent cataract surgery with implantation of a toric lens (N=1119)), for evaluation of overall and meridional magnification changes after corneal (here: exemplary restrictions to corneorefractive) surgery we selected those patients where ametropia was larger than 1.5 diopters or refractive cylinder exceeded 1.5 diopters (N=5017), and for evaluation of situations with implantation of a keratoprostheses again we included all patients (N=8998). None of these patients in our dataset received corneorefractive surgery or keratoprostheses surgery.

For modelling, we assumed without loss of generality a back vertex distance of 14 mm, considered spectacle refraction with a thin lens, and derived refractive indices of cornea (n_C=1.376), aqueous (n_A=1.336), lens (n_L=1.41) and vitreous (n_V=1.336) from a schematic model eye. Corneal front and back surface data as well as all distances in the eye were grabbed from the biometric measurement with the IOLMaster. As phakometry is difficult and unreliable, we used refraction data and front / back vertex data of the crystalline lens alongside with the ration of front to back surface power derived from a schematic model eye to extract the refractive power of the lens' front and back surface. For simplicity, we restricted to objects located at infinity, which means that ocular magnification refers to the ratio of retinal image size to slope angle of the incident ray in radians, which is quoted in the literature in general without dimensions. Gain in ocular magnification refers to the change from preoperative to postoperative magnification in %. Meridional magnification refers to the ratio of meridional magnifications in the magnification meridian and the magnification axis (with respect to an elliptical image distortion) in %. For evaluation of change in meridional magnification, a circular object at object space (at infinity) is considered, and change in meridional magnification refers to the ratio of magnification change comparing the magnification meridian and the magnification axis by transforming the preoperative to the postoperative retinal image. For evaluation of magnification properties of the keratoprostheses we included the (half angle) field of view (VFA).

4. Results

The dataset included axial length measurement (AL), central corneal thickness (CCT), aqueous depth (AQD), anterior chamber depth (ACD) as a sum of CCT and AQD, phakic or pseudophakic lens thickness (LT), corneal front surface curvature in the flat (R1) and the steep (R2) meridian with orientation of the flat meridian (RA), corneal back surface curvature in the flat (PR1) and the steep (PR2) meridian with orientation of the flat meridian (PRA), spectacle refraction with sphere (Sphere), cylinder (Cylinder) and axis (Axis), the power of the implanted IOL (IOLP for rotational symmetric lenses and IOLP as equivalent power, IOLPAST as lens toricity and implantation axis IOLPA for toric lenses) alongside with the refractive index n_{IOL} and the ratio of average lens back surface to front surface power (q). Mean corneal front (R_{mean}) and back (PR_{mean}) surface radius was derived as average from R1 and R2 or PR1 and PR2, respectively, and spherical equivalent of refraction (SEQ=Sphere + 0.5·Cylinder). Astigmatism of the corneal front (AST) and back (PAST) surface was derived using $AST=(n_C-1)(1/R2-1/R1)$ and $PAST=(n_V-n_C)(1/PR2-1/PR1)$.

Ocular magnification in cataract surgery with implantation of a standard lens

Overall ocular magnification (OM: ocular magnification x1000) before cataract surgery as derived with our calculation strategy from the clinical dataset was 16.2700±0.5215 (median 16.2494. range 14.2371 to 19.2368) and gained to 16.7128±1.1189 (median 16.5667, range 12.6524 to 24.0111) after cataract surgery with implantation of a standard replacement lens. The gain in overall ocular magnification was 2.6767±5.1252% (median 1.9081&, range -16.6503 to 37.7394%). The 95% confidence interval for the change in overall magnification ranged in between -5.6 and 14.2%.

Overall and meridional ocular magnification with implantation of a toric lens

Before surgery, overall OM was 16.0606±0.5381 (median 16.0634, range 13.9398 to 18.1613) in the phakic eye. Postoperatively, in the pseudophakic eye, it was 16.9501±1.3782 (median 16.7817, range

12.4182 to 23.8516). Meridional magnification as the ratio of magnification in the magnification meridian to magnification in the magnification axis was 2.75±1.03% (median 2.51%, range 0.9112 to 7.85%) in the phakic eye and 0.42±0.29% (median 0.36%, range 0.01 to 2.46%) in the pseudophakic eye after cataract surgery. Overall OM gains due to cataract surgery by 5.51% on average. Image distortion due to meridional disparity in OM decreases from 2.75% preoperatively to 0.42% postoperatively.

Change in overall and meridional magnification due to corneal surgery

Corneal curvature is one of the major effect sizes, which determine OM. The dominant portion of ocular astigmatism refers to the corneal front surface shape. Especially in keratoplasty or corneorefractive surgery such as LASIK, LASEK, or PRK, the correction with spectacles is shifted in part or completely to the corneal plane, which affects overall OM, and in case of corneal astigmatism also meridional OM. In this simulation we address the change in overall and meridional OM due to change of corneal curvature in corneorefractive surgery. The cornea is considered as a thick lens with a spherocylindrical front and back surface. Transforming the elliptical retinal image before surgery to the elliptical retinal image yields a change in the magnification axis of 0.57±5.79% (median 1.13%, range -18.39 to 30.89%) and in the magnification meridian 2.23±6.17% (median 3.03%, range -16.60 to 32.47%). The change in difference of meridional magnification reads 1.64±1.50% (median 1.21%, range 0.00 to 13.83%). In contrast, the change in overall OM resulted in 1.40±5.93% (median 2.28%, range -17.49 to 31.32%).

Overall, OM gains due to corneorefractive surgery based on our dataset by -7.88% to 13.69% (95% confidence interval), and distortion in terms of difference between the meridian with the maximum and the minimum change ranges in between 0.06% and 5.58% (95% confidence interval).

Ocular magnification and visual angle in keratoprostheses

Keratoprostheses are an artificial replacement of the cornea for clinical situations, where the prognosis of a standard keratoplasty procedure is poor. Keratoprostheses such as the Boston I or II are assembled from a central optics cylinder made from polymethylmethacrylate (PMMA) and a haptics part for fixation in the host cornea. As the optics cylinder is intended to have a rotationally symmetric shape, it is defined with a surface curvature for the front (R_f) and back (R_b) surface, as well as a diameter (D) and length (L). The diameter and length characterize the VFA, whereas the refraction is defined by the thickness and the curvature of both refractive surfaces. The optical model that we used consists of a spectacle correction (to mimic target refraction), the optics cylinder which typically extends the cornea by around half a millimetre, and the focal distance as interspace between the optics cylinder and the retina (aqueous / vitreous). With variation of TR of -0.07±3.21 dpt (median -0.04 dpt, range -13.29 to 12.85 dpt), a variation of R_f of 6.04±1.14 mm (median 6.13 mm, range 2.66 to 13.05 mm), a variation of D with 2.60±0.25 mm (median 2.61 mm, range 1.75 to 3.67 mm) and a variation of L with 3.00±0.20 mm (median 3.00 mm, range 2.28 to 3.78 mm) OM could be fully adapted to the target OM of 19.47±1.75 (median 19.36, range 14.05 to 34.01). The radius of curvature for the respective back surface R_b had to be adjusted to 4.74±2.78 mm (median 4.60 mm, range -9.97 to 9.99 mm) in order to emmetropise the spectacle corrected eye after keratoprosthesis surgery. The equivalent power of the aphakic eye with keratoprosthesis was 51.76±4.50 dpt (median 51.65 dpt, range 29.41 to 71.18 dpt). The VFA defined by the optics cylinder resulted in 37.14±3.61° (median 37.15°, range 24.81 to 50.54 °).

4. Discussion

Magnification and problems caused by magnification disparities

In modern ophthalmic surgery, the major goal is to reach the intended refraction and to get out perfect image performance in terms of high visual acuity, high contrast sensitivity, negligible blur and halos. The focus of today’s research is mostly on reduction of optical aberration, chromatic errors and elimination of photic phenomena, and in this context, classical problems such as magnification disparity, image fusion and stereopsis are mostly ignored. Ocular magnification is determined by the entire optical system, which includes the spectacle refraction in addition with the shape of the glasses, contact lenses, corneal shape and thickness, lens shape and thickness and the interspaces between cornea and lens, as well as between lens and retina.

In most of the textbooks, the disparity of retinal image size mostly refers to the overall magnification difference between both eyes. For this classical perspective of aniseikonia, we have lots of clinical data about tolerance and problems of fusion, summation or suppression of images in the brain. As soon as we have at least one astigmatic surface in the optical system, we deal with a cylindrical telescope and even if all optical elements are centred and aligned, a circular structure at object space is distorted to an ellipse at the retina. That means that all structures show distortions, and meridional difference in ocular magnification refers to the ratio of the large to the short diameter of the ellipse (mostly provided in % of difference). With modern diagnostic techniques based on Scheimpflug imaging, optical coherence tomography (OCT) or confocal microscopy, we get a detailed insight into ocular structures, and lots of measures could be grabbed from those instruments. Today, some biometers provide the tomographic data of corneal front and back surface and a central OCT image of the para-foveal space. Anterior segment OCT gives some complementary information about the geometry of the chamber angle, the pupil outline, as well as the geometry of the crystalline or artificial lens' front and back surface in dedicated phakometry measurement modules. Therefore, alongside with the refractive error of the eye, we have all relevant parameters to investigate ocular magnification.

Handling with magnification disparities

There are several strategies for addressing retinal image size disparity. First of all, clinicians have to measure the tolerance of a patient to retinal image size disparities and image distortions due to variations in meridional magnification. For that purpose, we have standard approaches such as eikonometers. But such instruments do not yield reliable data about the long-term tolerance, as most of the fusion problems typically arise in daily life and may be absent under ideal test conditions. If the tolerance levels are derived, the evaluation of the actual eikonic status should be mandatory, prior to any type of ocular surgery, where refractive surfaces or distance in the eye are systematically changed. With that baseline estimation of ocular magnification, we could use prediction models to estimate the effect of ocular surgery on the eikonic status of the patient.

The most popular surgical intervention which may change the eikonic status of the patient are cataract surgery, corneorefractive procedures such as LASIK, LASEK, PRK, refractive procedures at the lens such as implantation of an artificial lens in a phakic or pseudophakic eye, or keratoplasty. In cases where an implantation of a toric lens is scheduled or a corneorefractive procedure includes a correction of cylindrical refraction errors, the meridional magnification may change in addition to the overall magnification, and should be considered in the calculation concept.

Options for calculating ocular magnification

In this thesis we restricted to models based on linear Gaussian optics (paraxial optics), which can be applied to thick lens models as well as simplified thin lens models. Here we used matrices for analysing paraxial optical systems. The benefit of the matrix notation is that the calculation is performed *en bloc*, instead of a step-by-step approach. Refractive surfaces are defined using refraction matrices, and interspaces with a homogeneous medium are represented by translation matrices. A system matrix, which represents the entire optical system is calculated by multiplying all matrices from the object to the image (in an inverse order) together. Ocular magnification can be directly extracted from the system matrix of the entire system if it is corrected to form a sharp image at the retina. If we deal with rotationally symmetric optical systems, a simple 2x2 matrix strategy is sufficient, and if at least one refractive surface is astigmatic, an upgrade to 4x4 matrices is sufficient. In that case the system matrix is of dimension 4x4 and decomposes into 4 2x2 submatrices. One of those 2x2 submatrices describes the ocular magnification properties, and with a principal component analysis, we could derive the ocular magnification in both principal meridians (the major and the minor axis of the ellipse including orientation, if a circle is imaged to the retina). If the optical system is not fully corrected, we have to calculate the principal ray, which passes through the centre of the aperture stop, and magnification of such an uncorrected system is referenced to that principal ray. For investigation of change in ON due to corneal surgery, we did not postulate that the preoperative or postoperative optical system is corrected, therefore we considered the preoperative and postoperative situation in general as uncorrected eye.

In general, phakometry is difficult and in this thesis we back-calculated the refractive properties of the crystalline lens from biometric data of the cornea, all distances in the eye, refractive error, and an average refractive index (n_L=1.41) and curvature ratio of front and back surface (10 mm / 6 mm), derived from a schematic model eye.

Currently, there are only few attempts to provide eikonic glasses or implants to reach a specific target ocular magnification. The major problem is that lenses are limited in thickness, and as the optical thickness between front and back surface is a critical parameter for the change of magnification, the variation of the shape of both surfaces necessary for achieving a target magnification could be dramatical. But if we are not restricted to plano target refraction, combinations of corneal surgery or lens implants with a spectacle refraction allows for a wide range of eikonic correction even with small or moderate modifications in the target refraction and the corneal shape or lens power. In contrast to using individual eikonic designs for the glasses or the IOL, we could deal with standard lenses and glasses, as the combination of both maintains the eikonic correction.

Application of a calculation strategy to clinical data

In this PhD thesis, we applied our calculation strategy for analysing and predicting overall and meridional magnification to the special condition of standard cataract surgery (with implantation of rotational symmetric IOL), to cataract surgery with implantation of a toric lenses, to situations of corneal surgery, as well as to optics design in keratoprostheses implanted in the aphakic eye in situations with severe corneal pathologies. The calculation strategy for standard cataract surgery is very simple dealing with 2x2 matrices, and therefore it could be implemented and integrated easily in all IOL calculation concepts (even with an Excel spreadsheet). If the biometric data of both eyes of an individual together with the actual refraction and the target refraction after surgery is entered, we can read out the baseline eikonic status and estimate the postoperative eikonic status for situations, if only one or if both eyes is treated. The calculation concept for astigmatic systems which are treated with a standard or toric lens implant is much more complex, as we have to deal with 4x4 matrices. As long as the principal meridians of all astigmatic surfaces are properly aligned, magnification can be simplified to a separate calculation for both principal meridians. But in general, the principal meridians are not aligned and we consider crossed cylinders by using 4x4 matrix calculations. As a result of our calculation scheme we read out the average ocular magnification as well as the disparity in meridional magnification (comparing the meridional magnification) at image plane, if a circular object is traced through the optical system. Finally, we get out an ellipse for the left and for the right eye each for the preoperative and the postoperative situation, in total 4 ellipses. If comparing the ellipses of both eyes in the preoperative or in the postoperative situation, we could analyse the preoperative and the estimated postoperative eikonic situation of the patient. By comparing the preoperative and the postoperative situation for the left and the right eye, we calculate the gain or loss in overall or meridional magnification, due to surgery. For the application of our concept to corneal surgery, we restricted to analysis of ocular magnification change and ignored absolute magnification values and a comparison of both eyes. In those situations, the measurement of the posterior eye segment is not required for this analysis, and we are restricted to measurement of the anterior eye segment. In general cases, if we have no data whether the eye is fully corrected or not, we require the measurement of the anterior segment from the object to the aperture stop (pupillary plane) for calculation.

For the application of keratoprostheses, the situation is completely different. Keratoprostheses are implanted into aphakic eyes, and therefore, we have a very simple optical system with a spectacle correction and both surfaces of the optics cylinder of the prosthesis. Designing such an optics cylinder we modulate the front and back surface curvature of the cylinder and the aspect ratio defined by the length and diameter. The diameter as an artificial aperture stop solely changes the amount of light entering the eye and the visual field which can be realized, but the length and both radii affect the refraction status, magnification properties as well as the visual field.

We used a large clinical dataset from a modern optical biometer, where data of the corneal front surface (keratometry and optical coherence tomography data), from the corneal back surface (optical coherence tomography data) as well as data on all distances in the eye are available. In this patient cohort, measurements were performed prior to and after cataract surgery, and alongside to the preoperative and postoperative biometry, we have data of subjective refraction (derived with trial glasses in a trial frame). These data are properly reflecting the standard cataract population. For our analysis of toric intraocular lenses, we restricted to those eyes where due to a moderate or high corneal astigmatism, toric lenses have been implanted. In contrast, for the application of our calculation strategy to the change in overall and meridional magnification due to corneorefractive surgery or to analysis of the situation with keratoprostheses, the study population might be inappropriate. Corneorefractive surgery (e.g. LASIK) is typically performed in a young study population, where the proportions of the eye – especially the crystalline lens – are somehow different and we have a significant refraction error which should be corrected by corneal ablation procedure. Therefore, we decided to extract those patients from the dataset, where the preoperative ametropia is larger than 1.5 dpt or the refractive cylinder is more than 1.5 dpt. But even though, this is a typical cataract population where due to the growth of the crystalline lens, the anterior chamber is flattened and the lens thickness is increased. For our simulation on ocular magnification in situations of keratoprostheses implantation, the age and cataract related changes of aqueous depth and lens thickness is of minor relevance as keratoprostheses are implanted in aphakic eyes.

Our most relevant results

Overall, from our dataset of N=8998 clinical cases, we learn that mean ocular magnification is 0.0162700±0.0005215 with a 95% confidence interval ranging from 0.0153243 to 0.0173993. That means that e.g. the retinal image size of an object with an angular field of 1 arc minute (according to the opening of a Landolt ring for vision test with acuity of 1.0) is on average 4.733 µm, which is about 2 diameters of a photoreceptor. After cataract surgery, retinal image size is on average gained to 4.862 µm, which is about 3% more than preoperatively. But for the individual change in magnification, we calculated a range (95% confidence interval) from-5.6% to 14.2%, which could have a strong impact on image fusion, summation or suppression in the brain, if only 1 eye is treated.

If we deal with astigmatism in the eye, we have to consider an overlay of overall and meridional ocular magnification in the phakic as well as in the pseudophakic eye. This astigmatism in the optical system is mostly due to the corneal shape and especially in the corneal front surface with a large index step from air to cornea even small variation in curvature between meridians induces some astigmatism. For that purpose, we extracted those eyes from our dataset where a toric lens was implanted. Decades ago, ophthalmologists were more reluctant with indication for toric lenses, but today, indication for toric lenses starts already with a corneal astigmatism of 1 diopter. With implantation of multifocal lenses or additional lenses, correction of corneal astigmatism could be even indicated with a small corneal cylinder of half a dioptre and manufacturers of IOLs reacted on this trend and include a large toricity range for their IOLs. In our dataset, the portion of toric lenses was relatively high with 12.4%. For this study population, which received a toric lens implant, we analysed the ratio of the long to the short axis of the ellipse at retinal plane, if a circle was imaged at object plane. Preoperatively, we derived an image distortion due to astigmatism of 2.8% on average, with a range from 1.42% to 5.43% (95% confidence interval). If both eyes are anisometric or if the orientation of the magnification meridians is asymmetric, there might arise some problems of image fusion in the brain, and stereopsis or binocular vision might be lost. Postoperatively, image distortion is much less and ranges between 0.06% and 1.16% (95% confidence interval). This reduction in meridional aniseikonia is obvious, because the refractive correction of corneal astigmatism is shifted from spectacle plane to lens plane, which is located much closer to the nodal point and principal point of the eye. That means, if patients with corneal astigmatism indicated for cataract surgery show some image fusion problems, clinicians should think about a correction with toric lenses instead of standard lenses and a postoperative correction of the residual astigmatism with spectacles. The potential meridional magnification at baseline and the estimated meridional magnification after cataract surgery with implantation of a standard lens or a toric lens implant could be directly derived using our calculation strategy.

For analysing the impact of corneal surgery on overall and meridional magnification changes of the eye, we modelled ‘simulated’ situations with corneorefractive surgery (e.g. LASIK) and a plano target refraction to keep the simulation model simple. The change in corneal front surface curvature and the reduction in central corneal thickness due to tissue ablation were derived from the preoperative corneal front surface curvature, assuming that corneal back surface curvature keeps unchanged. From the patient cohort we selected those cases with a sufficient mean ametropia or refractive cylinder, where corneorefractive surgery procedure seems to be justified. The change in ocular magnification means, that if a circle at object plane is imaged to the retina both for the preoperative to the postoperative situation, we read out an elliptical image at image plane both for the preoperative and the postoperative situation. In general, both ellipses are defined by the long and short axes as well as the orientation, and what we calculated is the transform from the preoperative to the postoperative ellipse, using a principal component analysis. This transform again refers to an elliptical design, which yields a meridian with the lowest change in magnification and an orthogonal meridian, where we have the highest change in ocular magnification. In general, the meridional change ranges in between -8.76% and 15.22% (95% confidence interval), and the distortion due to surgery ranges in between 0.05% and 5.58% (95% confidence interval). On average, we observed a loss in ocular magnification up to 7.88% (mostly hyperopic interventions) and a gain up to 13.69% (mostly myopic corrections)(95% confidence interval).

For investigation of magnification with keratoprostheses, we extracted from our data axial length and subjective refraction in terms of spherical equivalent and cylinder. The optics cylinder was defined a) to ensure that the entire optical system including spectacle refraction was corrected to image sharply to the retina, and b) to achieve target refraction as proposed in the literature. As we have the option to split the required refractive power into front and back surface of the optics cylinder and to spectacle correction after surgery, we could aim for some target magnification. The more fraction of refractive power is given to the front surface of the optics cylinder (and the less to the back surface) the higher will be ocular magnification, but this gain of magnification is on cost of field angle. The same situation is observed with the target refraction: the more plus (patient will be hyperopic), the higher is ocular magnification, but on cost of field angle. The optics diameter is independent of ocular magnification, and the larger the diameter (and the shorter the optics cylinder) the larger the field angle.

5. Conclusions

In conclusion, we developed a calculation scheme for analysis of overall and meridional magnification of the eye. This calculation scheme is based in linear Gaussian optics and considers rotationally symmetric optical systems as well as astigmatic systems without restrictions to cylinders, which are aligned in orientation. This algorithm has been applied to situations before and after cataract surgery in standard situations, as well as with implantation of toric intraocular lenses, to situations before and after corneal surgery, as well as to keratoprostheses. From a comparison of the left to the right eye, we read out overall and meridional magnification disparities in terms of aniseikonia for the preoperative and the postoperative situation. By comparing for both eyes, the preoperative with the estimated postoperative situation, we read out data on gain or loss in the overall or meridional magnification. The applicability of this calculation scheme has been shown on a large study population before and after cataract surgery.

We strongly recommend integrating assessment of eikonic evaluation at baseline and estimation of postoperative eikonic situation into the routine preoperative cataract biometry and intraocular lens power calculation procedure, as well as in the planning of corneorefractive surgery.

6. Bibliography of the candidate's thesis related publications

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