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Calculation of ocular magnification in phakic and pseudophakic eyes based on anterior segment OCT data

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Abstract

Purpose: The purpose of this study is to develop a straightforward mathematical concept for determination of object to image magnification in both phakic and pseudophakic eyes, based on biometric measures, refractometry and data from an anterior segment optical coherence tomography (OCT).

Methods: We have developed a strategy for calculating ocular magnification based on axial length measurement, phakic anterior chamber and lens thickness, keratometry and crystalline lens front and back surface curvatures for the phakic eye, and axial length measurement, anterior chamber and lens thickness, keratometry and intraocular lens power, refractive index and shape factor for the pseudophakic eye. Comparing the magnification of both eyes of one individual yields aniseikonia, while comparing the preoperative and postoperative situation of one eye provides the gain or loss in ocular magnification. The applicability of this strategy is shown using a clinical example and a small case series in 78 eyes of 39 patients before and after cataract surgery.

Results: For the phakic eye, the refractive index of the crystalline lens was adjusted to balance the optical system. The pseudophakic eye is fully determined and we proposed three strategies for considering a potential mismatch of the data: (A) with spherical equivalent refraction, (B) with intraocular lens power and (C) with the shape factor of the lens. Magnification in the phakic eye was -0.00319 ± 0.00014 and with (A) was -0.00327 ± 0.00013, with (B) was -0.00323 ± 0.00014 and with (C) was -0.00326 ± 0.00013. With A/B/C, the magnification of the pseudophakic eye was on average $2.52 \pm 2.83\%$/$1.31 \pm 2.84\%$/$2.14 \pm 2.80\%$ larger compared with the phakic eye. Magnification changes were within a range of $\pm 10\%$.

Conclusions: On average, ocular magnification does not change greatly after cataract surgery with implantation of an artificial lens, but in some cases, the change could be up to $\pm 10\%$. If the changes are not consistent between the left and right eyes, then this could lead to post-cataract aniseikonia.

Introduction

Over the last two decades, anterior segment optical coherence tomography (OCT) instruments have become established in clinical practice, increasingly replacing corneal topographers. These OCTs are not restricted to measuring the shape of the corneal front and back surfaces, but additionally derive data from the anterior chamber of the eye. The newest generation of OCTs, with a measurement field of more than 10 mm in depth and a lateral scan field exceeding 10 mm, have the capability to measure the shape of the crystalline lens before cataract surgery, as well as the position of the artificial intraocular lens post-operatively.[1,2] OCTs with light sources in the near infrared range provide acceptable results in phakometry even with dense cataracts. In contrast to ultrasound measurements using an ultrasound biomicroscopy (UBM) or Scheimpflug cameras,[1] OCT offers a much higher resolution and a non-contact measurement of the entire anterior eye segment within seconds. With dedicated software tools, the curvature of the front and back surface of the crystalline lens is evaluated, and with an extrapolation of both surfaces, the equatorial plane of the crystalline lens is derived.[2] With such software tools, the decentration (magnitude and orientation) and degree of tilt (tilt angle and orientation) of the crystalline lens in a phakic eye, or artificial lens in a pseudophakic eye, can be assessed alongside the axial position and thickness.

In general, in all types of intraocular surgery where a refractive element is extracted from the eye, implanted or replaced, or where any distance or corneal curvature is changed, the lateral magnification also changes. However, lateral magnification of the eye is often not considered in modern cataract surgery.[3,4] As the shape of both surfaces of the crystalline lens could not be measured properly in the past, estimation of lateral magnification was either ineffective or not possible. However, it is known that disparate retinal image sizes could result in eikonic problems such as headaches or lack of stereopsis.[5–8] As we now have measurement tools available for phakometry, rather than simple estimation,[9,10] it is now possible to calculate the ocular magnification as a ratio of image to object size in the phakic eye prior to and after cataract surgery from the eye's biometric data. This enables investigation of the change in magnification resulting from surgery as well as the disparity of magnification between each eye before and after surgery.[6]

The purpose of this study was to present a calculation strategy detailing how the lateral magnification can be derived in the phakic and the pseudophakic eye based on biometric data and measurements from a modern high resolution anterior segment OCT. This strategy is explained with a comprehensive example and clinical dataset.

Methods

Patients and measurement data

A total of 78 eyes from 39 patients with age-associated cataract were enrolled in this study. A full ophthalmological examination was performed prior to cataract surgery and another 4 to 8 weeks after surgery. Before surgery, ocular biometry was carried out using the IOLMaster 700 (Carl Zeiss Meditec, zeiss.com). In addition, measurement using the 'Corneal Tomographic', 'Anterior Segment' and 'Preop Cataract'[2] modes was undertaken with the Casia 2 anterior segment OCT (Tomey Corporation, tomey.com). At the postoperative follow-up examination, the 'Postop Cataract' measurement mode was used to derive lens biometry data from the postoperative situation. We confirm that the study was conducted in adherence to the tenets of the Declaration of Helsinki and that informed consent from the patients was obtained.

Table 1 provides a list of the measurement data, which were documented at the preoperative and postoperative examinations using the IOLMaster 700, the Casia 2 and refractometry. Intraoperatively, the equivalent power (IOLP) and the Coddington shape factor (q) of the lens implant were documented. The Coddington shape factor refers to the sum of both lens surface radii divided by the difference of both radii as shown in equation (3) of the method section entitled calculation scheme.

Preoperative and postoperative eye model

For the preoperative situation, we assumed a schematic model eye with four refracting surfaces:

1. A spectacle correction with power SEQ_{pre} at VD_{pre} in front of the cornea;
2. The corneal power re-scaled from Javal keratometer index to Zeiss keratometer index ($K_{preZ} = 332/337.5 \cdot K_{pre}$);
3. The front surface of the lens with a radius of curvature LRF_{pre} located ACD_{pre} behind the corneal vertex;
4. The back surface of the lens with a radius of curvature LRB_{pre} located LT_{pre} behind the lens front vertex.

[SEQ, spherical equivalent refraction; VD, vertex distance; K, keratometry; LRF, lens radius front; ACD, anterior chamber depth; LRB, lens radius back; LT, lens thickness].

For both the refractive indices of the aqueous (n_{AQ}) and vitreous humour (n_V), we used values of 1.336, and the refractive index of the crystalline lens (n_L) was adjusted in such a way that an object at an object distance (OD) in front of the spectacle correction was sharply focused on the retina. For the postoperative situation, we again assumed a schematic model eye with four refracting surfaces:

1. A spectacle correction with a power SEQ_{post} at VD_{post} in front of the cornea;

Table 1. List of measurement data which are documented at the preoperative and postoperative examination using the IOLMaster 700, the Casia 2, and refractometry

Description	Pre-operatively	Post-operatively	Dimension	Device
Axial length (AL)	AL_{pre}		mm	IOL-Master 700
Anterior chamber depth (ACD) measured from epithelium to anterior lens vertex	$ACD_{preIOLM}$		mm	
Central lens thickness (LT)	$LT_{preIOLM}$		mm	
Average corneal radius®	$R_{preIOLM}$		mm	
Average corneal power (K) derived from corneal front and back surface	REAL AVGK, K_{pre}	REAL AVGK, K_{post}	D	Casia 2
Anterior chamber depth (ACD) from front corneal vertex to front lens vertex	ACD_{pre}	ACD_{post}	mm	
Central lens thickness (LT)	LT_{pre}	LT_{post}	mm	
Curvature of the front surface of the crystalline lens (LRF)	LRF_{pre}		mm	
Curvature of the back surface of the crystalline lens (LRB)	LRB_{pre}		mm	
Spherical equivalent (SEQ) of subjective refraction	SEQpre	SEQpost	D	Refracto-metry
Vertex distance (VD) between spectacle back vertex and corneal front vertex	VD_{pre}	VD_{post}	mm	
Object distance (OD) for refractometry	OD_{pre}	OD_{post}	mm	

2. The cornea with a corneal power re-scaled from Javal keratometer index to Zeiss keratometer index (K_{postZ} = 332/337.5·K_{post});
3. The front surface of the lens (radius of curvature IOLRF) located ACD_{post} behind the corneal vertex;
4. The back surface of the lens (radius of curvature IOLRB) located LT_{post} behind the lens front vertex.

[SEQ, spherical equivalent refraction; VD, vertex distance; K, keratometry; ACD, anterior chamber depth; IOLRF, intraocular lens radius front surface; IOLRB, intraocular lens radius back surface; LT, lens thickness].

For the refractive indices of air, aqueous and vitreous humours we used values of 1.000, 1.336 and 1.336, respectively, and the axial length (AL) was assumed to be the same as for the preoperative situation ($AL_{post} = AL_{pre}$).

Once the postoperative model was fully determined, we considered three different scenarios for a potential mismatch of the optical system: in A, we assumed that the equivalent power of the intraocular lens power (IOLP), the shape factor q and the refractive index of the intraocular lens n_{IOL} are correct, and therefore, we re-adjusted the postoperative spherical equivalent refraction at the spectacle plane ($SEQ_{postadj}$) to focus an object sharply onto the image plane and documented the difference between SEQ-post and SEQpostadj for proof of concept. In scenario B, we assume that postoperative refraction SEQ_{post}, the shape factor q and the refractive index of the lens are correct, and therefore, we re-adjusted the power of the intraocular lens ($IOLP_{adj}$) to focus an object sharply onto the image plane and documented the difference between IOLP and $IOLP_{adj}$ for proof of concept. In scenario C, we assume that postoperative refraction SEQ_{post}, the refractive index of the lens and the power of the lens IOLP are correct, and therefore we re-adjusted the Coddington shape factor (q_{adj}) to focus an object sharply onto the image plane and documented the difference between q and q_{adj} for proof of concept.

Calculation scheme

In our notation, the parameters $V1_{pre}$ to $V4_{pre}$ refer to the vergences in the preoperative situation directly in front of and $V1_{pre\_}$ to $V4_{pre\_}$ to the vergences directly behind the refractive surfaces 1 to 4 as listed above. For the postoperative situation, $(.)_{post}$ is used instead of $(.)_{pre}$, respectively.

In the phakic eye, the vergence in front of the crystalline lens $V3_{pre}$ and the vergence behind the crystalline lens $V4_{pre\_}$ are calculated using:

$$V3_{pre} = \frac{1}{\frac{1}{\frac{1}{\frac{1}{\frac{-1}{OD_{pre}} + SEQ_{pre}} - VD_{pre}} + K_{Zpre}} - \frac{ACD_{pre}}{n_{KW}}}$$

$$V4_{pre-} = \frac{n_V}{AL_{pre} - ACD_{pre} - LT_{pre}}. \qquad (1a,b)$$

With equations (1) and (2)

$$V4_{pre\_} = \frac{1}{\frac{1}{V3_{pre} + \frac{n - n_{AQ}}{LRF_{pre}}} - \frac{LT_{pre}}{n_L}} + \frac{n_V - n_L}{LRB_{pre}}, \qquad (2)$$

Inserting $V3_{pre}$ and $V4_{pre}$ into equation (2) above means this can solve for the refractive index of the crystalline lens n_L. The lateral magnification M_{pre} is derived from the object vergence O (referenced to the object side principal plane) and the image vergence I (referenced to the image side principal plane) as $M_{pre} = O/I$.

For the pseudophakic eye in the postoperative situation, we have a fully determined optical system. With a shape factor of the lens defined by:

$$q = \frac{IOLRB + IOLRA}{IOLRB - IOLRA}. \quad (3)$$

The power of the lens back surface IOLPB can be expressed as:

$$IOLPB = \frac{n_V - n_{IOL}}{n_{IOL} - n_{AQ}} \cdot \frac{q-1}{q+1} \cdot IOLPF, \quad (4)$$

where IOLPF refers to the front surface power of the lens. With IOLP being the equivalent power of the intraocular lens according to ISO 11979, we can retrieve IOLPF (and IOLPB) from equation (4) and the following relationship (5):

$$IOLP = IOLPF + IOLPB - IOLPF \cdot IOLPB \cdot \frac{LT_{post}}{n_{IOL}}. \quad (5)$$

For scenario A, the adjusted spherical equivalent at spectacle plane yields:

$$SEQ_{postadj} = \frac{1}{\frac{1}{\frac{1}{\frac{1}{\frac{1}{\frac{1}{\frac{n_V}{AL_{post} - ACD_{post} - LT_{post}} - IOLPB} + \frac{LT_{post}}{n_{IOL}}} - IOLPF} + \frac{ACD_{post}}{n_{AQ}}} - K_{Zpost}} + VD_{post}} + \frac{1}{OD_{post}}. \quad (6)$$

For scenario B, the vergences in front of ($V3_{post}$) and behind ($V4_{post\_}$) the intraocular lens are derived from formulae (1a and b) with indices $(.)_{pre}$ replaced by indices $(.)_{post}$. In the next step, the vergence deficit, which has to be compensated by the lens implant, is given by:

$$V4_{post\_} = \frac{1}{\frac{1}{V3_{post} + IOLPF} - \frac{LT_{post}}{n_{IOL}}} + IOLPB, \quad (7)$$

With equations (7) and (4) we can derive the surface power for the front surface IOLPF and back surface IOLPB of the lens implant. The adjusted lens power $IOLP_{adj}$ is calculated using equation (5).

For scenario C, the strategy is similar to scenario B. The vergences in front of ($V3_{post}$) and behind ($V4_{post\_}$) the intraocular lens implant are derived from formulae (1a and b) with indices $(.)_{pre}$ replaced by indices $(.)_{post}$, and the vergence deficit, which has to be compensated by the lens implant, is calculated using equation (7). Then, the front surface power of the lens is modulated in a way that the equivalent power of the lens retains its IOLP:

$$V4_{post\_} = \frac{1}{\frac{1}{V3_{post} + IOLPF} - \frac{LT_{post}}{n_{IOL}}} + \frac{IOLP - IOLPF}{1 - IOLPF \cdot \frac{LT_{post}}{n_{IOL}}}. \quad (8)$$

With equation (8) and the back surface power of the lens defined by:

$$IOLPB = \frac{IOLP - IOLPF}{1 - IOLPF \cdot \frac{LT_{post}}{n_{IOL}}} \quad (9)$$

The adjusted shape factor is derived using equation (4).

Statistics

Descriptive statistics are shown for magnification of the phakic eye preoperatively, and for scenarios A, B and C for the pseudophakic eye postoperatively using mean, standard deviation (SD), minimum, maximum and median. In addition, the relative change in preoperative to postoperative magnification is shown in percent for all scenarios ($100 \cdot (M_{post}/M_{pre} - 1)$).

Results

Clinical case series

The mean age of the patients at time of surgery was 71 ± 13 years. The refractive power of the intraocular lens was 21.9 ± 2.0 D (range 16.5 to 25 D, median 22.25 D). Descriptive statistics of the preoperative (IOLMaster 700 and Casia 2) and postoperative (Casia 2) measurement parameters are shown in *Table 2* alongside the subjective refraction data. Object to image magnification in the phakic eye M_{pre} was −0.00319 ± 0.00014 (range −0.00368 to −0.00290, median −0.00319). After surgery, with scenario A magnification was −0.00327 ± 0.00013 (range −0.00363 to −0.00306, median −0.00325) and on average 2.52 ± 2.83% (range −5.71% to 9.49%, median 2.28%) larger compared with the preoperative situation. With scenario B, magnification was 0.00323 ± 0.00014 (range −0.00360 to −0.00301, median −0.00322) and on average 1.31 ± 2.84% (range −7.22% to 8.18%, median 1.29%) larger compared with the preoperative situation. With scenario C, magnification was −0.00326 ± 0.00013 (range −0.00362 to −0.00304, median −0.00324) and on average 2.14 ± 2.80% (range −6.12% to 9.06%, median 1.97%) larger compared with the preoperative situation.

Figure 1 (left) shows the overlay histogram of the distribution for the preoperative object to image magnification in the phakic eye (M_{pre}) and the postoperative distribution in the pseudophakic eye (M_{post}) for scenario A. On the

Table 2. Descriptive statistics of the measurement data before and after cataract surgery

		Mean	SD	Min	Max	Median
Phakic eye before surgery	AL_{pre} in mm	21.91	2.01	16.50	25.00	22.25
	ACD_{pre} in mm	3.21	0.37	2.38	3.98	3.24
	LT_{pre} in mm	4.70	4.20	3.86	5.77	4.74
	K_{preZ} in D	43.01	1.44	39.93	46.22	42.92
	SEQ_{pre} in D	−0.33	1.82	−4.37	3.87	−0.06
	LRA in mm	9.30	1.36	7.58	14.11	9.11
	LRP in mm	5.78	0.52	4.40	7.17	5.76
Pseudophakic eye after surgery	ACD_{post} in mm	4.61	0.25	4.10	5.24	4.58
	LT_{post} in mm	1.06	0.06	0.89	1.15	1.07
	K_{postZ} in D	43.01	1.44	39.93	46.22	42.92
	SEQ_{post} in D	−0.71	0.81	−3.62	2.37	−0.63

Axial length AL_{pre} was measured with the IOLMaster 700, anterior chamber depth before (ACD_{pre}) and after (ACD_{post}) cataract surgery, lens thickness before (LT_{pre}) and after (LT_{post}) cataract surgery, corneal power (REAL average corneal power as a composite value for corneal front and back surface, already converted to Zeiss keratometer index) before (K_{preZ}) and after (K_{postZ}) cataract surgery, and curvature of the crystalline lens front (LRF) and back (LRP) surface were determined with the Casia 2. Subjective refraction was determined preoperatively (SEQ_{pre}) and postoperatively (SEQ_{post}) with trial lenses in a trial frame with a measurement distance of 5 m.

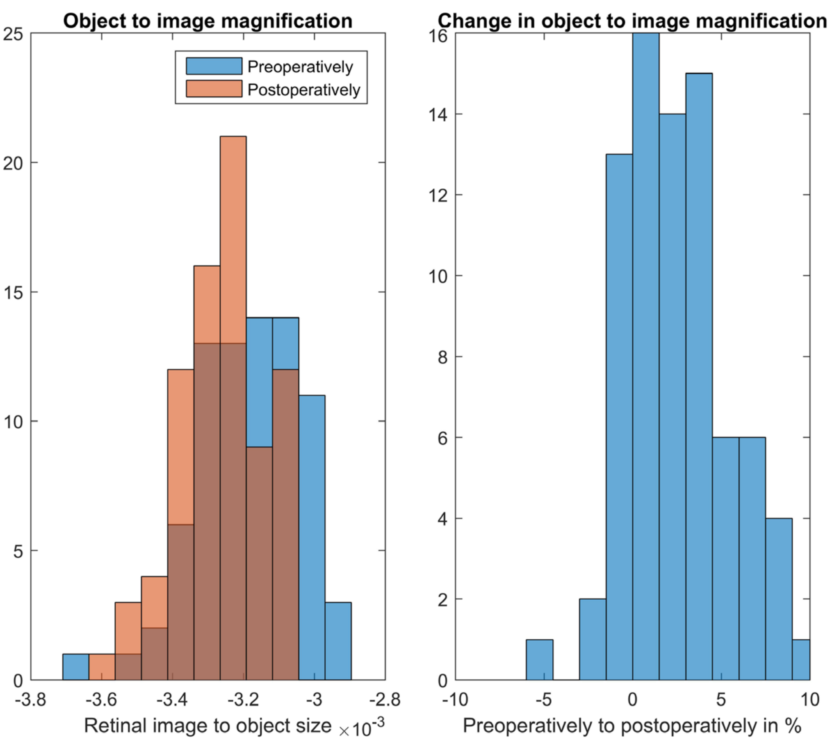

Figure 1. Left image: Overlay of the distributions of object to image magnification in the phakic eye before cataract surgery and in the pseudophakic eye after cataract surgery with implantation of a standard intraocular lens (Hoya Vivinex). Right image: Distribution of the change in object to image magnification from the preoperative situation (phakic eye) to the postoperative situation (pseudophakic eye). In the postoperative situation, the nominal lens power is known resulting in a fully determined optical system; this figure refers to scenario A, where a potential mismatch of the data is transferred to the spherical equivalent (SEQ) refraction ($SEQ_{postadj}$ instead of SEQ_{post}). Data are derived from 78 eyes of 39 patients.

right side, the post-surgical change in object to image magnification is displayed. *Figures 2 and 3* show the corresponding overlay histograms for scenarios B and C, respectively.

Case study

A 68-year-old man with cortical cataracts was scheduled for surgery on both eyes at Vienna General Hospital (AKH)

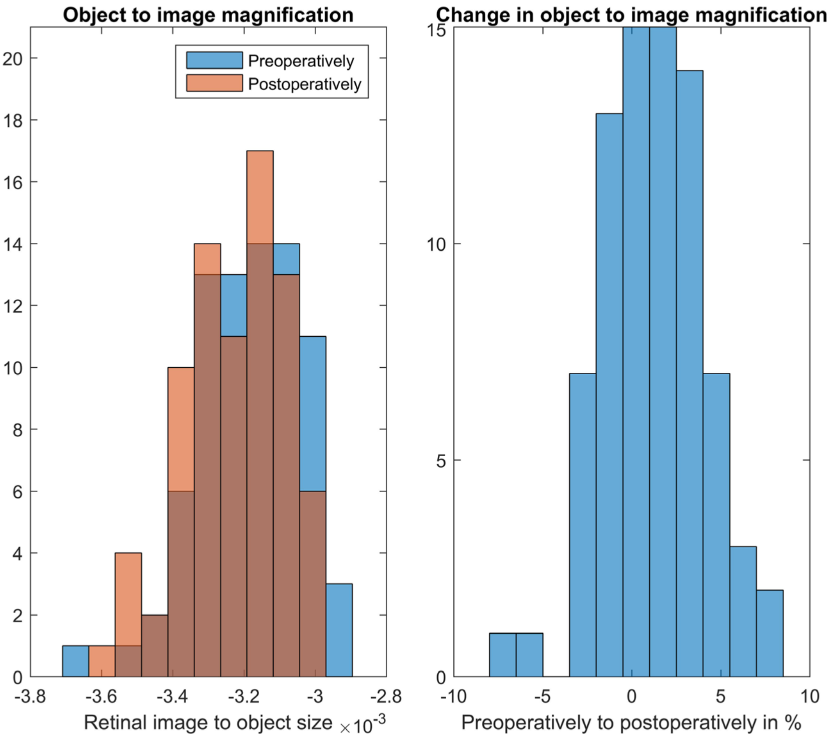

Figure 2. Left image: Overlay of the distributions of object to image magnification in the phakic eye before cataract surgery and in the pseudophakic eye after cataract surgery with implantation of a standard intraocular lens (Hoya Vivinex). Right image: Distribution of the change in object to image magnification from the preoperative situation (phakic eye) to the postoperative situation (pseudophakic eye). In the postoperative situation the nominal lens power is known resulting in a fully determined optical system; this figure refers to scenario B, where a potential mismatch is transferred to intraocular lens (IOL) power ($IOLP_{adj}$ instead of IOLP). Data are derived from 78 eyes of 39 patients.

University Eye Clinic in Vienna, Austria. Biometric data from each eye measured with the IOLMaster 700 and the Casia 2 are shown in *Table 3*. Object distance for subjective refractometry was 5 m and vertex distance $V_{pre} = V_{post} = 12$ mm. In each eye an intraocular lens (IOL) with IOLP = 22.00 D (Hoya Vivinex, hoyasurgicaloptics.com, $n_{IOL} = 1.55$) was implanted (we assumed the lens was equiconvex, q = 0).

The vergences for each eyes calculated from the biometric data as well as preoperative and postoperative measurements obtained with the Casia 2 are shown in *Table 4*. For the phakic eye preoperatively, we obtained a refractive index for the crystalline lens of the left and right eyes of 1.4177 and 1.4169, respectively. Magnification (M_{pre}) for the left and right eyes was −0.0034061 and −0.0034553, respectively. Postoperatively, for the pseudophakic eye, scenario A gave an adjusted spherical equivalent $SEQ_{postadj}$ for the left and right eyes of 0.05 and 0.31 D, respectively; scenario B gave an adjusted intraocular lens power ($IOLP_{adj}$) for the left and right eyes of 22.93 and 23.28 D, respectively, and scenario C gave an adjusted shape factor (q_{adj})- for the left and right eyes of 1.06 and 1.49, respectively. Lateral magnification in the pseudophakic left and right eyes was −0.0033822 and −0.0034115 (scenario A), −0.0033450 and −0.0033597 (scenario B) and −0.0033718 and −0.0033974 (scenario C), respectively. Image size disparity between the left and right eye (aniseikonia) was −1.42% preoperatively and −0.86%, −0.44% and −0.44% for postoperative scenarios A, B and C, respectively. The postoperative change in magnification compared with the preoperative value for scenarios A, B and C was −0.70%, −1.79% and −1.00%, respectively, for the left eye and −1.27%, −2.77% and −1.67%, respectively, for the right eye.

Discussion

For many decades there was no commercially available instrument that could precisely measure the curvature of the front and back surfaces of the crystalline lens *in situ*. With Scheimpflug cameras such as the Orbscan or Pentacam, it was possible to assess the front surface of the lens in many cases, but the limitation in depth of the measurement field meant that it was often not possible to measure the back surface geometry of the crystalline lens.[1] With the new generation of anterior segment OCTs, this measurement

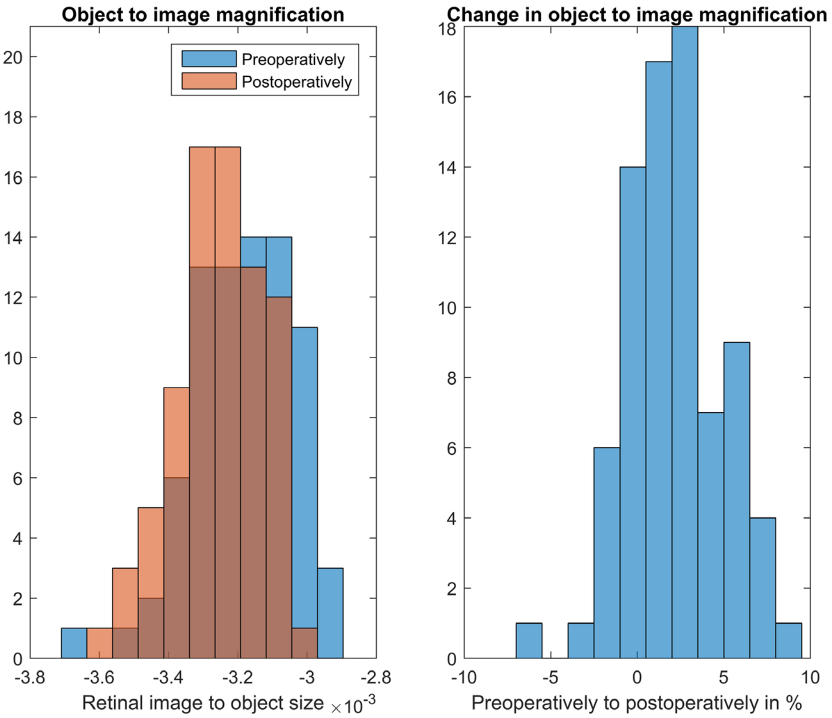

Figure 3. Left image: Overlay of the distributions of object to image magnification in the phakic eye before cataract surgery and in the pseudophakic eye after cataract surgery with implantation of a standard intraocular lens (Hoya Vivinex). Right image: Distribution of the change in object to image magnification from the preoperative situation (phakic eye) to the postoperative situation (pseudophakic eye). In the postoperative situation the nominal lens power is known resulting in a fully determined optical system; this figure refers to scenario C where a potential mismatch is transferred to the shape factor (q) of the lens (q_{adj} instead of q). Data are derived from 78 eyes of 39 patients.

Table 3. Biometric data of the left and right eye from the clinical case study

			Left eye	Right eye
Preoperatively	IOLMaster 700	Axial length AL_{pre}	24.39 mm	24.51 mm
		Anterior chamber depth $ACD_{preIOLM}$	3.15 mm	3.14 mm
		Lens thickness $LT_{preIOLM}$	4.46 mm	3.42 mm
		Corneal radius $R_{preIOLM}$	8.18 mm	8.31 mm
	Casia 2	Corneal power K_{pre}	40.4 D	39.7 D
		Anterior chamber depth ACD_{pre}	3.31 mm	3.32 mm
		Lens thickness LT_{pre}	4.58 mm	4.66 mm
		Lens curvature LRA/LRP	9.81 / 5.85 mm	9.54 / 6.08 mm
	Refractometry	Refraction (SEQ_{pre})	1.25 + 0.50 D/69° (1.50 D)	2.00 + 0.25 D/10° (2.12 D)
		Corrected visual acuity	0.8	0.8
Postoperatively	Casia 2	Corneal power K_{post}	40.1 D	39.7 D
		Anterior chamber depth ACD_{post}	4.50 mm	4.60 mm
		Lens thickness LT_{post}	1.05 mm	1.05 mm
	Refractometry	Refraction (SEQ_{post})	−0.75 + 0.25 D/75° (−0.63 D)	−0.75 + 0.25 D/0° (−0.63 D)
		Corrected visual acuity	1.25	1.25

Measurement data were obtained with the IOLMaster 700, the Casia 2 anterior segment OCT, and by subjective refractometry (trial lenses in a trial frame). For refractometry, an object distance (OD_{pre} = OD_{post}= 5 m; V_{pre} = V_{post} = −0.2 D: V, vergence) was used, and back vertex distance (VD) was measured as VD_{pre} = VD_{post} = 12 mm.

can be obtained provided that the measurement field is sufficient in both depth and width. Some instruments have software tools dedicated for phakometry.[2] Even when the refractive index of the crystalline lens is unknown, and therefore measurement of the back surface curvature of the lens might be somewhat inaccurate (as it is affected by the

Table 4. Vergences (V) directly in front of and behind refractive surface 1 (spectacle correction), surface 2 (cornea), surface 3 (front surface of the lens) and surface 4 (back surface of the lens) for the preoperative and postoperative situation

Vergences in D	$V1_{pre}$	$V1_{pre\_}$	$V2_{pre}$	$V2_{pre\_}$	$V3_{pre}$	$V3_{pre\_}$	$V4_{pre}$	$V4_{pre\_}$
Left eye	−0.2	1.30	1.32	41.91	46.76	55.09	67.01	80.97
Right eye	−0.2	1.92	1.97	41.89	46.77	55.24	67.52	80.82
Vergences in D	$V1_{post}$	$V1_{post\_}$	$V2_{post}$	$V2_{post\_}$	$V3_{post}$	$V3_{post\_}$	$V4_{post}$	$V4_{post\_}$
Left Eye Scenario A	−0.2	−0.15	−0.15	40.44	47.08	58.12	60.53	71.57
Left Eye Scenario B	−0.2	−0.83	−0.82	39.77	46.18	57.69	60.06	71.57
Left Eye Scenario C	−0.2	−0.83	−0.82	39.77	46.18	68.84	72.24	71.57
Right Eye Scenario A	−0.2	0.11	0.11	40.04	46.44	57.48	59.83	70.88
Right Eye Scenario B	−0.2	−0.83	−0.82	39.11	45.20	56.89	59.19	70.88
Right Eye Scenario C	−0.2	−0.83	−0.82	39.11	45.20	72.46	76.24	70.88

refractive index), anterior segment OCT provide a simple method to get an estimate of this curvature without direct contact with the patient. Postoperatively following cataract surgery, phakometry is more difficult as the artificial lens material is less reflective.[3] Successful measurement of the geometry of the lens implant depends on the optical properties of the lens material. However, the refractive index of the lens material can be obtained from the data sheet and design data such as surface curvature and the Coddington shape factor can be sought from the lens manufacturer. As the implanted lens is typically much thinner than the crystalline lens, the shape factor has less effect on lateral magnification compared with the preoperative situation where a crystalline lens might have a central thickness of 4 mm or more.

In modern cataract surgery, goals are mostly with regard to refractive outcomes and image performance, and many attempts have been made to enhance vision with special lens designs such as aspheric or toric intraocular lenses, or to recover near vision either in part using extended depth of focus lenses or completely with multifocal lenses. However, estimation of the retinal image size, the disparity between the two eyes (aniseikonia) and the change in magnification following surgery is often overlooked.[3,11,12] Even if perfect visual performance was achieved following cataract surgery, image size disparity could affect the well-being of the patient, leading to diplopia, suppression, disorientation, eyestrain, headaches, dizziness and balance disorders.[7,8,13] According to the literature, typically an image size disparity of up to 5% or 7% can be tolerated, although asthenopic symptoms may occur even if the image size difference is lower. Therefore, during ocular biometry for IOL power calculations, we suggest adding an estimation of the actual magnification properties preoperatively, as well as the postoperative magnification properties for each eye based on the power and refractive index of the selected lens implant and its estimated lens position. For estimation of the crystalline lens position prior to cataract surgery we could use established strategies which are integrated in most theoretical optical formulae, or raytracing concepts for IOL power calculation. In the case of a dissatisfied patient after an otherwise uneventful surgical procedure, and with good monocular visual performance, we should measure the actual axial position and thickness of the lens implant and repeat biometric measurements in each eye to cross-check the lateral magnification disparity between the two eyes.

In the present study we have developed a mathematical concept to derive the lateral magnification for both phakic and pseudophakic eyes. All the relevant data for such calculations can be obtained using a modern anterior segment OCT and standard biometer. In the phakic eye, we require the phakic anterior chamber depth (e.g., from the front vertex of the cornea to the front vertex of the crystalline lens) and the central thickness of the lens. In addition, as the power and refractive index of the crystalline lens is unknown, we require data regarding the curvature of the front and back surface for a fully determined optical system. Based on the assumption of a constant refractive index, this value can be obtained using ocular refraction, corneal power, the axial position of the lens and the curvature data for the front and back surfaces, as well as the ocular magnification described by the quotient of object to image vergence, both referenced to the nodal points of the eye.[14]

After cataract surgery, the optical system can be fully determined by the actual refraction, corneal power, axial length, pseudophakic anterior chamber depth, lens thickness, lens power and the refractive index of the lens; furthermore, the shape factor is also known. According to ISO 11979, the labelled intraocular lens power refers to the paraxial power referenced to the image-side principal plane (the so-called equivalent power). The principal plane itself may be calculated from the shape factor of the lens, and in most cases is a biconvex lens with a Coddington factor equal or close to zero with minimal variation. With very low power lenses, manufacturers prefer meniscus lens designs rather than a bi-convex design, and in these cases a simplification of the true shape factor of the lens using q = 0 is no longer valid. The lens implant typically has a central thickness around 1 mm; therefore, the shape factor does not affect lateral magnification significantly. Even with all data available for the definition of our optical model, it is important to be aware that measurement inaccuracies or calibration errors of the instruments or refractometry errors can mean that the focus of our optical model is not exactly at the retina. This means that this mismatch has to be transferred into any measurement parameter to place the retina in focus again. Therefore, we have shown three different scenarios to place the retinal plane into focus. First, we assumed that the mismatch was due to an inaccuracy in refractometry, and therefore transferred the imbalance of the optical system to the spherical equivalent postoperative refraction, or in other words, calculated an adjusted spherical equivalent at the spectacle plane, which might differ from the measured spherical equivalent from refractometry (scenario A). Alternatively we assumed that the mismatch was due to a labelling error of the lens implant, and therefore transferred the imbalance of the optical system to the intraocular lens power. We calculated an adjusted intraocular lens power that might differ from the labelled lens power (scenario B). As a third option, we assumed that the manufacturer of the lens implant provided a shape factor and that the mismatch was due to an inaccuracy in the shape factor of the lens. In other words, we needed to change the design of the lens by modulating the front and back surface curvature such that the equivalent power matched the labelled lens power (scenario C). With thick lenses, even small variations in the shape factor q might be sufficient to balance the optical system, but in our case the lens implant had a central thickness of only approximately 1mm; therefore, a large variation in q was necessary to balance the system.

These results show that the absolute object to image magnification for objects at a 5 m distance is around −0.0032. That means that an object (e.g., the opening of a Landolt ring) for a visual acuity test of logMAR 0.0 (5/5) with a height of [5000/5 * Tan 5'] = 1.45 mm is imaged to 5 μm (around 2 times the diameter of a foveal cone). On average, the retinal image size is slightly larger after cataract surgery, compared to preoperatively, but the individual change in magnification may be up to 10%. As long as each eye experiences similar changes in magnification following surgery, we would not expect eikonic problems postoperatively. But where the magnification changes in the two eyes are not comparable, e.g., due to anisometropia,[13,15] eikonic problems after cataract surgery might be expected. In such cases, we could use the calculation scheme presented here to predict the changes in ocular magnification due to cataract surgery in each eye and compare the preoperative and postoperative situation in either eye. In cases where postoperative aniseikonia is predicted from the calculations, the surgeon could modulate the ocular magnification of one or both eyes with combinations of spectacle correction (target refraction),[6] contact lenses[15] or the power of the intraocular lens.

Ocular magnification with a finite object distance always refers to the object distance itself. In this study we considered a refractometry measurement distance of 5 m, and all magnification values were referenced to this distance. According to the ISO standard, the measurement distance for refractometry should range between 4 m and 6 m, and ocular magnification as the ratio of retinal image size to object size decreases with increasing object distance. If we consider a situation with an infinite object distance, then our definition of ocular magnification must be adapted to angular magnification, and will refer to the retinal image divided by the object angle in radians. The mathematical concept as described here does not change in general.

In conclusion, this paper shows a mathematical strategy based on biometric, refraction and phakometric data from a modern anterior segment OCT device for determination of ocular object to image magnification in a phakic eye prior to cataract surgery, as well as in a pseudophakic eye after surgery. The strategy is explained with a clinical sample and a small case series. If applied to the pre-and postoperative situations for each eye, then we are able to derive retinal image size disparity (preoperatively and postoperatively), as well as the change of magnification of each eye before and after surgery. However, the calculation scheme is not restricted to surgical changes. Rather, it can be applied in general to phakic or pseudophakic eyes to estimate image size disparities or changes.

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Conflict of interest

The authors report no conflicts of interest and have no proprietary interest in any of the materials mentioned in this article.

Author contributions

Achim Langenbucher: Study planning, development and implementation of the calculation concept, interpretation of data, writing of the manuscript. **Nóra Szentmáry:** Data

curation (supporting); Investigation (supporting); Project administration (supporting); Validation (equal); Visualization (equal). **Christina Leydolt:** Conceptualization (equal); Formal analysis (equal); Resources (equal); Validation (equal). **Alan Cayless:** Approval of methodology, assistance in writing the manuscript, critical revision**. Zoltán Zsolt Nagy:** Data curation (equal); Methodology (equal); Visualization (equal). **Luca Schwarzenbacher:** Conceptualization (equal); Formal analysis (equal); Resources (equal); Writing-review & editing (equal). **Rupert Menapace:** Conceptualization (equal); Investigation (equal); Project administration (equal); Supervision (equal); Validation (equal); Writing-review & editing (equal).

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Appendix

For estimation of the effect of input parameters on ocular magnification we set up a linear model using the partial derivatives quoted at the respective mean values of each input parameter. The error in ocular magnification ΔM_{pre}/ΔM_{post} is expressed as a sum of weighted errors in the input parameters with ocular magnification as the output parameter and all the relevant input parameters as effect sizes. In total, 4 linear models were calculated, one for the preoperative situation and 3 for the postoperative situation for scenarios A, B and C.

In the preoperative situation the linear model for the ocular magnification error ΔM_{pre} with respect to the input parameter errors (ΔV_{obj}, ΔSEQ_{pre}, ΔK_{preZ}, ΔACD_{pre}, ΔLRA, ΔLT_{pre}, ΔLRP, ΔAL_{pre}; all quoted in m or D) reads:

$$\begin{aligned}\Delta M_{pre} &= 1.58e-2\Delta V_{obj} - 5.72e-5\Delta SEQ_{pre}\\ &-1.95e-5\Delta K_{preZ} + 6.15e-2\Delta ACD_{pre} + 9.14e-3\Delta LRA\\ &+4.1e-2\Delta LT_{pre} + 7.19e-3\Delta LRP - 1.89e-1\Delta AL_{pre}.\end{aligned}$$

As an example, for the input vergence this means that a refraction lane distance of 4 m instead of 5 m (V_{obj} = −0.25 D instead of −0.2 D) the respective error in ocular magnification is expected to be ΔM_{pre} = 1.58e−2 (−5e−2) = −7.90e−4 (or a relative increase of retinal image size of 24.6%).

In the postoperative situation with scenario A (adjusted SEQ), the linear model for the ocular magnification error ΔM_{post} with respect to the input parameter errors (ΔV_{obj}, ΔK_{postZ}, ΔACD_{post}, $\Delta IOLP$, ΔLT_{post}, Δq, ΔAL_{post}; all quoted in m or D) reads:

$$\Delta M_{post} = 1.63e-2\Delta V_{obj} + 3.93e-5\Delta K_{postZ} - 2.36e-2\Delta ACD_{post} + 3.79e-5\Delta IOLP - 6.69e-3\Delta LT_{post} + 1.08e-5\Delta q - 2.71e-2\Delta AL_{post}.$$

As an example, for the axial length this means that a measurement error of 20 µm (ALpost = 23.55 instead of 23.53 mm) the respective error in ocular magnification is expected to be ΔM_{post} = –2.71e–2·2.0e–5 m = −5.42e–7 (or a relative increase of retinal image size of 0.0164%).

In the postoperative situation with scenario B (adjusted IOLP), the linear model for the ocular magnification error ΔM_{post} with respect to the input parameter errors (ΔV_{obj}, ΔSEQ_{post}, ΔK_{postZ}, ΔACD_{post}, ΔLT_{post}, Δq, ΔAL_{post}; all quoted in m or D) reads:

$$\Delta M_{post} = 1.61e-2\Delta V_{obj} - 5.26e-5\Delta SEQ_{post} - 1.45e-5\Delta K_{postZ} + 5.51e-2\Delta ACD_{post} + 4.70e-2\Delta LT_{post} - 2.53e-5\Delta q - 1.76e-1\Delta AL_{post}.$$

As an example, for the pseudophakic anterior chamber depth this means that a measurement error of 50 µm (ACD_{post} = 4.66 mm instead of 4.61 mm) the respective error in ocular magnification is expected to be ΔM_{post} = 5.51e–2·5.0e–5 m = 2.75e–8 (or a relative decrease of retinal image size of 0.0083%).

In the postoperative situation with scenario C (adjusted Coddington shape factor q), the linear model for the ocular magnification error ΔM_{post} with respect to the input parameter errors (ΔV_{obj}, ΔSEQ_{post}, ΔK_{postZ}, ΔACD_{post}, $\Delta IOLP$, ΔLT_{post}, ΔAL_{post}; all quoted in m or D) reads:

$$\Delta M_{post} = 1.62e-2\Delta V_{obj} - 1.60e-5\Delta SEQ_{post} + 2.31e-5\Delta K_{postZ} + 1.07e-3\Delta ACD_{post} + 2.65e-5\Delta IOLP + 1.01e-2\Delta LT_{post} - 7.30e-1\Delta AL_{post}.$$

As an example, for the refractive power of the implanted lens this means that a measurement error of 0.2 D (IOLP = 22.11 D instead of 21.91 D) the respective error in ocular magnification is expected to be ΔM_{post} = 2.65e–5·0.2 D = 5.30e–6 (or a relative decrease of retinal image size of 0.16%).

ACD, anterior chamber depth; AL, axial length; K, corneal power; IOLP, intraocular lens power; LRA, anterior lens radius of curvature; LRP, posterior lens radius of curvature; LT, lens thickness; M, magnification; q, shape factor; SEQ, spherical equivalent refraction; V, vergence.

