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Retinal image size in pseudophakia

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Abstract

PURPOSE:

Approaches are developed to determine relative retinal magnifications in anisometropic patients undergoing cataract surgery; these can be used to balance between full spectacle corrections with equal IOL powers and a pure IOL power correction.

METHODS:

The analysis started from the original and pseudophakic Navarro eye models, where in the latter an intraocular lens (IOL) replaced the natural lens. A third model was a simplified Navarro-IOL model with a single surface cornea and a thin lens. These models were manipulated by altering vitreous length, corneal power, and lens position. Retinal image sizes were determined for both full IOL corrections and full spectacle corrections by raytracing and approximate equations. Relative magnification (*RM*) was determined as the ratio of retinal image size of an eye to that of the appropriate standard eye.

RESULTS:

For raytracing and full IOL correction, vitreous length led to *RM* change of 5%/mm, while for corneal power and IOL position this was –0.4%/D and 1.4%/mm, respectively. For raytracing and spectacle correction, effects were 0%/D (vitreous depth), −1.6%/D (corneal power), and +1.0%/mm (IOL position). For full IOL correction, the approximate *RM* calculations were highly accurate. For spectacle correction, the approximate *RM* calculations were exact for vitreous length changes, reasonably accurate for corneal power changes, but very inaccurate for changes in anterior chamber depth.

CONCLUSION:

The relative magnification approximations may be useful to assess the risk of aniseikonia in anisometropic patients targeted for postoperative emmetropia. Some of these patients would best be corrected by a combination of spectacles and IOLs.

Key Points

- Useful approaches have been provided to determine relative retinal magnifications as a screening tool for aniseikonia risk in anisometropic patients undergoing cataract surgery.
- Under full IOL correction, the relative magnification changes by +5.2%/mm of vitreous length, +0.4%/D of corneal power and −1.4%/mm of effective IOL position.
- For spectacle correction with a fixed IOL power, effects are 0%/mm (vitreous length), –1.6%/D (corneal power) and +1.0%/mm (IOL position).

Introduction

Calculating the appropriate power for an intraocular lens (IOL) has become a routine task in clinical practice, provided that ocular dimensions remain near the population average.[1] For excessively short or long eyes, similar procedures are available to take the pseudophakic eye as close as possible to emmetropia.[2] This strategy works well in most cataract patients as both eyes often have very similar dimensions. In patients with eyes of very different dimensions, targeting emmetropia may not be necessarily in the patient's best interest as aniseikonia, a difference in retinal image size between eyes, may be induced or exacerbated in case of pre-existing anisometropia.[3]

The concepts of aniseikonia, spectacle magnification and relative spectacle magnification are well known in ophthalmic optics and have ready application for patients with anisometropia. Spectacle magnification (*SM*) is the ratio of retinal image sizes for an eye after and before spectacle correction, or more simply how much larger or smaller objects appear when a spectacle lens is placed in front of the eye. For a distant object, this is given by:

$$SM = 1/(1 - dF) \tag{1}$$

where *d* is the distance from the second principal point of the lens to the eye entrance pupil and *F* is the equivalent power of the lens. Other equations, that consider different object distances and the shape and thickness of the lens, were provided by Jalie.[4] Suppose, for example, two eyes have ocular biometries identical to an emmetropic eye, but have anterior corneal powers that are 4 D lower in the first eye and 4 D higher in the second eye. The respective correcting lenses placed 18 mm from the entrance pupil (which is itself located 3 mm inside the eye) would have powers +3.77 and −4.26 D and SMs of 1.073 and 0.929.

SM is of limited value, however, because it does not tell the relative retinal image size of different eyes. This is covered by relative spectacle magnification (*RSM*), which is the ratio of retinal image sizes for a corrected eye compared with that of a standard emmetropic eye, as is the case for a pair of anisometropic eyes. The calculation of *RSM* in the literature distinguishes between extremes of axial anisometropia, which is caused by differences in eye length, and refractive anisometropia, where other components such as the corneal power are different between the eyes. Atchison[5] calculated RSM by deriving simple equations to determine the relative retinal image sizes of eyes for anisometropia in corneal refractive surgery. As correction may be only partially, if at all, by spectacle lenses, he used the term relative magnification (*RM*) rather that relative spectacle magnification.

This paper aims to extend the previous works on assessing and correcting aniseikonia in anisometropic, post-refractive,[5] and pseudophakic eyes[3,6] through a new approach to consider relative image sizes in pseudophakic eyes targeting emmetropia by deriving a general equation and three special situations. These equations can help clinicians to assess the risk for postoperative aniseikonia if they follow the standard protocol of emmetropising in anisometropic patients. The important symbols to be used and the equations to be derived are listed in the Appendix at the end of the paper.

Method

Eye models

The starting point was the Navarro model eye, referred to here as the standard Navarro eye.[7] This was modified into the standard Navarro-IOL eye, with an IOL replacing the natural lens at a position as explained by Charman et al.[8] The aperture stop was 4.0 mm rather than 3.6 mm behind the anterior cornea. The IOL was 0.5 mm behind the aperture stop rather than at the stop itself. Its thickness was 0.8 mm, its refractive index was 1.45, and it was of equiconvex form with radii of curvature 11.82 mm. This corresponds with an effective lens position (usually abbreviated to ELP) for the IOL of about 4.9 mm behind the anterior cornea. Its power was 18.778 D, 3.0 D less than that of the Navarro eye lens. Vitreous chamber depth became 18.704 mm rather than 16.404 mm, with a retinal image size 1.024 times that of the standard Navarro eye. Both eyes' details are given in Table 1 and Figure 1.

Table 1: Model eyes. Numbers before and after "/" are those of the standard Navarro eye and the standard Navarro-IOL eye, respectively.

Surface	Radius of curvature (mm)	Refractive index	Distance to next surface (mm)
Air	–	1.0	infinity
Correcting lens	*		14.969/15.815#
Anterior cornea	7.72	1.376	0.55
Posterior cornea	6.50	1.3374	3.05/3.45
Aperture stop	infinity	1.3374	0/0.5
Anterior lens	10.2/11.82	1.42/1.45	4.0/0.8
Posterior lens	–6.0/–11.82	1.336	16.404/18.704
Retina	–	–	–

*Thin lens, power depends on correction required when eye parameters changed.
#Distance is the negative of the front vertex focal length of the standard Navarro eye/standard Navarro-IOL eye.

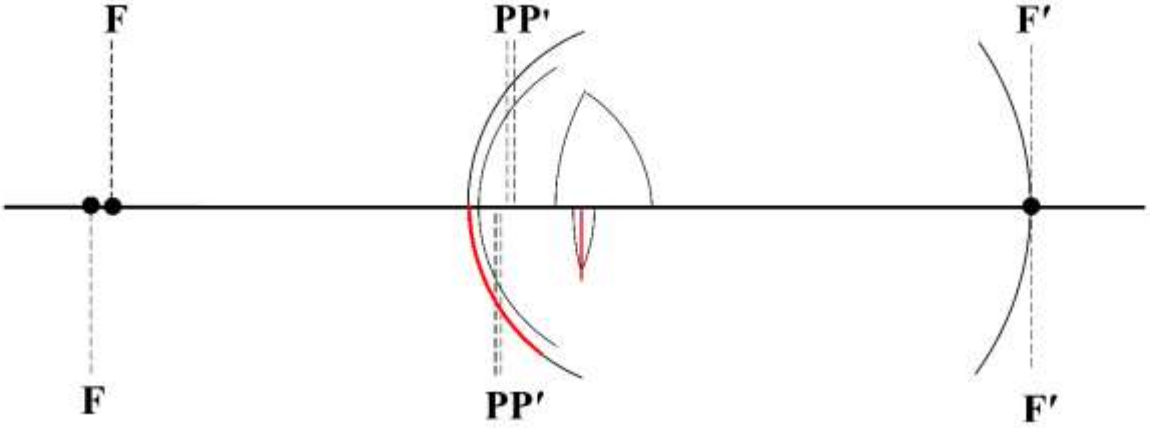

Figure 1. Model eyes: top standard Navarro eye, bottom Navarro-IOL eye. The simplified Navarro-IOL eye's single surface cornea and thin IOL are shown in the bottom in red. F and F'- first and second focal points, P and P'- first and second principal points.

To produce ametropia the standard Navarro and standard Navarro-IOL eyes were considered with variations in vitreous length between ±1.5 mm, anterior corneal surface power between ±4.0 D, and aperture stop position between ±2.0 mm. When the aperture stop position was varied, the distance between the stop and the lens was retained, and the vitreous chamber depth was varied by the opposite amount to retain axial length. To correct the ametropia, the eyes were corrected by placing an appropriate thin lens at the first (anterior) focal point of the standard eye (either Navarro or Navarro-IOL) or, in the case of the eyes with IOLs, changing the IOL power. Paraxial raytracing and equations described below were used to determine ratios of retinal image sizes.

In practice, a simplified version of the standard Navarro-IOL eye was used to assess the proposed equations. The cornea was replaced by a single surface of power 43 D, the distance between the cornea and a thin IOL was set to 4.9 mm (also approximately the ELP), a vitreous length was set to 19.1 mm, and the IOL power was 20.5 D. These values were based on the consideration that, for aqueous and vitreous indices of 1.336, the corneal equivalent power of the standard Navarro-IOL eye is 42.88 D, with principal points about 0.06 mm in front of the eye. From this follows an effective anterior corneal power of 43 D. A thin IOL at the centre of a 0.8 mm thick IOL would be located at 4.9 mm from the thin cornea and lead to a vitreous depth became 19.1 mm to maintain eye length of 24.00 mm. Emmetropia would then require a lens power of 20.5 D. This simplified version is shown in Table 2 and Figure 1.

Table 2. Simplified Navarro IOL eye

Surface	Power of thin lens (D)	Refractive index	Distance to next surface (mm)
Air	–	1.0	infinity
Correcting lens*	*	1.0	15.815
Cornea	43	1.336	4.9
IOL	20.5	1.336	19.1
Retina	–	–	–

*Not used in any calculations

Theory – full IOL correction

IOL powers are selected so that two eyes being compared are rendered emmetropic. We start from a reference eye, indicated by index ‘1’, which could be the standard Navarro-IOL eye. It has corneal power F_{C1}, IOL power F_{L1}, aqueous and vitreous refractive index n, aqueous chamber depth a_1 and vitreous length l_1'. Here the anterior chamber depth is from the second principal point of the cornea to the first principal point of the lens, and the vitreous length is from the second principal point of the lens to the retina. The vitreous length is the back vertex focal length, and is related to the back vertex power F_{v1}' by

$$F_{v1}' = n/l_1' \tag{2}$$

The power F_1 of the eye is

$$F_1 = F_{C1} + F_{L1} - (a_1/n)F_{C1}F_{L1} \tag{3}$$

From raytracing,

$$F_{v1}' = \frac{F_{C1}}{\left[1-\left(\frac{a_1}{n}\right)F_{C1}\right]} + F_{L1} \tag{4a}$$

Comparing equations (3) and (4a) gives

$$F_{v1}' = F_1/\left[1-\left(\frac{a_1}{n}\right)F_{C1}\right] \tag{5a}$$

From equations (2), (4) and (5a) we get

$$F_{L1} = \frac{n[1-\left(\frac{a_1}{n}\right)F_{C1}]-l_1'F_{C1}}{l_1'[1-\left(\frac{a_1}{n}\right)F_{C1}]} \tag{6a}$$

A comparison eye, indicated by index ‘2’, can have power F_2 where

$$F_2 = F_{C2} + F_{L2} - (a_2/n)F_{C2}F_{L2} \tag{7}$$

with corneal power F_{C2}, IOL power F_{L2}, and aqueous depth a_2.
The size of the comparison eye's retinal image, relative to that of the reference eye, and here called relative magnification (*RM*), is given by the ratio of focal lengths f_2'/f_1', or

$$RM = \frac{F_1}{F_2} = [F_{C1} + F_{L1} - (a_1/n)F_{C1}F_{L1}]/[F_{C2} + F_{L2} - (a_2/n)F_{C2}F_{L2}] \tag{8}$$

Comparison eye with different length than reference eye

Let the vitreous length be changed by $\Delta l'$ to have length l_2'. The corneal power is unchanged, i.e., $F_{C1} = F_{C2}$, but the lens power must change to F_{L2} to correct the eye. Changing the power of the lens will have small effects on anterior chamber depth and vitreous depth, even if the shape of the lens is unchanged, but these are ignored in this treatment (so $a_1 = a_2$).

From raytracing, similar to equations (4a), (5a) and (6a)

$$\frac{F_{C1}}{\left[1-\left(\frac{a_1}{n}\right)F_{C1}\right]} + F_{L2} = \frac{n}{l_1' + \Delta l'} = F_{v2}' \tag{4b}$$

$$F_{v2}' = F_2 / \left[1 - \left(\frac{a_1}{n}\right)F_{C1}\right] \tag{5b}$$

$$F_{L2} = \frac{n\left[1-\left(\frac{a_1}{n}\right)F_{C1}\right] - l_2' F_{C1}}{l_2' \left[1-\left(\frac{a_1}{n}\right)F_{C1}\right]} \tag{6b}$$

Substituting the right-hand sides of equations (6a) and (6b) for F_{L1} and F_{L2}, respectively, into equation (8), gives after simplification,

$$RM = l_2'/l_1' = (l_1' + \Delta l')/l_1' \tag{9}$$

Alternatively, using equations (5a) and (5b)

$$RM = \frac{F_{v1}'}{F_{v2}'} = l_2'/l_1' = (l_1' + \Delta l')/l_1' \tag{9a}$$

These last two equations correspond with what was reported earlier by Gobin et al.[3]

Comparison eye with different corneal power than reference eye

Let the corneal power be changed by ΔF_C so that

$$F_{C2} = F_{C1} + \Delta F_C \tag{10}$$

The lens power must change to F_{L2} to correct the eye. The powers of the cornea and lens will have small effects on anterior chamber depth and vitreous depth, even if the shape of the lens is unchanged, but these are ignored. From raytracing,

$$\frac{F_{C2}}{\left[1-\left(\frac{a_1}{n}\right)F_{C2}\right]} + F_{L2} = \frac{n}{l_1'} \tag{4c}$$

or

$$F_{L2} = \frac{n\left[1-\left(\frac{a_1}{n}\right)F_{C2}\right] - l_1' F_{C2}}{l_1' \left[1-\left(\frac{a_1}{n}\right)F_{C2}\right]} \tag{6c}$$

Substituting right-hand sides of equations (6a) and (6c) for F_{L1} and F_{L2}, respectively, into equation (8) gives, after simplification,

$$RM = \frac{n - a_1 F_{C1}}{n - a_1 F_{C2}} = \frac{n - a_1 F_{C1}}{n - a_1 (F_{C1} + \Delta F_C)} \tag{11}$$

Comparison eye with different aperture stop position than reference eye

In this case the length of the eye is unaffected while the lens position within the eye changes. Let the lens position be changed by Δa so

$$a_2 = a_1 + \Delta a \tag{12}$$

The vitreous depth changes also, to be

$$l_2' = l_1' - \Delta a \tag{13}$$

The lens power must change to F_{L2} to correct the eye. Changing the power of the lens will have small effects on anterior chamber depth and vitreous depth even if the shape of the lens is unchanged, but these are ignored in this treatment.
From raytracing,

$$F_{C1}/[1 - (a_2/n)F_{C1}] + F_{L2} = n/l_2'$$

or

$$F_{L2} = \frac{n\left[1 - \left(\frac{a_2}{n}\right)F_{C1}\right] - l_2' \ F_{C1}}{l_2' \ [1 - \left(\frac{a_2}{n}\right)F_{C1}]} \tag{6d}$$

Substituting right-hand sides of equations (6a) and (6d) for F_{L1} and F_{L2}, respectively, into equation (8) gives, after simplification,

$$RM = \frac{\left[1 - \left(\frac{a_1}{n}\right)F_C\right] l_2'}{\left[1 - \left(\frac{a_2}{n}\right)F_C\right] l_1'} = \frac{\left[1 - \left(\frac{a_1}{n}\right)F_C\right](l_1' - \Delta a)}{\left[1 - \left(\frac{a_1 + \Delta a}{n}\right)F_C\right] l_1'} \tag{14}$$

Theory - Position of correcting spectacle lenses

Knapp's law states that a correcting lens placed at the first focal point of an axially ametropic eye will give a RSM of 1.0, that is, the sizes of the retinal image of the standard Navarro eyes and of the corrected axial ametropic eyes are the same. We can determine this position relative to the anterior cornea, the front vertex focal length f_{v1} of the eye, as

$$f_{v1} = -\frac{1}{F_{v1}} = -\frac{1}{\frac{F_{L1}}{\left[1 - \left(\frac{a_1}{n}\right)F_{L1}\right]} + F_{C1}} = -\frac{1 - \left(\frac{a_1}{n}\right)F_{L1}}{F_{L1} + F_{C1}\left[1 - \left(\frac{a_1}{n}\right)F_{L1}\right]} \tag{15}$$

For standard Navarro and standard Navarro-IOL eyes, the focal lengths are –14.97 mm and –15.82 mm, respectively.

Theory - Determining RM with full spectacle correction

In this section, RM is determined when IOL powers of reference and comparison eyes are identical, and thus the eyes require different spectacle corrections. The usual term for the ratio of the retinal image size in a spectacle corrected eye to that of a standard eye is relative spectacle magnification, but relative magnification (RM) will continue to be used here.

Atchison[5] derived equations for RM related to eyes undergoing corneal refractive surgery. The basic equation, a combination of (8) and (9) in that paper, was

$$RM = \frac{F_{SR1}+F_{u1}-x_1F_{u1}F_{SR1}}{F_{SR2}+F_{u2}-x_2F_{u2}F_{SR2}} = (k'_2/k'_1)(1-x_1F_{SR1})/(1-x_2F_{SR2}) \qquad (16)$$

Here the subscripts "1" and "2" indicate that optical systems consisting of eyes and spectacle lenses are being compared, F_{SR} is the equivalent power of a spectacle lens, F_u is the equivalent power of an uncorrected ametropic eye, k' is the length of an uncorrected eye measured from its second principal point, and x is the distance from the second principal point of a spectacle lens to the first principal point of an uncorrected eye.

Two situations are worthy of consideration. One is when a corrected axially ametropic eye is compared with a standard emmetropic eye according to Atchison's equation (14), which, replacing F_{SR1} by 0 and F_{u2} by F_1, gives

$$RM = F_1/(F_1 + F_{SR2} - x_2F_1F_{SR2}) \qquad (17)$$

where F_1 is the equivalent power of the standard eye, F_{SR2} is the power of the correcting lens, and x_2 is the distance between the second principal plane of the lens and the first principal plane of the standard eye. Placing the lens second principal point at the first focal point of the eye, i.e. $x_2 = 1/F_1$, satisfies Knapp's law and equation (17) reduces to Atchison's equation (15)

$$RM = 1 \qquad (17a)$$

The second situation is when a spectacle corrected refractive ametropic eye is compared with a standard eye according to Atchison's equation (18), which replacing F_{SR1} by 0, and assuming $k'_2 = k'_1$ and $x_2 = x_1$ gives:

$$RM = 1/(1 - x_1F_{SR2}) \qquad (18)$$

This equation appears in texts such as Jalie.[4] It is approximate as it assumes the differences between principal points of the refractive ametropic eye and standard eyes can be ignored. Accurately, equation (16) would be used with:

$$k'_1 = f'_1,\ k'_2 = f'_{u2} - f'_{uv2},\ F_{SR1} = 0, \text{ and } x_2 = v + f_{uv2} - f_{u2}$$

where f'_1 and f'_{u2} are second focal lengths and f'_{uv2} is a back vertex focal length, v is vertex distance, f_1 and f_{u2} are first focal lengths and f_{v1} and f_{uv2} are front vertex focal lengths.

Results

This section assumes that all spectacle lenses and/or IOL powers are selected to achieve emmetropia.

Figure 2 shows RM for Navarro eyes, modified by changing vitreous length, anterior corneal power, or anterior chamber depth. Here the reference is the standard Navarro eye. Altering the length of the vitreous changes image size by 1%/1 mm (not shown), but correcting the eye with a lens placed in front of it gives the same image size as that for the standard eye (Knapp's law). Altering corneal power and correcting the eye gives a considerable effect of −1.5%/D. As is well known, this is similar to SM: the examples in the Introduction for corneal changes of -4 D and +4 D gave respective SMs of 1.073 and 0.929, and the corresponding RMs here are 1.060 and 0.940. Altering anterior chamber depth and correcting the eye gives an effect of +1.2%/1 mm.

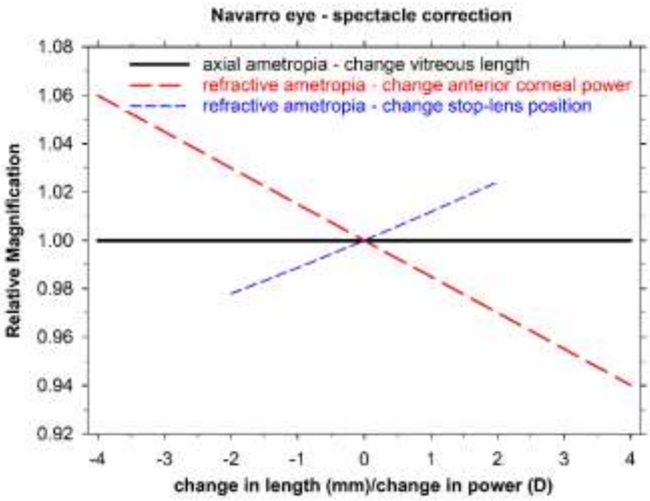

Figure 2. *Relative magnifications for Navarro eyes, modified by varying vitreous length, anterior corneal power, and stop-lens position.*

Figure 3 shows changes in power for Navarro-IOL eyes that have been modified by varying vitreous length, anterior corneal power, and stop-lens position. The powers shown are the changes in full IOL power correction, or the spectacle correction when the IOL power is unchanged from that for the standard Navarro-IOL eye. For changes in vitreous length and anterior corneal power, the relationship between the two powers is close to linear (slope ratio approximately 1.35), but that for stop-lens position is variable.

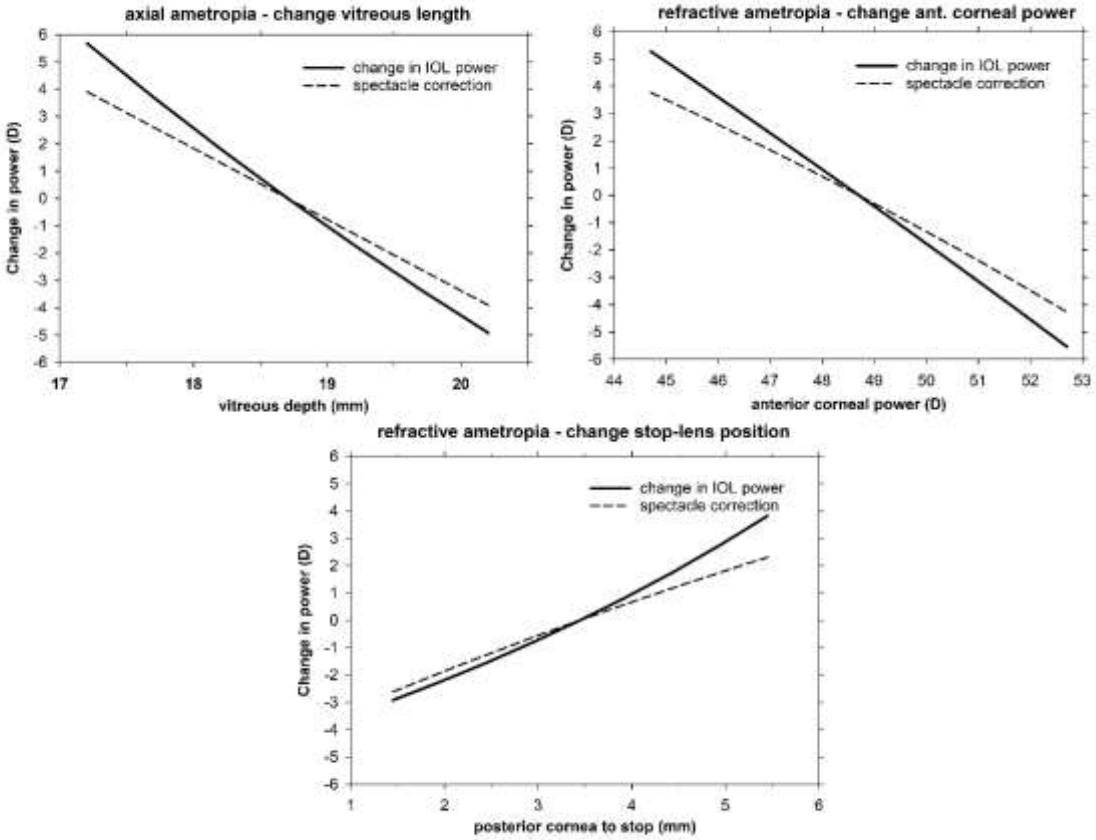

Figure 3. *Change in power for Navarro-IOL eyes modified by varying vitreous length, anterior corneal power, and stop-lens position: change in full IOL correction and change in spectacle correction when the IOL power is unchanged from that for the standard Navarro-IOL eye.*

Figure 4 shows RMs for modified Navarro-IOL eyes using the standard Navarro-IOL eye as a reference. For full IOL corrections (solid green lines), there is a considerable effect of vitreous length of +5.2%/mm, while effects of corneal power and anterior chamber depth are +0.4%/D and −1.4 %/mm, respectively. For the case in which the same IOL power is used in both eyes, supplemented by spectacle corrections (solid black lines), these effects are 0%/D (vitreous depth), −1.6%/D (corneal power), and +1.0%/mm (IOL position), similar to those for the modified Navarro eyes (Figure 2). Relative to the effects for full IOL corrections, the effects of spectacle lens correction are −5.2%/mm (vitreous depth), −2.0 %/D (corneal power) and +2.4%/mm (anterior chamber depth).

In addition to the full raytracing results given by the solid curves, we have used the approximate approaches described in the Methods section. For full IOL corrections, equations (9), (11) and (14) give highly accurate results for the simplified Navarro-IOL eyes (red dotted lines). For spectacle corrections when the same IOL power is used in both eyes, equation (17a) gives exact results for changes in vitreous length, while the approximate equation (18) gives reasonably accurate results for changes in anterior corneal power, but is not at all accurate for changes in anterior chamber depth (black dotted lines).

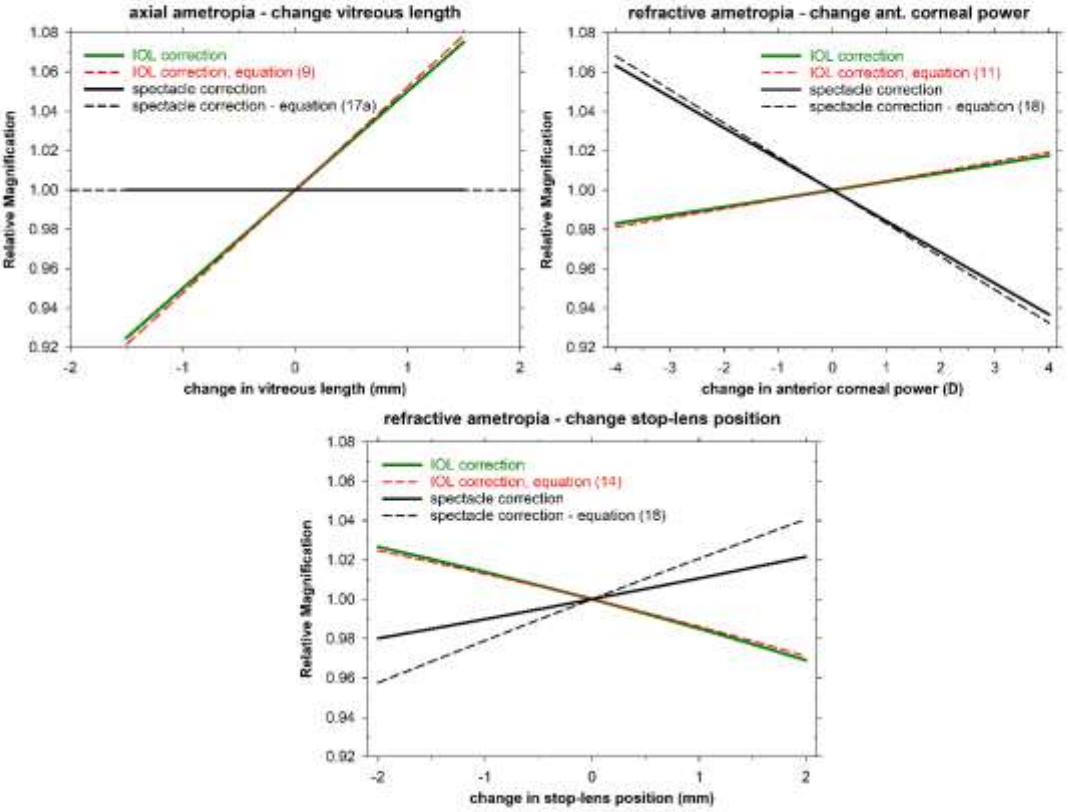

Figure 4. Relative magnifications for Navarro-IOL eyes, modified by varying vitreous length, anterior corneal power, and stop-lens position. The eyes are corrected by varying IOL power (green lines) or by spectacle correction (black lines). The solid lines are determined by ray tracing. The dotted red lines for full IOL correction are from equations (9), (11) and (14). The dotted black lines are determined by spectacle correction and a fixed IOL power according to equation (17a) for axial ametropia and approximate equation (18) for refractive ametropia.

Discussion

One of the least known complications of cataract surgery is postoperative aniseikonia. Although the expected magnitude can be estimated based on the preoperative biometry,[3] many clinicians are still unaware of the risk posed by a large inequality in axial length between both eyes. Based on the standard Navarro model, axial differences greater than 0.5 mm could lead to a noticeable aniseikonia of 2% in pseudophakic eyes targeting emmetropia, and differences greater than 1 mm lead to truly bothersome levels of over 4%.[9-10] The actual bother for the patient is highly subjective, however, and these values should not be considered as strict guidelines.

As seen in Figure 4 and as given by Gobin et al.,[3] axial aniseikonia can easily be corrected by spectacles, but not by IOL alone since there is no pseudophakic equivalent of Knapp's law. Consequently, a perfectly emmetropic IOL correction could in such situations lead to an aniseikonic surprise. This issue can be addressed quite easily by calculating the IOL to purposefully under- or overcorrect the eye and then supplementing the IOL by a spectacle correction. Together, the spectacles and the IOL will adjust the retinal magnification to match that of the fellow eye.

To calculate the optimal IOL power, one would only need to know the axial length, corneal power, and the anticipated distance between the cornea and IOL ("effective lens position", *ELP*). Fundamentally, most IOL calculation formulas in the literature only differ in the way that *ELP* is estimated. Equating *ELP* to the aperture stop position a used in the calculations above, it is clear that the simplified Navarro eye model of Table 2 is sufficient for the current purposes and there is no need to make the proposed equations more detailed with additional parameters. Given the increasing importance assigned to the posterior corneal curvature, variations can be considered in which e.g. the total corneal power is included instead of only the anterior surface, but then a value of 0.05 mm must be added to aperture stop position a to account for the corneal principal point shifting to in front of the cornea.

Note that the models did not consider the RMs for IOL corrections targeting mild ametropia. This would have led to far more complicated equations and are already well described by Gobin et al.[3] Instead, equations (8), (9), (11), and (14) supplement this earlier work by providing a screening tool to assess the risk of postoperative aniseikonia that can easily be used in clinical practice.

Appendix. Symbols and important equations

RM	relative magnification
1, 2	subscripts indicating reference and comparison eyes, respectively

Full IOL correction

F_{C}	corneal power
F_{L}	lens power
n	refractive index of aqueous and vitreous
a	aqueous depth (from second principal point of the cornea to first principal point of lens)
l'	vitreous length (from second principal point of the lens to the retina)
F_v'	back vertex power of eye
F	(equivalent) power of eye
$\Delta l'$	change in vitreous length
ΔF_C	change in corneal power

Δa	change in aqueous depth
f_v	front vertex focal length of eye
F_v	front vertex power of eye

<u>Full spectacle correction</u>

F_{SR}	(equivalent) power of a spectacle lens
F_u	(equivalent) power of an ametropic eye
k'	length of an uncorrected eye measured from its second principal point
x	distance from second principal point of a spectacle lens to first principal point of an uncorrected eye
f'_u	second (equivalent) focal length of an uncorrected ametropic eye
v	vertex distance
f_u	first (equivalent) focal length of an uncorrected eye
f_{uv}	front vertex focal length of an uncorrected eye

Full IOL power correction - general equation

$$RM = \frac{F_1}{F_2} = [F_{C1} + F_{L1} - (a_1/n)F_{C1}F_{L1}]/[F_{C2} + F_{L2} - (a_2/n)F_{C2}F_{L2}] \qquad (8)$$

Full IOL power correction - effect of changing vitreous length

$$RM = l'_2/l'_1 = (l'_1 + \Delta l')/l'_1 \qquad (9)$$

Full IOL power correction - effect of changing corneal power

$$RM = \frac{n - a_1 F_{C1}}{n - a_1 F_{C2}} = \frac{n - a_1 F_{C1}}{n - a_1(F_{C1} + \Delta F_C)} \qquad (11)$$

Full IOL power correction - effect of changing distance between cornea and IOL (axial length kept fixed)

$$RM = \frac{\left[1 - \left(\frac{a_1}{n}\right)F_C\right]l'_2}{\left[1 - \left(\frac{a_2}{n}\right)F_C\right]l'_1} = \frac{\left[1 - \left(\frac{a_1}{n}\right)F_C\right](l'_1 - \Delta a)}{\left[1 - \left(\frac{a_1 + \Delta a}{n}\right)F_C\right]l'_1} \qquad (14)$$

Full spectacle correction - general equation

$$RM = \frac{k'_2}{k'_1} = \frac{F_{SR1} + F_{u1} - x_1 F_{u1} F_{SR1}}{F_{SR2} + F_{u2} - x_2 F_{u2} F_{SR2}} = (k'_2/k'_1)(1 - x_1 F_{SR1})/(1 - x_2 F_{SR2}) \qquad (16)$$

Full spectacle correction - axially ametropic eye

$$RM = F_1/(F_1 + F_{SR2} - x_2 F_1 F_{SR2}) \qquad (17)$$

Full spectacle correction - axially ametropic eye with spectacle lens at eye first focal point

$$RM = 1 \qquad (17a)$$

Full spectacle corrected refractive ametropic eye (with approximations regarding principal point positions)

$$RM = 1/(1 - x_1 F_{SR2}) \qquad (18)$$

References

1. Shammas HJ. *Intraocular lens power calculations*. Slack Incorporated, 2004.
2. Hoffer KJ & Savini G. IOL power calculation in short and long eyes. *Asia-Pacific J Ophthalmol* 2017; 6: 330–331.
3. Gobin, L Rozema J & Tassignon MJ. Predicting refractive aniseikonia after cataract surgery in anisometropia. *J Cataract Ref Surg* 2008; 34: 1353–1361.
4. Jalie M. Principles of Ophthalmic Lenses. 6th ed. Association of British Dispensing Opticians, 2021.
5. Atchison DA. Calculating relative retinal image sizes of eyes. *Ophthal Physiol Opt* 1996; 16: 532–538.
6. Langenbucher A, Szentmary N, Leydolt C *et al*. 2021. Calculation of ocular magnification in phakic and pseudophakic eyes based on anterior segment OCT data. *Ophthal Physiol Opt* 2021; 41: 831-841.
7. Navarro R, Santamaría J & Bescós R. Accommodation dependent model of the human eye with aspherics. *J Opt Soc Am A* 2 1985; 2: 1273–1281.
8. Charman WN, Liu Y & Atchison DA. Small-aperture optics for the presbyope: do comparable designs of corneal inlays and intraocular lenses provide similar transmittances to the retina? *J Opt Soc Am A* 2019; 36: B7-B14.
9. Burian HM. Clinical significance of aniseikonia. *Arch Ophthalmol* 1943; 29: 116–133.
10. Rutstein RP. Update on aniseikonia. *Contemp Optom* 2010; 8(9): 1–7.