Treatment-induced shifts of ocular reference axes used for measurement centration

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PURPOSE: To determine the shifts of the main corneal reference points in dependence of the chosen centration axis for the treatment.

SETTING: Federal Institute of Technology Zurich, Institute of Biomedical Engineering, Zurich, Switzerland.

METHODS: Computer simulations were performed on several variants of the Gullstrand-Emsley schematic eye, which was modified by an off-axis fovea. Refractive corrections were simulated by centering Munnerlyn's formula on each of the 4 corneal reference points determined in the preoperative eye: the optical axis, the line of sight, the visual axis, and the first corneal reflex. Subsequently, the postoperative locations of these axes were determined and compared with the preoperative values.

RESULTS: The postoperative line of sight was found to depend least on the choice of the preoperative centration axis for both myopic and hyperopic treatments. It undergoes a maximum movement of 0.040 mm when centering a +5 diopter correction on the preoperative line of sight, whereas the corneal reflex, which is used for centering most topography systems, can move by more than 0.10 mm.

CONCLUSIONS: Centration of the correction on the preoperative line of sight enabled good comparability between preoperative and postoperative measurements that use the line of sight as a reference axis. Yet, centration of the treatment on the preoperative line of sight does not ensure comparability between preoperative and postoperative measurements that use the corneal reflex as a reference axis such as most corneal topography systems. Axis shifts might lead to misinterpretation of data such as a wrong diagnosis of a decentered ablation or changes in the Zernike representation.

J Cataract Refract Surg 2005; 31:1986–1994 © 2005 ASCRS and ESCRS

Optical measurements and corneal surgical procedures require proper alignment on the cornea because even small decentration from a determined reference axis will introduce new types of optical aberrations.[1–4] However, alignment of a measuring or treatment device is not a simple task because of the lack of direct target points on the transparent cornea.

A number of ocular axes can be defined to describe the optical properties of the eye. The points of intersection of these axes with the corneal anterior surface can be used for centering ocular surgical procedures as well as measurement devices. Unlike most technical optical devices, the human eye is not a centered optical system and does not contain a true optical axis because the cornea and the lens are slightly decentered and tilted relative to each other. This fact further complicates the determination of ocular reference axes in a clinical environment. In all centering methods, the patient is advised to fixate on a target light, usually located on the optical axis of the technical system. Based on this general principle, the system axis can be centered on various reference points on the eye that are determined by the investigator.

The following axes are defined in the eye: the optical axis, the line of sight, the visual axis, the pupillary axis, and the line of the coaxially sighted corneal reflex

Accepted for publication March 14, 2005.

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Supported by the Swiss National Science Foundation, Bern, Switzerland.

No author has a financial or proprietary interest in any material or method mentioned.

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Published by Elsevier Inc.

0886-3350/05/$-see front matter
doi:10.1016/j.jcrs.2005.03.068

(Figure 1). Detailed definitions are provided in the discussion section. Because the axes definitions are based on characteristic values of the eye such as the cardinal points (focal, nodal, or principal points), the corneal center of curvature, and the position of the fovea, the exact orientation of each axis and the location of its corneal intercept depend on a number of variables such as corneal refractive power, lens power, or ocular length. Thus, as corneal refractive surgery is meant to change the refractive properties of the cornea, the ocular reference axes are subject to changes as well. The corneal intercept of a certain axis that is used for centering a measurement on the preoperative eye might shift significantly through the treatment. This assumption raises questions regarding the comparability of preoperative and postoperative measurement data. Misleadingly, different sections of the cornea might be compared with each other if a shift in the centration axis occurred between preoperative and postoperative corneal topography measurements in the same eye (Figure 2). Furthermore, fitting Zernike polynomials to topography or wavefront data relative to a shifted reference axis can introduce reference-axis-dependent aberrations such as coma.

It might be presumed further that the amount of reference axis shift depends on the choice of centration axis for the correction on the preoperative eye. Reference axes used for acquiring preoperative and postoperative measurement data do not necessarily have to coincide with the axis used for centering the refractive correction. A myopic treatment may be centered on the line of sight, whereas preoperative and postoperative corneal topography, which could be used to check centration of the ablation, might be aligned on the first corneal reflex. However, some refractive surgeons tend to center hyperopic treatments on the corneal reflex, whereas wavefront measurements are acquired relative to the line of sight.[5]

The general objective of this investigation was to determine the shifts of the main ocular reference axes in dependence of the type of refractive correction, the choice of centration axis for measurement as well as for the refractive treatment in the preoperative eye, and the combination of refractive elements in the schematic eye model. Computer simulations were performed on the Gullstrand-Emsley schematic eye to investigate the shifts of the main reference axes. The following questions were addressed: (1) How do the corneal intercept locations of the reference axes depend on the refractive state of the preoperative eye as well as on the combination of refractive elements? (2) How do the corneal intercept locations change with refractive correction, and what is the influence of the choice of centration axis for the refractive correction? (3) Is the amount of such an expected shift of clinical relevance for the comparison of preoperative and postoperative measurements?

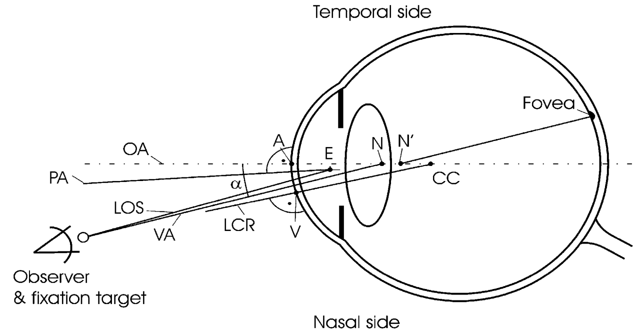

Figure 1. Axes of the eye: optical axis (OA), line of sight (LOS), visual axis (VA), line of the coaxially sighted corneal reflex (LCR), and pupillary axis (PA). Defined points in the eye: corneal vertex (V), entrance pupil center (EPC), nodal points (N,N'), and corneal center of curvature (CC).

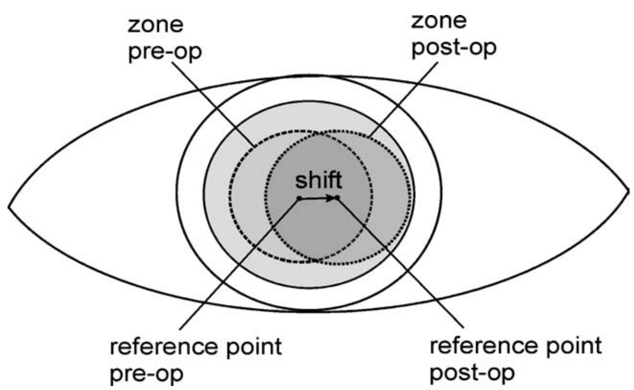

Figure 2. Different zones of the cornea might be compared to each other if a shift of a reference point occurs between the preoperative and postoperative measurements.

MATERIALS AND METHODS

Variants of a Schematic Eye

The optical dimensions of schematic eyes used to study imagery in the emmetropic case are based on mean values from measured data. Defined states of ametropia can be introduced by considering the reported variations in the main ocular dimensions, such as corneal and lens power, and by calculating appropriate ocular lengths. Bennett and Rabbetts[6] reported variants of the Gullstrand-Emsley schematic eye for various combinations of corneal and lens power.[7] The change in ocular length required to produce various degrees of spherical ametropia for these cases can be calculated using equation 1[8]:

$$\delta l' = \frac{-R_e \cdot n'}{F^2} \quad (1)$$

where $\delta l'$ is the change in ocular length, R_e is the refractive error, n' is the refractive index of the vitreous, and F is the equivalent power of the eye.

For both corneal power and lens power, a minimum, a maximum, and a mean value can be derived from data measured by

Stenström.[9] Nine variants of the Gullstrand-Emsley schematic eye result from permutation of these 2 sets of variables.[6] The ocular lengths corresponding to refractive errors that require corrections of −10, 0, and +5 diopters (D) were calculated for the 9 variants using equation 1. A total of 27 versions of the schematic eye including myopic, emmetropic, and hyperopic eyes were finally available (Table 1). For the following investigation, the Gullstrand-Emsley schematic eye was modified by introducing an off-axis fovea. Thereby, it was assumed that the distance of the foveola from the optical axis remained constant at 1.44 mm in all eyes. This value was derived from the assumption of a mean α angle of 5 degrees in the emmetropic standard eye (mean corneal and lens power).[6] The α angle changes according to the change in ocular length and the shift of the nodal points in the other variants of the schematic eye compared with the emmetropic standard eye. As the optical elements of Gullstrand-Emsley schematic eye are centered, a true optical axis can be defined. The pupil was assumed to be concentric about the optical axis and to be located 3.6 mm behind the corneal apex.[10] Furthermore, a spherical retina of −12.0 mm radius of curvature was added to the eye model according to Escudero-Sanz and Navarro.[11]

Calculation of Ocular Reference Axes in the Preoperative Eye

Assuming a fixation point at infinity, the corneal intersect locations of both the line of sight and the visual acuity, as well as the position of the coaxially sighted first corneal reflex, were determined for all 27 versions of the schematic eye. Calculations were performed by analytically intersecting the lines connecting the fixation point with the entrance pupil center, the object nodal point, or the corneal center of curvature with the corneal front surface after determination of the corresponding α angle of fixation. All corneal distances were measured from the optical axis of the eye model.

Simulation of Refractive Corrections

Corneal refractive corrections of myopia and hyperopia were simulated on 2 variants (combinations of corneal and lens power) of the schematic eye. The combination that produces median distances of the corneal reference points from the optical axis for all refractive states determined in the previous calculations (Table 1, variant 5) and the 1 that exhibits the largest distances (Table 1, variant 7) were used for further investigations. The first combination of corneal and lens power will be called the standard eye, and the latter will be referred to as the high-power-cornea eye. Thereby, Munnerlyn's formulas for myopia and hyperopia[12] were centered on each of the 4 corneal reference points determined in the preoperative eye: the optical axis, line of sight, visual axis, and corneal reflex. Centration on these points was performed by coordinate transformation within the Munnerlyn formula ($M[x - \Delta x_{axis}]$). The coordinates x are measured from the optical axis, and Δx_{axis} determines the distance of a specific corneal reference point from the optical axis. Subsequently, the formula of the ablation profile was subtracted analytically from the spherical equation of the original corneal surface ($C_{preop}[x]$) to obtain the equation of the postoperative cornea ($C_{postop}[x]$) (equation 2).

$$C_{postop}(x) = C_{preop}(x) - M(x - \Delta x_{axis}) \qquad (2)$$

It is well known that Munnerlyn's formula tends to introduce spherical aberration in the eye because it is based on paraxial considerations on a single-lens eye model. Yet, as the calculations presented here refer to corneal coordinates well within the paraxial region of the eye (axes locations and shifts within a circle of 1 mm radius), Munnerlyn's formula can be expected to provide

Table 1. Variants of the Gullstrand-Emsley schematic eye.*

Corneal Power (D)	+38.00			+42.73			+48.00		
Lens Power (D)	+15.88	+21.76	+28.18	+15.88	+21.76	+28.18	+15.88	+21.76	+28.18
Variant Number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
r1 (mm)	8.77	8.77	8.77	7.80	7.80	7.80	6.94	6.94	6.94
r2 (mm)	13.78	10.00	7.66	13.78	10.00	7.66	13.78	10.00	7.66
r3 (mm)	−8.27	−6.00	−4.59	−8.27	−6.00	−4.59	−8.27	−6.00	−4.59
d1 (mm)	4.1	3.6	3.0	4.1	3.6	3.0	4.1	3.6	3.0
d2 (mm)	2.9	3.6	4.5	2.9	3.6	4.5	2.9	3.6	4.5
AP (mm)	1.35	1.67	1.96	1.25	1.55	1.83	1.15	1.44	1.71
AP′ (mm)	1.65	2.03	2.35	1.50	1.85	2.17	1.35	1.69	1.98
AE (mm)	3.48	3.01	2.46	3.54	3.05	2.49	3.61	3.1	2.52
AE′ (mm)	4.21	3.69	3.01	4.21	3.69	3.01	4.21	3.69	3.01
AN (mm)	8.06	6.97	5.70	8.20	7.06	5.77	8.36	7.18	5.83
AN′ (mm)	8.36	7.27	6.00	8.50	7.36	6.07	8.66	7.48	6.13
Length at +5 D (mm)	25.13	23.64	22.24	23.30	22.07	20.91	21.55	20.56	19.58
Length at 0 D (mm)	27.67	25.75	24	25.46	23.89	22.45	23.37	22.12	20.93
Length at −10 D (mm)	32.75	29.97	27.51	29.76	27.53	25.53	27.01	25.25	23.62

A = corneal apex; d = surface separations; E/E′ = entrance and exit pupils; N/N′ = front and back nodal points; P/P′ = front and back principal points; r = radii of curvature

*For each of the 9 permutations of the 3 different corneal and lens powers, the ocular lengths corresponding to refractive errors that require corrections of −10, 0, and +5 D were calculated.

good results. The mechanisms that lead to a reference axis shift are as follows: First, the eye's cardinal points, the entrance pupil center, and the corneal center of curvature are changed through the refractive correction. Second, a small decentration of a spherical correction from a certain centration axis introduces tilt.[13] Tilt causes a transverse displacement of the retinal point-spread function away from the center of the fovea. If the decentration from the ideal axis is within a certain tolerance range, the induced tilt can be compensated by the eye by adjusting the fixation angle α to reassume foveal fixation. Both the adjustment of the angle α and the shift of the eye's cardinal points through the refractive correction move the corneal reference points relative to their preoperative locations.

Calculation of Ocular Reference Axes in the Postoperative Eye

For each case of centration on the preoperative eye, the main corneal reference axes were determined in the corresponding postoperative eye by means of ray tracing from the retinal plane to the cornea. It was assumed that the optical axis remained constant even after corrections centered on axes different than the optical axis itself. The light ray that comes from the fovea and passes through the pupil center after refraction in the crystalline lens is determined iteratively by optical ray tracing. The extension of this ray outside of the eye after refraction in the cornea corresponds to the line of sight, connecting the point of fixation with the entrance pupil center. The line within the eye that is parallel to the line of sight and that passes through the fovea intersects the optical axis at the new image nodal point. The angle between this line and the optical axis is the postoperative fixation angle α. The shift of the object nodal point caused by the change in refractive power of the cornea was calculated by tracing a paraxial ray parallel to the optical axis from the image space back through the system into object space according to Atchison and Smith.[8] The line that passes through the new object nodal point and that is parallel to the connection between the fovea and the image nodal point corresponds to the postoperative visual axis. Finally, the radius of the anterior corneal surface is changed through the correction according to the formula of Munnerlyn. The new center of curvature was calculated by analytically intersecting 2 lines perpendicular to the postoperative corneal surface. The line that finally enters the eye parallel to the visual axis and passes through the new center of curvature of the anterior corneal surface marks the line of the coaxially sighted corneal reflex. The main corneal reference points in the postoperative eye were calculated by intersecting the above lines with the postoperative corneal surface. These points were then compared with the corresponding locations before the correction.

RESULTS

Dependence on Refractive State and Combination of Ocular Elements

The locations of the main corneal reference points depend on the refractive properties of the eye. Figure 3 shows the corneal intercept locations of 3 ocular axes (line of sight, visual axis, and corneal reflex) as a function of the refractive error of the Gullstrand-Emsley model eye. For each of the 3 investigated refractive states, emmetropia, −10 D myopia, and +5 D hyperopia, the mean, the maximum, and the minimum intercept distance of each axis over the 9 variants of the schematic eye were determined. Figure 3 indicates that the corneal intercepts of the axes were closer to the optical axis for myopic eyes and farther away for hyperopic eyes. The line of sight appears to have changed least with changing refractive error. The mean distance from the optical axis was 0.21 mm nasally from the optical axis in case of −10 D myopia and 0.30 mm for +5 D hyperopia. The visual axis changed from a mean distance of 0.48 mm at −10 D myopia to 0.69 mm at +5 D hyperopia, and the coaxially sighted corneal reflex moved from a mean distance of 0.56 mm at −10 D myopia to 0.76 mm at +5 D hyperopia. As indicated by the error bars, the intercept location of the visual axis varied strongly depending on the combination of cornea and lens power. For the case of a high corneal refractive power and a small lens power combined in a hyperopic eye of +5 D, the visual axis could be as far away as 0.93 mm from the optical axis. In contrast, the first corneal reflex appeared to have varied weakly over the investigated variants of the schematic eye.

Myopic Correction

Both the adjustment of the angle α and the shift of the cardinal points (focal, nodal, and principal points of the eye) through the refractive correction moved the corneal

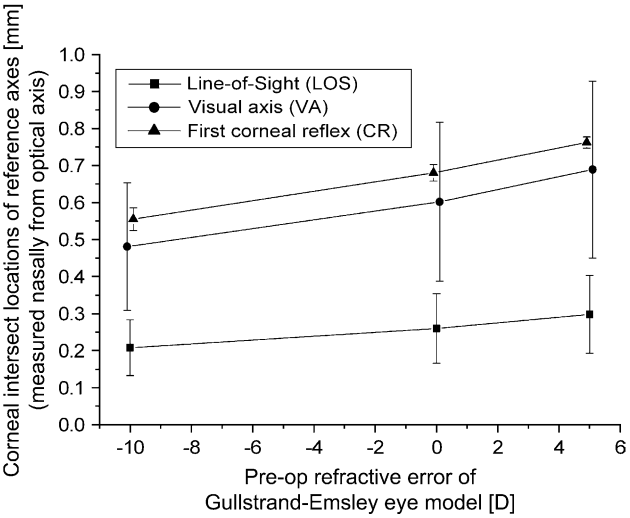

Figure 3. Horizontal corneal intercept locations of 3 ocular axes (line of sight, visual axis, and corneal reflex) in dependence of the refractive error of the Gullstrand-Emsley schematic eye with off-axis fovea. Lateral distances were measured from the optical axis in nasal direction; thus, the *y*-axis represents the location of the optical axis. For each of the 3 investigated refractive states, emmetropia, −10 D myopia, and +5 D hyperopia, the mean distances over the 9 variants of the schematic eye are indicated by solid symbols and connected with lines, whereas the maximum and minimum values are displayed by error bars.

reference points relative to their preoperative locations. Figure 4 shows these relative shifts for the correction of 10 D axial myopia for the myopic standard eye (*A*) and for the myopic high-power-cornea eye (*B*). The *x*-axis indicates the centration of the procedure on the preoperative eye, with the optical axis at zero. Centration on the mean corneal intercept locations of the optical axis, line of sight, visual axis, and the coaxially sighted corneal reflex was simulated (Figure 3). In contrast to the standard eye, the visual axis was located farther from the optical axis than the corneal reflex in the high-power-cornea eye as the object nodal point was located behind the corneal center of curvature (Table 1). The *y*-axis shows the change of the corneal intersect locations preoperatively to postoperatively, with positive values indicating a shift in the temporal direction.

In the standard eye, the corneal reflex had the largest change after centration on the optical axis by moving 180 μm in the nasal direction, whereas the visual axis shifted by 90 μm in the same direction. The line of sight moved only 25 μm in the nasal direction. Centration on the preoperative corneal reflex caused a shift of 40 μm nasally in the position of the visual axis, whereas the line of sight and the corneal reflex did not significantly move. The line of sight showed the highest stability toward varying centration of the procedure as the induced shifts were small for all possible centration points. The same observation could be made in the high-power-cornea eye, as depicted in Figure 4, *B*. The corneal reflex appeared to moved by 100 μm in temporal direction if the correction was centered on the visual axis and by the same amount in the nasal direction if centration was done on the optical axis.

Hyperopic Correction

Figure 5 shows the relative shifts for the correction of 5 D hyperopia for the hyperopic standard eye (*A*) and for the high-power-cornea eye (*B*). In the hyperopic standard eye, the corneal reflex and the visual axis had the largest changes after centration on the optical axis by moving 100 μm or 70 μm, respectively, in the temporal direction, whereas the line of sight shifted by only 15 μm in the same direction. Centration on the preoperative corneal reflex caused a shift of 45 μm temporally in the position of the visual axis, whereas the line of sight and the corneal reflex did not significantly move. Again, the line of sight showed the highest stability toward varying centration of the procedure on the preoperative eye. The same observation applies to the high-power-cornea eye, as depicted in Figure 5, *B*. In contrast, both the corneal reflex and the visual axis moved considerably by 170 μm in temporal direction if the correction was centered on the preoperative optical axis. Centration on the preoperative visual acuity shifted the postoperative corneal reflex in the temporal direction by 50 μm, while the visual axis moved 130 μm in the same direction.

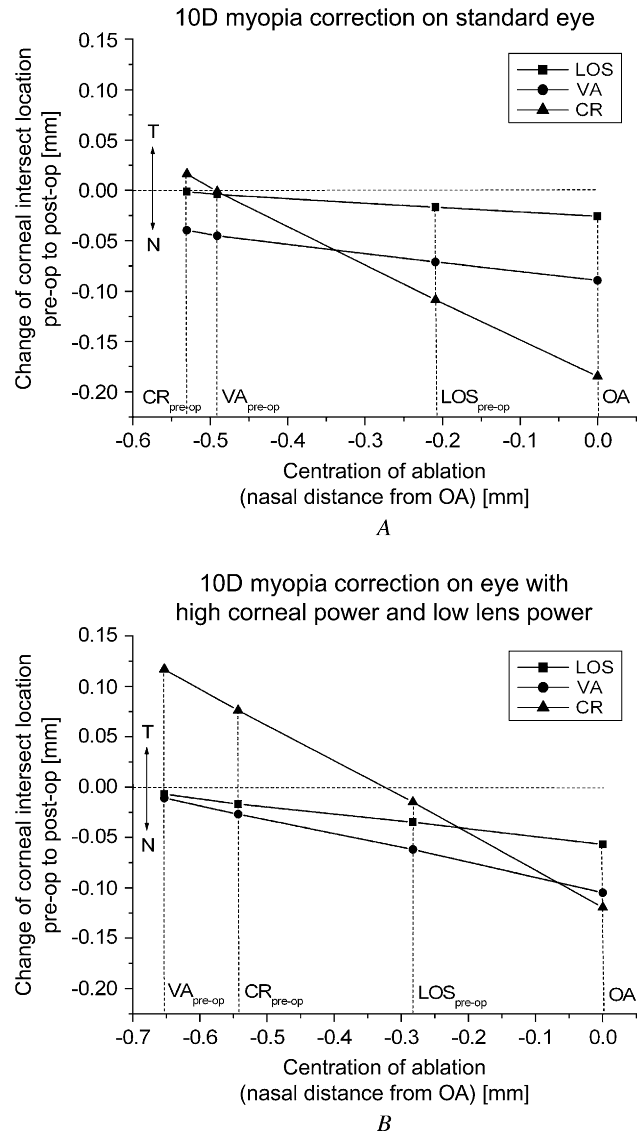

Figure 4. Change of the corneal intercept locations preoperatively to postoperatively in dependence of the chosen centration point on the preoperative eye (optical axis at zero) in case of a −10 D myopic correction on the standard eye (*A*) and the high-power-cornea eye (*B*). Centration on the corneal intercepts of the optical axis, line of sight, visual axis, and coaxially sighted corneal reflex was simulated.

Table 2 provides a summary of the induced reference point shifts in dependence of the chosen eye model, the type of correction, and the chosen centration axis on the preoperative eye.

DISCUSSION

The preoperative locations of the main corneal reference points were shown to depend on the refractive state

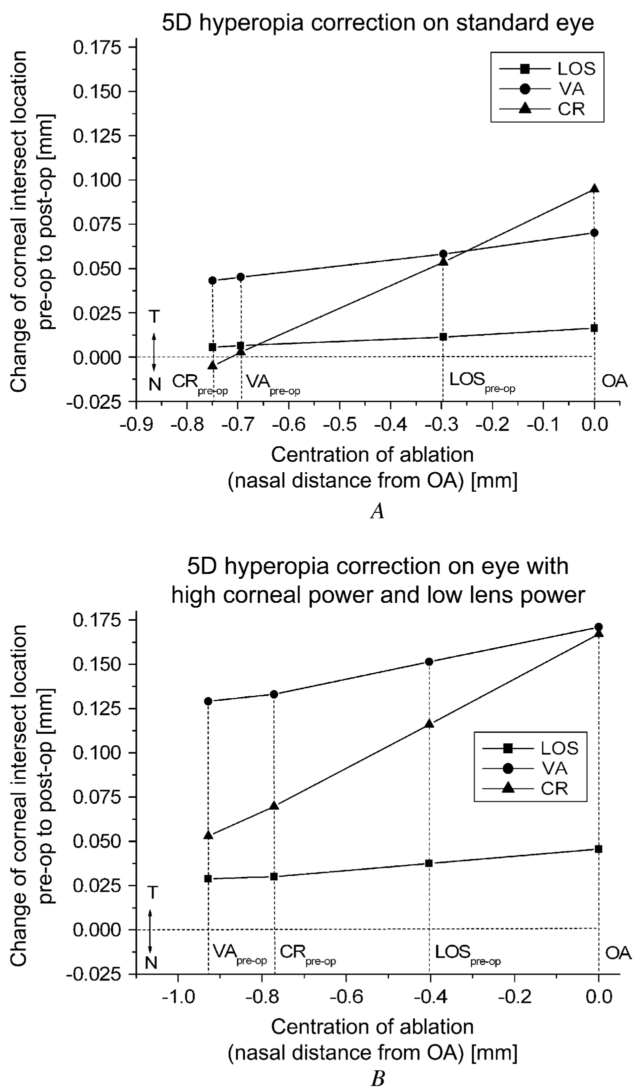

Figure 5. Change of the corneal intercept locations preoperatively to postoperatively in dependence of the chosen centration point on the preoperative eye (optical axis at zero) in case of a +5 D hyperopic correction on the standard eye (*A*) and the high-power-cornea eye (*B*). Centration on the corneal intercepts of the optical axis, line of sight, visual axis, and the coaxially sighted corneal reflex was simulated.

of the eye as well as on the combination of corneal and lens power. The corneal intercepts of the axes are located closer to the optical axis in myopic eyes and farther away in hyperopic eyes. The intercept location of the visual axis varies strongly depending on the combination of cornea and lens power. For the case of a high corneal refractive power and a small lens power combined in a hyperopic eye of +5 D, the visual axis can be as far away as 0.93 mm from the optical axis. In contrast, the first corneal reflex appears to vary weakly over the investigated variants of the schematic eye. These findings answer the first question of how the corneal intercepts depend on the combination of the refractive elements and on the refractive state of the preoperative eye.

The concept of an optical axis can be applied to the eye by defining the optical axis as the "best-fit" line through the centers of curvature of the "best-fit" spheres of each surface.[8] Assuming an eye with nearly centered optical elements, the optical axis passes through the centers of curvature of the refracting surfaces as well as through the corneal apex A (Figure 1). The line of sight is the chief ray joining the fixation point and the center of the entrance pupil. It is considered the most important axis for describing visual function, including refractive procedures, because it defines the center of the light bundle entering the eye.[8] Unfortunately, this axis is not fixed as the pupil center shifts with changing pupil size.[14–16] The visual axis is the line joining the fixation target and the foveal image through the nodal points. The exact location is difficult to determine in a clinical environment; therefore, it primarily has theoretical applications. The pupillary axis is perpendicular to the cornea and passes through the center of the entrance pupil. The line of the coaxially sighted corneal reflex joins the fixation target and the center of curvature of the anterior corneal surface and thus is normal to the cornea. This line is also called the vertex normal, and it is frequently used for aligning corneal topography systems. The corneal intercept of this axis, which is marked by the coaxially sighted first corneal reflex, is defined as the corneal vertex V by Maloney.[17] The vertex is thus the point on the cornea closest to the fixation target and has to be distinguished from the corneal apex, which has been described as the region of greatest curvature. The angle between the visual axis and the optical axis is referred to as the angle α. It is positive if the visual axis is on the nasal side of the optical axis in object space. The mean value in an emmetropic eye is +5 degrees in the horizontal plane and 2 to 3 degrees downward in the vertical plane.[6,8]

Current discussions on the ideal reference axis for centering refractive procedures focus on the line of sight and the coaxially sighted corneal reflex because of their simple detectability in a clinical environment. These 2 axes can differ up to 0.6 mm in hyperopic eyes of +5 D and up to 0.4 mm in myopic eyes of −10 D. If these refractive errors are corrected, the locations of the main reference points in the postoperative eye strongly depend on the chosen centration axis for the treatment on the preoperative eye (Table 2). The fact that these shifts can go up to 100 μm and more raises questions regarding the comparability of preoperative and postoperative measurement data. These results answer our second question about how the corneal intercept locations change through the correction and the influence of the choice of centration axis for the refractive correction.

Table 2. Relative shift of the line of sight and the coaxially sighted first corneal reflex in dependence of the chosen eye model, the type of correction (myopia −10 D, hyperopia +5 D), and the chosen centration axis on the preoperative eye (LOS_{preop}, CR_{preop}).

	Standard Eye				High-Power-Cornea Eye			
	Δ LOS (mm)		Δ CR (mm)		Δ LOS (mm)		Δ CR (mm)	
Centration	Myopia	Hyperopia	Myopia	Hyperopia	Myopia	Hyperopia	Myopia	Hyperopia
LOS_{preop}	−0.015	+0.010	−0.100	+0.050	−0.035	+0.040	−0.015	+0.115
CR_{preop}	0	+0.005	+0.015	−0.005	−0.015	+0.030	+0.080	+0.070

CR = corneal reflex; LOS = line of sight
Lateral shifts are given in microns; positive values indicate a shift in temporal direction, negative values a shift in nasal direction.

The postoperative line of sight was found to depend least on the choice of the preoperative centration axis for both myopic and hyperopic treatments. In myopic corrections of −10 D, the line of sight does not move more than 35 μm. For hyperopic corrections of +5 D, the line of sight moves by a maximum of 40 μm. The line of sight appears thus to be best suited as a general reference axis for measurement procedures as it enables comparison of preoperative and postoperative measurement data more or less independent of the chosen axis of treatment centration.

In contrast, the corneal reflex can move by more than 100 μm in both myopic and hyperopic treatments if centration of the refractive treatment is performed on the preoperative line of sight. Consequently, if certain measurement procedures such as corneal topography use the first corneal reflex as a reference, care has to be taken when comparing preoperative and postoperative measurement data. Estimation of the reference axis shift might be necessary to compare identical corneal zones in the topography maps. Although comparison of preoperative and postoperative wavefront data centered on the line of sight might indicate a well-aligned ablation, the corresponding preoperative and postoperative topography maps might wrongly suggest a decentration of the ablation. Our group theoretically investigated the effect of constant lateral decentration of the correction based on measured wavefront aberration data from 130 eyes.[4] Computer simulations have indicated tolerable zone translations of up to 200 μm to achieve the level of the best 10% of eyes in an uncorrected population (7.0 mm pupil). A translatory precision of 70 μm or better was found to be tolerable to achieve a nearly diffraction-limited optical performance in 95% of the measured normal eyes (7.0 mm pupil). Because the reference axis shifts between the preoperative and the postoperative eye determined in this investigation are in the same order of magnitude as the required accuracies for measurement and treatment, they might not be neglected right away.

More important, fitting Zernike polynomials to topography or wavefront data relative to a shifted reference axis can introduce new types of optical aberrations, mainly coma. This is because coma is a reference axis–dependant aberration. That means that coma cannot only result from intrinsic asymmetry of the refracting elements of the eye but also from eccentric measurement in an otherwise symmetrical system. A result of this phenomenon might be that a preoperative myopic eye with only some residual amounts of spherical aberration when measured along a different reference axis suddenly exhibits some additional amounts of coma in addition to the uncorrected spherical aberration, if measured along the same reference axis in the postoperative eye after myopic correction. The appearance of coma might be misinterpreted as being a result of a poorly centered measurement, an irregular ablation, or a decentered ablation. In reality, however, none of the suspected sources of error is responsible for the appearance of coma.

We have performed some calculations to estimate the amount of introduced coma when decentering the measurement of a purely intrinsic spherical aberration. Table 3 shows that a measurement of a purely spherical aberration with a Zernike coefficient of 0.5 μm (OSA standard) decentered by 100 μm introduces additional coma of 0.1 μm. Porter and coauthors[18] reported wavefront aberrations measured in a large population. They found a mean plus standard deviation in the order of 0.25 μm for spherical aberration and approximately 0.1 μm for coma. Thus, relating to the investigated reference axis problem, a shift of 100 μm when measuring a purely spherical aberration of 2 times the mean plus standard deviation appears to produce coma of 1 times the mean plus standard deviation of a large population. Such an increase appears to be large when just comparing the isolated preoperative and postoperative coma terms. However, the postoperative coma has to be set in relation to the dominant type of aberration (ie, the spherical aberration in Table 3) to rate its importance within the whole measurement. Salmon and Thibos[19] have addressed a similar problem in connection with the comparison of topography and wavefront data to separate corneal and internal ocular aberrations. They investigated the potential error of incorrect estimation of aberrations

Table 3. Change of Zernike coefficients with increasing translation of the reference axis.

Parameter	Zernike Coefficient	Translation of Measurement Axis*		
		0 μm	50 μm	100 μm
	1	0.00	0.00	0.00
	2	0.00	0.04	0.07
	3	0.00	0.00	0.00
	4	0.00	0.01	0.01
	5	0.00	0.00	0.01
	6	0.00	0.00	0.00
	7	0.00	0.00	0.00
Horizontal coma	8	0.00	0.05	0.10
	9	0.00	0.00	0.00
	10	0.00	0.00	0.00
	11	0.00	0.00	0.00
Spherical aberration	12	0.50	0.50	0.50
	13	0.00	0.00	0.00
	14	0.00	0.00	0.00
Higher-order RMS		0.50	0.50	0.51

*When no translation is present, only spherical aberration of 0.5 μm is measured; Zernike coefficients are reported according to the OSA standards in μm; translation of 100 μm introduces coma of 0.1 μm.

owing to the fact that the 2 measurement methods are using different reference axes.

The magnitude of the corneal reflex movement was shown to strongly depend on the combination of corneal power and lens power. On 1 hand, good comparability seems to be ensured in a myopic eye with high corneal power and low lens power because the corneal reflex moves by only 15 μm when centration of the ablation is done on the corneal reflex (Figure 4, *B*). On the other hand, the same treatment in an eye with the same refractive error but featuring mean corneal and lens powers leads to a shift of 110 μm when centration of the correction is done on the line of sight as well (Figure 4, *A*). Similar observations can be made in the hyperopic eye, however, with the difference that the shift of corneal reflex is small for the standard eye and large for the eye with high corneal power and low lens power. The combination of the optical elements in the eye appears to be as important as the refractive state when investigating the change of reference axes. Some refractive surgeons base their decision on which axis to use for centration on whether the eye is myopic or hyperopic.[5] Consideration of the combination of the optical elements might have to be further included in this decision-making process.

It was already shown by Keller and coauthors[20] that decentration of 1.0 mm of a 5 D myopic photorefractive keratectomy treatment on the cornea can shift the corneal vertex normally used for centering corneal topography by 0.13 mm. Decentration was measured from the corneal vertex. The simulations showed the importance of reference axis assumptions on the generation of power maps from corneal topography. However, the model used in those simulations was basic and did not take the entire eye and its adjustment to decentered ablations into account. In a nonrotationally symmetrical multilens system such as the eye, centration of the correction on a certain reference axis on the preoperative eye can still lead to a shift of the same axis in the postoperative eye as shown in Figures 4 and 5. Our simulations have shown that the shift of reference axis further depends on the chosen eye model, the type of correction, and the chosen centration axis on the preoperative eye.

The goal of this study was not to answer the question of the ideal centration axis for refractive corrections from an optical point of view. Currently, most laser manufacturers suggest centering the procedure on the line of sight; ie, the entrance pupil center. In the same way, the VSIA taskforce on standards for reporting optical aberrations of the eye recommend the use of the line of sight as the reference axis for the purpose of calculating and measuring the optical aberrations of the eye.[21] As the line of sight defines the chief ray of the light bundle entering the eye, aberrations measured with respect to this axis will have the pupil center as the origin of a Cartesian reference frame.

It can be concluded from our findings that centration of the correction on the preoperative line of sight enables good comparability between preoperative and postoperative measurements that use the line of sight as a reference axis. Yet, centration of the treatment on the preoperative line of sight does not ensure comparability between preoperative and postoperative measurements that use the corneal reflex as a reference axis, such as is done in most corneal topography systems. Shifts of more than 0.1 mm between the preoperative and the postoperative locations can occur that might lead to misinterpretation of data such as wrong diagnosis of decentered ablations or an overrated appearance of coma in the postoperative eye.

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