Extent and effect of surface tilt on the data display of the EyeSys videokeratoscope

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Abstract

Aims—This study examined the occurrence, magnitude, and the consequences of a possible tilt between the corneal surface and optical axis of the EyeSys videokeratoscope.

Methods—Initially, a theoretical model was developed to calculate the angle of tilt. The predictions of the model were verified empirically using a convex conicoid surface and were found to predict the tilt to within 0.5° of the actual tilt. The likely effects of the tilt on the corneal power were also examined. The angle of tilt was then measured on the human cornea and the effect of neutralising the tilt on the videokeratoscopic data display was observed.

Results—The angle of tilt was found to lie between 1° and 6° in a temporal direction.

Conclusion—When the corneal tilt on the human subjects was neutralised, then a reduction in the nasal/temporal asymmetry was observed.

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Videokeratoscopes are becoming increasingly popular for examining the refractive power and the topography of the cornea. Detailed knowledge of corneal topography provides a tool for early detection and diagnosis of corneal pathology, a method for defining the optical properties of the cornea's anterior surface, a foundation on which to base a rationale for therapy, and a sensitive means of evaluating therapy.¹⁻³ In addition, the information can be used in contact lens practice to calculate the back surface geometry to provide an optimum fit.⁴ The precision and accuracy of such systems has also received some attention.⁵⁻⁷ A detailed overview of the current state of the technology designed to measure corneal topography, and important issues such as the fundamental limitations of the operating principles, the limitations of the hardware, data analysis, and display are given by Applegate and Howland.²

One issue of importance is that the videokeratoscope (VK) is designed with the assumption that the corneal apex or vertex and the major axis of the corneal elliptical section lie on the optical axis of the instrument. The corneal vertex, in this paper, is considered to be the point where the surface radius of curvature is at a minimum when the cornea is considered to have a prolate (flattening) ellipsoidal form. The VK measures the distance of a peripheral cor-

neal point from its own optical axis, which is assumed to be the distance from the corneal axis. If the corneal axis does not lie on the optical axis of the instrument then the measured distance for the point in question will be inaccurate. Subsequent description of the corneal topography would then be questionable. Although the manufacturers' manuals stress the importance of well centred images, adherence to this recommendation is no guarantee that the cornea and the VK are coaxial. In most patients the corneal vertex is decentred and correct alignment would require that the subject view an eccentric fixation point.^{8,9} The result is that even when the eye fixes on a point on the optical axis of the instrument and the image on the monitor screen is centred, the cornea will probably be tilted in relation to the instrument's optical axis and the corneal vertex will be at some extra-axial point (see Fig 1). Further details on the relation between the various reference points and axes of the eye can be obtained from Mandell and colleagues.⁸⁻¹⁰ An error is therefore produced as a result of the misalignment between the optical axis of the instrument and the major axis of the corneal elliptical section. This misalignment results in a tilted cornea with important implications for the accuracy of VK measurements in both refractive surgery and contact lens fitting.

Some previous studies have demonstrated ways of correcting this error by viewing an eccentric fixation point on the instrument. Mandell⁸ suggested that the position of this eccentric point could be obtained empirically by measuring the distance by which the apex, indicated by the steepest point, has been displaced from the centre of the display. An additional fixation point placed at the measured distance would then align the apex with instrument's optical axis. Using this method, he showed that in one case of keratoconic cornea, the corneal apex was decentred by as much as 1.84 mm which, when corrected, changed the apex power from 57.79 D to 76.70 D. The cylindrical component changed from 8.19 D to 1.27 D.¹⁰ Significant shifts of corneal power, toricity, and axis are also obtained on young subjects when the optical axis and the line of sight are aligned.¹¹ This method, however, requires a measurement of the distance between the centre and the steepest point on the data display. Sometimes, the steepest point may not be obvious and it is questionable whether the steepest point displayed marks the position of the apex in a tilted cornea. Also, using the line of sight as the reference implies that the cornea is optically

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Figure 1 The effect of tilting an ellipsoidal surface. The diagram illustrates the elliptical section of the surface which is assumed to be a prolate (flattening) ellipsoid. The surface vertex is the point where the radius of curvature is minimal.

Figure 2 Light reflected from a tilted ellipsoidal surface. C represents the point where the optical axis of the keratoscope intersects the surface being measured. O is the surface vertex. Note that the light ray at point C is normal to the surface. This will be the case when the videokeratoscope (VK) image is centred on the monitor screen. Lateral displacement of the VK will be required to maintain a centred image as the tilt increases.

aligned with the remaining optical components of the eye. It is still possible that the cornea could be tilted and laterally displaced even when the line of sight is aligned with the optical axis of the instrument.

In this study, we developed a theoretical model, the corneal tilt model, for assessing the error in the topographic description of a surface in which the optical axis of the instrument and the major axis of the corneal elliptical section do not coincide. The model was then verified by means of measuring the tilt on a predetermined convex conicoidal plastic surface. We then examined the extent of tilt present in a group of normal young subjects. In addition, we devised a method to correct the tilt and examined the changes in the data display when the tilt was neutralised. Our approach makes no assumptions about the relation between the cornea and the remaining

optical components of the eye. The cornea is considered as an isolated reflecting surface, which is simply supported by the globe.

The corneal tilt model

Keratometry relies on the measurement of the reflected image to determine the radius of curvature of the surface. If a spherical surface is being measured, tilting of the surface, accompanied by recentring of the image on the monitor screen, will not affect the readings because the reflecting regions are all self similar. In contrast, tilting an aspheric surface causes regions of different curvature and separation to be instrumental in image formation thereby affecting the results. Figure 1 illustrates keratometric ray paths for an elliptical section before and after rotational tilting. In both cases the incident rays from the mire are reflected through the same angle at the points of reflection. In the case of the tilted cornea the reflected ray, at the larger displacement from the surface vertex, results in a larger image and hence a keratometric assessment of a longer radius of curvature. Similarly, the smaller displacement results in a shorter radius of curvature. The VK will thus display asymmetry when measuring a symmetrical surface.

The mathematical synthesis which follows incorporates certain assumptions:

- The keratoscope mires are reasonably distant from the ellipsoidal surface, so that longitudinal displacement has a negligible effect on the angle of incidence.
- The viewing system is reasonably distant from the ellipsoidal surface, so that longitudinal displacement has a negligible effect on the measured image size.
- The surface meridian under measurement is elliptical.

THEORY

Rather than consider a tilted ellipse, it is simpler to consider tilted ray paths.

In Figure 2 the mire angle ϕ is the arbitrary fixed angle through which the incident rays from the mire extremities are reflected to result in observation by the viewing system. θ is the angle of surface tilt. Thus, the upper incident ray makes an angle of $(\theta + \phi)$ with respect to the horizontal while the lower ray makes an angle of $(\theta - \phi)$. NB ϕ is a negative angle for the lower ray. The rays reflected from A and B both make an angle θ . Since angles of incidence and reflection are equal with respect to surface normals, the gradients of the normals at A and B can be given as:

$$G_A = \tan (\theta + (\phi/2))$$

$$G_B = \tan (\theta - (\phi/2))$$

If the ellipse is described by Baker's equation¹²:

$$y^2 = 2r_0x - px^2$$

then it can be shown that the coordinates of the reflection points (x_A, y_A) , (x_B, y_B) can be found from:

$$y = \frac{G \cdot r_0}{\sqrt{(G^2 \cdot p + 1)}} \quad (1)$$

$$x = \frac{r_o - \sqrt{(r_o^2 - p \cdot y^2)}}{p} \quad (2)$$

Having established these coordinates, the distance of the reflected rays from the origin O, measured perpendicular to the keratoscope optical axis can be found from:

$$h = x \cdot \sin \theta + y \cdot \cos \theta \quad (3)$$

Finally, the keratoscopic assessment of the radius of curvature can be deduced from the separation of the reflected rays which indicates the image size:

$$r_{ka} = \frac{h_A - h_C}{\sin(\theta/2)} \quad (4)$$

$$r_{kb} = \frac{h_C - h_B}{\sin(\theta/2)} \quad (5)$$

It must be noted that keratometers and keratoscopes measure the sagittal radius of curvature. This, in an ellipsoid, is the distance from the surface point to the major axis of the ellipse measured in a direction normal to the surface at the point in question.

Keratoscopes specify the distance of the points A and B from the instrument optical axis, measured in a direction perpendicular to that axis. In Figure 2 the instrument optical axis passes through the ellipsoidal surface at point C. The displacement of this point from the surface vertex O must be known :

$$G_C = \tan \theta \quad (6)$$

G_C is the gradient of the normal at C

$$y_C = \frac{G_C \cdot r_o}{\sqrt{(G_C^2 \cdot p + 1)}} \quad (7)$$

$$x_C = \frac{r_o - \sqrt{(r_o^2 - p \cdot y_C^2)}}{p} \quad (8)$$

$$h_C = x_C \cdot \sin \theta + y_C \cdot \cos \theta \quad (9)$$

These equations can be used to calculate the theoretical radius values provided by a keratoscopic device with the ellipsoidal surface tilted at any given angle. When h_C is calculated, this indicates the displacement of the surface vertex from the optical axis of the keratoscope.

The vertex radius (r_o) and the p value (p) fully describe the elliptical section: ($p = 1 - e^2$, where e is the eccentricity of the elliptical section). The vertex radius, r_o , indicates whether the surface is steep or flat and p indicates the rate of surface flattening (or steepening) from the vertex to the periphery. The variables r_o and p can be derived by plotting a graph of displacement distance squared versus radius of curvature squared using the tabulated data displayed by the EyeSys VK.³ In the case of a conicoidal surface, the points should theoretically lie on a straight line whose intercept indicates the square of the vertex radius (r_o) and gradient indicates $(1 - p)$ where p is the p value of the conic section of the meridian under investigation.

The study was conducted in two main parts in order to (a) verify the validity of the model (experiment 1). Experiment 1 verifies the validity of the model by using a convex conicoidal surface which could be tilted by a given amount; (b) measure the effect of tilt on convex conicoidal surfaces and human corneas (experiments 2 and 3).

If a VK image is captured with ostensibly coaxial components and yet the ring images are disposed asymmetrically, we can deduce that there is a tilt of the surface axis when examining a rotationally symmetrical surface. The extent of the tilt of the surface is unknown. It could be a small angle on a highly aspheric surface, or a large angle on a near spherical surface. If the tilt angle is increased, the asymmetry will increase.

Figure 3 The displacement of the image rings when the surface being measured is tilted. (A) The image produced when no tilt is present. (B) The image observed when the surface is tilted. In using the videokeratoscope, the point C would be placed at the centre of the monitor screen.

Figure 4 The relation between the angle of tilt and the displacement of a ring centre.

The asymmetry can be described by the displacement of the geometric centre of a specified ring from the centre of the ring system (point C in Fig 3B). The ring selected is the fifth from the centre. The displacement (the distance from C to the geometric centre of the fifth ring) q is zero when the components are coaxial as in Figure 3A. The displacement q will increase as the tilt increases. By calculation, the relation between the tilt and the displacement is a linear one, at least up to 10° of tilt. Figure 4 illustrates the relation.

Let us start with a captured image where the tilt angle is s° and q_s is the displacement in mm, which can be measured on the image. If the angle of tilt is increased by t° , the actual tilt angle is now $(s + t)^\circ$ and the value of the displacement will be q_{s+t} . This displacement can be measured from the second captured image.

From Figure 4:

$$\begin{aligned} \text{gradient} &= s/q_s \\ \text{Also gradient} &= \frac{(s+t) - s}{q_{s+t} - q_s} = \frac{t}{q_{s+t} - q_s} \\ \frac{s}{q_s} &= \frac{t}{q_{s+t} - q_s} \\ \text{therefore } s &= \frac{t \cdot q_s}{q_{s+t} - q_s} \end{aligned} \quad (10)$$

Where s is the original tilt in degrees, q_s is the original displacement, in mm, of the ring centre, t is the tilt angle between the first and second videokeratograms, and q_{s+t} is the displacement present in the second image.

Thus, equation (10) allows us to calculate the original tilt from two VK images with a given tilt angle difference between the two.

From the above, an EyeSys VK measurement on a human cornea can be obtained with central fixation and then a second image can be captured after the eye rotates to fix on a second off axis target. The displacements q_s and q_{s+t} can be extracted from

the tabular data provided in the display options. These tabular data give the distance of each ring image from the optical axis of the instrument with the captured image centred on this axis. This means that the tabular data give D_a and D_b in Figure 3.

$$q = \frac{D_a - D_b}{2} \quad (11)$$

Before attempting to use this approach on human corneas, it is appropriate to validate it using aspheric convex surfaces which are known to be rotationally symmetrical and which can be positioned at known angles of tilt. This is carried out in experiment 2. Experiment 3 uses the above technique on the human eye in order to estimate the magnitude of the initial tilt. If this tilt can be neutralised it may be possible to differentiate between apparent corneal asymmetry due to tilt and actual asymmetry.

Methods

EXPERIMENT 1: VERIFYING THE VALIDITY OF THE MODEL

EyeSys VK measurements (EyeSys Windows Workstation Version 2.00W) were made on a convex ellipsoidal plastic surface of vertex radius 7.316 mm and p value of 0.551 after carefully adjusting the surface and the instrument in order to ensure that the major axis of the ellipse was coincident with the instrument's optical axis. This was confirmed by examining the tabular data display of the VK, for the horizontal meridian, and establishing identical columns of figures for the nasal and temporal displays. The surface was then tilted through a 5° angle and another image was captured. The resulting distance²/radius² graphs for the horizontal meridian of the tilted and untilted surfaces were compared with the graphs produced by calculation using equations (1) to (9).

EXPERIMENT 2: MEASUREMENT OF THE EFFECT OF TILT ON CONVEX CONICOIDAL SURFACES

Four conicoidal surfaces were measured using the EyeSys VK. They are described in Table 1. Each button was positioned initially with a 4.5° tilt angle and the VK image was captured. The button was tilted a further 10° (total tilt 14.5°) and the second image was captured. The tilt angles were confirmed using a mirror, mounted on the conicoidal surface support, which was fixed to an optical bench. The reflected image position was measured on a tangent scale at a distance of 1.5 metres.

Equations (10) and (11) were used to calculate the original angle of tilt for each ring. This provided the potential to give 16 values for the original tilt angle. However, it was immediately obvious that the rings close to the axis were producing inaccurate results. This is not surprising when the equations for keratometry and keratoscopy are examined where it is obvious that a small mire size reduces the precision of the measurement of radius of curvature.¹³ The readings appeared to become consistent from ring 6 onwards. The 14.5° tilt resulted in the loss of the images of the more peripheral

Figure 5 Measurement of the horizontal meridian of a convex ellipsoidal surface using the EyeSys videokeratoscope (VK) (A) when the major axis of the ellipse coincides with the instrument optical axis; (B) when the surface is tilted 5° in the horizontal plane. The y axis represents the square of the radius values given by the VK with the x axis indicating the square of the distance of that point from the VK optical axis. These values are listed in the VK tabular display.

rings on one side. Calculations were performed, therefore, on rings 7 to 12 and these six results were averaged to determine the angle of the initial tilt. This result was compared with the 4.5° tilt known to be present.

EXPERIMENT 3: MEASUREMENT OF THE TILT ON HUMAN CORNEAS

Ten human subjects had their right eye corneal topography assessed by the EyeSys VK. Each subject was asked to look at the central green flashing instrument fixation target and a VK image was captured after observing all the precautions described by the manufacturer. The subject was then asked to fix on the border of the outer edge of the first white ring along the horizontal meridian, with the eye turning in a temporal direction. A small fixation spot was positioned here to ensure accurate fixation. The change in fixation angle was calculated to be 10.7° after making measurements with a travelling microscope. A second image was captured with the eye in this position. Note that the VK must be moved laterally in the direction of the tilt in order to maintain a cen-

tred image. The tabular data display produced by the instrument was used, with equations (10) and (11), to calculate the initial tilt of the cornea when the patient was looking at the instrument fixation target. The equations were used on data for the horizontal meridian from rings 7 to 12. This gave six values for the initial tilt which were then averaged. This process was repeated another two times. The resulting three values for initial tilt were compared and the two closest values were averaged.

The decision to repeat the measurement three times was based on measurements on two of the subjects who were measured 10 times where it was found that averaging the two closest measurements of any consecutive three measurements produced a tilt angle which was within one standard deviation of the mean of the 10 results.

Results

EXPERIMENT 1: VERIFYING THE VALIDITY OF THE MODEL

Figure 5 illustrates the respective distance²/radius² graphs for the untitled (A) and tilted (B) measurements of the convex ellipsoidal surface. These graphs illustrate the fact that the radius values decrease for one semimeridian and increase for the other when the surface is tilted. These changes also modify the

Figure 6 The theoretical graphs of the surface measured in Figure 3, obtained by calculation (A) when the major axis of the ellipse coincides with the instrument optical axis, (B) when the surface is tilted 5° in the horizontal plane.

Figure 7 The error in the vertex radius and p value predicted by calculation, when an ellipsoid is tilted 5° . The surfaces under consideration all have a vertex radius of 7.80 mm.

Table 1 The four convex ellipsoidal surfaces with the initial tilt calculated from the measurements. The actual initial tilt was 4.5°

Vertex radius (mm)	p Value	Measured tilt (degrees)
7.30	0.86	4.09
7.30	0.55	4.21
8.32	0.34	4.53
8.31	0.09	4.39

regression line produced by the untilted surface measurement and the predictions of the vertex radius and the p value are altered slightly.

Figure 6 illustrates the same two graphs based on the calculations using equations (1) to (9). There is a striking similarity between the measured and the calculated results. The 5° tilt produces a measured value for r_0 of 7.354 mm and p of 0.518 (Fig 5). The calculated result gives r_0 as 7.339 mm and p as 0.517 (Fig 6).

It is therefore possible to calculate the effects of tilting conicoidal surfaces without the worry of the influence of experimental error arising from measured results.

Figure 7 illustrates the error predicted by calculation when ellipsoidal surfaces are tilted through 5° . The surfaces all possess a vertex radius of 7.8 mm with the p value varying from 0.1 to 1. The graph illustrates that the VK is predicted to read high for vertex radius, particularly for p values around 0.5, and to read low for the measurement of the p value particularly as the p value decreases (as the surface becomes more aspheric).

The shift in the vertex away from the instrument visual axis is calculated to be 0.68 mm for all the p values considered. A similar exercise with steep (vertex radius 7.20 mm) and flat (8.20 mm) surfaces reveals a similar picture. The error in the p value is exactly the same for all three vertex radii—that is, the error in the p value arising from a 5° tilt is independent of the

vertex radius of the surface. The error in the vertex radius is very slightly greater (by 0.001 mm) for the flat surface and slightly less (by 0.002 mm) for the steep surface. The shift in the vertex off the instrument axis was 0.72 mm for the flat surface and 0.63 mm for the steep surface.

EXPERIMENT 2: MEASUREMENT OF THE EFFECT OF TILT ON CONVEX CONICOIDAL SURFACES

Table 1 describes the four convex aspheric surfaces measured by the EyeSys VK with the initial tilt calculated from the measurements. The actual initial tilt was 4.5° in all four cases.

EXPERIMENT 3: MEASUREMENT OF THE EFFECT OF TILT ON THE HUMAN CORNEA

Table 2 illustrates the extent of the initial tilt in the 10 subjects examined.

If we assume a normal distribution, as is suggested by the Kolmogorov Smirnov d test, then 95% of the population will lie within two standard deviations of the mean. The results suggest that the tilt is likely to be between 0.96° and 5.88° (two standard deviations either side of the mean).

Discussion

These results suggest that the magnitude of tilt of the human cornea is likely to be less than 6° when using the standard fixation target of the EyeSys VK (see Table 2). The type of graphs illustrated in Figure 5 where the distance²/radius² relation for a convex ellipsoidal button was measured in an untilted and tilted position were repeated for the human cornea. The measurement can be made with central fixation and then repeated with another fixation target placed on the nasal side in a position which neutralises the initial tilt calculated using the method described above.

Figure 8 shows a typical pair of graphs for the horizontal meridian from one of the subjects in Table 2. The apparent nasal/temporal asymmetry observed with central fixation largely disappears when the corneal tilt is neutralised (the tilt was 3.49°). If we consider Figure 8A the regression relation gives a p value of 0.75, a vertex radius of 7.92 mm, and a coefficient of determination (correlation coefficient squared r^2) of 0.58. The coefficient of determination indicates that only 58% of the variation is explained by the linear relation. When the corneal tilt is neutralised, Figure 8B gives the p value as 0.75, the vertex radius as 7.99 mm, with a coefficient of determination of 0.98. The temporal/nasal asymmetry has largely disappeared and the corneal section is very close to the elliptical form. Thus, the steps taken to attempt to neutralise the tilt have improved the correlation coefficient without substantially altering either the p value or the vertex radius. Plots on the other subjects also illustrate a reduction in the nasal/temporal asymmetry when the tilt is neutralised, although in some cases an obvious asymmetry remains in the corneal periphery.

It will be noted that one subject in Table 2 displays only a minor tilt of 0.34° . The distance²/radius² graph of this subject is

Table 2 The initial tilt of human corneal surfaces in right eyes looking at the instrument fixation target. In all cases the cornea is tilted in a temporal direction

Subject	Tilt ($^\circ$)
SP	2.66
DM	3.49
CJ	0.34
JH	4.62
SG	3.62
JK	4.23
DH	4.55
SL	3.87
NH	3.47
TS	3.35
Mean	3.42
SD	1.23

Figure 8 The EyeSys measured results on a human cornea (A) when using the standard central fixation target, (B) when the corneal tilt calculated for this eye is neutralised by using an off axis fixation target.

illustrated in Figure 9, where it can be seen that this cornea shows little nasal/temporal asymmetry for the horizontal meridian with normal, central fixation. It is also worth noting that the data points often appear to lack precision when the distance from the vertex is small. This is commonly observed in the scatterplots although it is pronounced in Figure 9.

Thus, the results on the human cornea support those obtained with the convex conicoidal surfaces. The EyeSys measurements on these human corneas suggest a cross section in the horizontal meridian which is very similar to that of an ellipse, with little evidence of asymmetry in the central regions of the cornea when the corneal tilt is reduced. The consensus view has always been that the corneal section approximates to an elliptical form¹⁴⁻¹⁶ and the results of this study support that proposal.

It must be noted that the distance²/radius² graphs for the tilted surfaces were calculated with the assumption that the surface was a symmetrical conicoid. It may be argued that the apparent symmetry seen in the human corneal VKs, when the tilt is neutralised, is produced by an asymmetrical surface which has been tilted to produce apparent symmetry. However, there is some evidence of tilt in the standard VK image denoted by the shortest

radius of curvature, which marks the corneal apex in a prolate ellipse, not coinciding with the image centre.

In order to determine the implications of the results we can consider the error induced in the measurement of corneal surface power arising from a measurement on a tilted surface.

CORNEAL SURFACE POWER

The problem with the prediction of the refractive power of the cornea, at an off axis point, is that there are four possibilities as described by Mandell.⁸ The most appropriate option, in Mandell's opinion, is the posterior focal power which represents the reciprocal of the distance (minus the surface sagitta) at which a parallel ray from left to right, after refraction, crosses the optical axis, times the refractive index of the refracting medium. In other words, the power is expressed as the emergent vergence of light from the anterior corneal surface, for a parallel ray of incident light. This emergent vergence can be calculated by performing a ray tracing exercise at the surface point under consideration using Snell's law. The other options for describing the power of the cornea at any specified point are fully discussed by Klein and Mandell.¹⁷

Opting for ray tracing using Snell's law, it is still necessary to assume a value for the corneal refractive index and to assume that the cornea is a single refracting surface. The value assumed by the EyeSys instrument, and most keratometers is 1.3375. We have assumed this popular value because it attempts to compensate for refraction at the posterior corneal surface.

The paraxial power of the cornea (the power of the vertex) is easily calculated by the paraxial equation:

$$F = (n - 1)/r_0 \quad (12)$$

where F is the surface power, n is the refractive index and r_0 is the vertex radius.

Unfortunately the off axis powers listed by most VKs are derived from this equation which is inappropriate for predicting the emergent ray direction of a non-paraxial ray.

Figure 9 The EyeSys measured result using the central fixation target for the subject with a small angle of corneal tilt (0.34°).

Table 3 The power error (D) arising from a 5° tilt on nine aspheric surfaces. The predicted power is lower when the surface is tilted

Vertex radius	p Value		
	0.1	0.5	0.8
7.2			
Paraxial	-0.05	-0.14	-0.09
Limiting	-0.08	-0.16	-0.10
7.8			
Paraxial	-0.06	-0.14	-0.08
Limiting	-0.08	-0.16	-0.10
8.2			
Paraxial	-0.05	-0.13	-0.08
Limiting	-0.07	-0.14	-0.08

If we assume that the VK gives an accurate assessment of the surface vertex radius and p value, for the horizontal meridian, when the surface and the instrument are coaxial and we then repeat the measurement with the surface tilted 5°, we can calculate the error induced by the tilt. Calculations were performed for vertex radii of 7.2, 7.8, and 8.2 mm. These values represent a steep, an average, and a flat corneal radius. The p values of 0.1, 0.5, and 0.8 were selected for the following reasons:

(1) 0.1 represents the near parabolic surface and Figure 7 shows that a 5° tilt induces the greatest error in the p value when this is low.

(2) 0.5 was chosen because the error in the vertex radius is maximal and there is still an error induced in the p value.

(3) 0.8 was chosen because this is the p value of the typical human cornea.

Table 3 illustrates the error in the paraxial power and the error in the emergent vergence of a limiting light ray from an infinite point source, through a 4 mm diameter aperture. The negative values indicate that the tilt induces a reduction in the predicted power.

Table 3 illustrates the fact that the paraxial error is less than the error for the limiting light rays at the edge of the 4 mm aperture. The greatest error arises for a p value of 0.5. The vertex radius has little influence on the error, although the flattest surface shows a very slight decrease in error. In all nine surfaces, the maximum calculated error is -0.16 D.

This work suggests that a tilt of 5° induces errors that are small enough to be disregarded in the clinical situation with normal corneas when using the EyeSys VK. The measurements on the normal human cornea suggest that the tilt is likely to be of this magnitude and, in consequence, it may not be necessary to incorporate a movable fixation target to deal with the problem of a tilted, normal corneal surface.

In the case of the more aspheric cornea, a movable fixation spot could be a useful facility as suggested by Mandell's work with keratoconus.¹⁰ Applegate and Howland² suggest placing two fixation points, at different distances, along the optical axis of the VK system. The

subject could fixate the nearer point and position his/her eye to superimpose the fixated spot onto the non-fixated one. This would make the line of sight coincide with the optical axis of the VK. Both Applegate and Howland and Mandell advocate the line of sight as the significant feature to consider to achieve appropriate alignment. Our approach makes no assumptions about the relation between the cornea and the remaining optical components of the eye. The cornea is considered as an isolated reflecting surface, which is simply supported by the globe.

Conclusions

(1) The measurements and calculations on convex conicoidal plastic surfaces indicate that the errors induced by a 5° tilt are small. The power measurement on a tilted surface VK image is likely to be within 0.25 D of the measurement on an untilted surface.

(2) The method for determining the tilt of a symmetrical surface was validated using plastic convex conicoidal surfaces and was then used on the human corneas. The method suggests that the normal human corneal tilt is in a temporal direction and is in the region of 1° to 6° (mean plus or minus two standard deviations on 10 subjects).

(3) Reduction of the tilt on the human cornea appears to eliminate most of the nasal/temporal asymmetry observed on the image display.

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