Surface Tilt Measured with the EyeSys Videokeratoscope: Influence on Corneal Asymmetry

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PURPOSE. To investigate whether the apparent corneal asymmetry in the EyeSys videokeratoscope (VK EyeSys Laboratories, Houston, TX) image is a result of the cornea being tilted in relation to the instrument and to examine the possibility of deducing this tilt from a single captured image.

METHODS. Videokeratoscopic images were captured with and without a front surface conicoidal contact lens (experiment 1). An image was captured with central fixation followed by image capture with fixation 10° off center. These two images were used to calculate the angle of tilt with central fixation. The approximate tilt of the cornea derived from a single captured image was determined by the use of a mathematical model applied to some of the ring images (experiment 2). Twenty-four subjects were used in each of the above experiments.

RESULTS. The mean tilt for the first group of subjects with the contact lens on the cornea was 2.8°, whereas the tilt for the cornea alone was 3.2° (experiment 1). The corneal tilt for the second group of subjects was 3.3°, and the approximate tilt derived from a single captured VK image, using the equation, was 3.2° (experiment 2).

CONCLUSIONS. The similarity of the tilt angle with and without the contact lens in place suggests that the apparent asymmetry seen in the VK images of human corneas may be largely an artifact arising from corneal tilt and not nasal/temporal asymmetry. The agreement of the corneal tilt derived from two VK images and the approximate tilt derived from a single image indicates that the latter may offer a quick and convenient way to determine the fixation adjustment required to eliminate corneal tilt. (Invest Ophthalmol Vis Sci. 1998;39:1727–1735)
76.70 diopters with a corneal astigmatism of only 1.27 diopters. The topographical map showed near perfect symmetry with the altered fixation whereas with the standard fixation the display showed asymmetry. There, therefore, a need to evaluate the extent of the misalignment between the optical axis of the instrument and the major axis of the corneal elliptical section. The misalignment results in a tilted cornea that has implications for the accuracy of the VK measurement for both refractive surgery and contact lens fitting. Although the inherent tilt influences the visual performance of the eye and it is important to consider the cornea as a tilted surface when considering this visual performance, it is desirable to start with a corneal model that is as accurate as possible. This will not be the case if the corneal VK image is acquired in a tilted state. Therefore, the corneal tilt should be eliminated to provide an accurate VK topographical map that can then be incorporated back into the eye model at the appropriate angle of tilt.

Some previous studies have demonstrated ways of correcting this error by viewing an eccentric fixation point on the instrument. Mandell7 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 center of the display. An additional fixation point placed at the measured distance would then align the apex with the instrument’s optical axis. This method, however, requires a measurement of the distance between the center 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. 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.4 Applegate and Howland5 have suggested a modification to the VK fixation target that would make the line of sight coincide with the optical axis of the VK. 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.

A VK image that illustrates asymmetry could arise from the measurement of an asymmetric surface or from a rotationally symmetrical surface that has been tilted or from a combination of the two. We previously developed a technique for assessing the amount of tilt in a conicoidal surface being examined by a VK.6 The work was performed using convex conicoidal plastic surfaces, and we went on to examine the extent of tilt present in the corneas of a group of normal young subjects. In addition we examined the changes in the data display when the tilt was neutralized. The results suggested that a major part of the nasal/temporal asymmetry observed on the VK images of the human cornea is an artifact arising from the corneal surface being tilted in relation to the VK optical axis in the horizontal plane. It was, however, noted that we could have been dealing with an asymmetrical surface that we tilted to produce apparent symmetry. This equivocal result could be resolved by placing a contact lens with an ellipsoidal front surface on the cornea. The eye will now possess an anterior surface that is rotationally symmetrical, which leaves only the surface tilt to create the apparent asymmetry. Therefore, if the magnitude of the tilt measured with and without the contact lens is the same, then the cornea must also be symmetrical. Thus, the initial apparent asymmetry seen in the standard corneal EyeSys display must be a result of a tilted cornea.

If a spherical front surface contact lens was used and the surface was tilted, this would result in a lateral shift of the VK image with the consequent need to re-center the image on the monitor screen. This centered image will be identical with one where no tilt is present.

**METHODS**

**Experiment 1: Measurement of Tilt with Two Images**

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 the surface will not affect the readings because the reflecting regions are all self-similar. In contrast, tilting an aspheric surface causes regions of different curvature, arising from dissimilar distances from the surface apex, to be instrumental in image formation, thereby affecting the results. The asymmetry displayed in the VK image could be a result of a slightly aspheric surface tilted to a considerable degree or it could be produced by a very aspheric surface tilted only slightly.

If we assume that the human cornea approximates to an ellipsoid, then the rate of change of curvature from the corneal apex to the limbus (the asphericity) can be quantified in a number of ways. The most familiar parameter is probably the eccentricity (e) of the elliptical section. This has the serious drawback that it cannot be used to describe the oblate (steepening) ellipsoids, and this form is not uncommon in the human cornea.7 The term popularized in the United Kingdom by Bennett8 is the P value (p), where $p = 1 - e^2$. This term will deal with both the prolate and oblate ellipsoids. A P value of zero indicates that the surface has a parabolic section and a P value of unity indicates that the section is circular so the surface is spherical. Thus the P value is a measure of nonpababoloidal shape. A P value between 0 and 1.0 indicates that the surface is of a prolate ellipsoidal form and a P value greater than unity indicates an oblate ellipsoid.

The extent of the surface tilt can be established by capturing a VK image and then tilting the surface by a known amount and capturing a new image. These two images allow the calculation of the tilt present in the first image.6 This technique was used with and without a specially manufactured contact lens with an ellipsoidal front surface.

The assessment of the apical radius and P value of the contact lens front surface was obtained by capturing a VK image with the contact lens held on a purpose-designed holder that was carefully adjusted to ensure that the major axis of the ellipsoid coincided with the VK optical axis.

The equation derived by Bennett8 for an elliptical section can be written as follows:

$$r_s^2 = r_o^2 + (1 - p)y^2$$  \(1\)

The apex radius ($r_o$) and the P value ($p$) are constants of the surface. Equation (1) is that of a linear function, plotting sagittal radius ($r_s$) squared on the y-axis and the perpendicular distance of the surface point from the instrument’s optical axis ($y$) squared on the x-axis will produce a straight line graph. The sagittal radius and the perpendicular distance of the point in question from the VK optical axis are listed on the tabular data display provided by the EyeSys software. The square root of the
FIGURE 1. (A) The scatterplot produced when the contact lens front surface is not tilted. The regression line indicates that \( r_0 = 7.56 \text{ mm}, \ p = 0.77 \). (B) The scatterplot produced when the contact lens front surface is tilted five degrees. The regression line indicates that \( r_0 = 7.55 \text{ mm}, \ p = 0.84 \). In both cases the points are derived from a measurement of the horizontal meridian. The separation of the points into two distinct curves shown in (B) illustrates the apparent nasal/temporal asymmetry induced by the tilt.

intercept on the y-axis of the graph indicates the apex radius. The slope of the line gives \((1 - \rho)\). The graph of the contact lens front surface is illustrated in Figure 1A, where it can be seen that the surface points come very close to the least squares regression line. Figure 1B illustrates the result of analyzing the VK image data when the surface is tilted 5° in relation to the VK's optical axis. This produces an apparent asymmetry that is obvious when inspecting the graph.

The theoretical treatment that follows has already been published, but is repeated here for clarity.

If we assume that we are dealing with a rotationally symmetrical surface, as is the case with the aspheric contact lens surface, and yet captured VK ring images are disposed asymmetrically, we can deduce that there is a tilt of the surface. If the fixation is altered to increase the tilt angle, the asymmetry will increase. The asymmetry can be described by the displacement of the geometric center of a specified ring from the center of the ring system (point R in Fig. 2B). The ring selected is the fifth from the center. The horizontal displacement (the distance from R to the geometric center of the fifth ring) \( d \) is zero when the components are coaxial as in Figure 2A. The displacement \( d \) will increase as the tilt increases.

By calculation, the relationship between the tilt and the displacement is a linear one, at least up to 10° of tilt. Let us suppose that the captured image has a tilt angle of \( s \) degrees and \( d_s \) is the displacement in mm, which can be measured on the image. If the angle of tilt is increased by \( t \) degrees, the actual tilt angle is now \((s + t)\) degrees and the value of the displacement will be \( d_{s+t} \). This displacement can be measured from the second captured image.

\[
\text{gradient} = \frac{s}{d_s} \quad (2)
\]

Also gradient \[
\frac{(s + t) - s}{d_{s+t} - d_s} = \frac{t}{d_{s+t} - d_s} \quad (3)
\]

From Eq (2) and (3)

\[
\frac{s}{d_s} = \frac{t}{d_{s+t} - d_s} \quad \Rightarrow \quad s = \frac{t \cdot d_s}{d_{s+t} - d_s} \quad (4)
\]

due to the geometric center of the fifth ring being zero when the components are coaxial as in Figure 2A.
where $s$ is the original tilt in degrees, $d_i$ is the original displacement, in millimeters, of the ring center, $t$ is the tilt angle between the first and second videokeratograms, and $d_{t+s}$ is the displacement present in the second image.

Thus Eq (4) allows us to calculate the original tilt from two VK images with a known tilt angle difference between the two.

An EyeSys VK measurement 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 $d_i$ and $d_{t+s}$ can be extracted from the tabular data provided in the display options. This tabular data gives the distance of each ring image from the optical axis of the instrument with the captured image centered on this axis. This means that the tabular data gives distances $D_a$ and $D_b$ in Figure 2 because the central (smallest) image circle is positioned at the center of the monitor screen.

Before attempting to use this approach on human corneas, it was appropriate to validate it by using the convex aspheric front surface of the contact lens which is rotationally symmetrical and which could be positioned at known angles of tilt. The contact lens was placed on a holder that positioned the lens so that it simulated a human cornea. The surface was initially positioned with a $5^\circ$ clockwise (in plan view) tilt. The VK image was captured. The contact lens was then tilted $10^\circ$ in an anticlockwise direction so that the contact lens was positioned with a $5^\circ$ anticlockwise tilt. The tilt angles were confirmed using a mirror mounted on the contact lens holder that was fixed to an optical bench. The reflected image position was measured on a tangent scale at a distance of 1.5 m. The initial tilt was calculated using Eqs (4) and (5). The equations were used on data for the horizontal meridian only, from rings 7 to 12 inclusive. This gives six calculated estimates of the tilt. These six results were averaged to give the final result for the initial tilt angle. Rings 7 to 12 were chosen because inspection of the VK and keratometer equations indicates that a small object size reduces the precision of the measurement and so the smallest ring images were not considered. The most peripheral rings on the other hand do not always produce ring images on a tilted or untilted cornea, and so the data for the outer four rings were unlikely to be displayed in both images and were in consequence discarded when present.

The same technique was then used on the right eyes of 24 human subjects. Informed consent was obtained from all participating subjects. The corneas of the subjects were normal, and refractive errors were within the range $\pm 3.00$
DS and ± 2.00 DC. Each subject was examined with a keratometer to establish the orientation of the two principal meridians of the cornea. Subjects were excluded from the study if their principal meridians were not near horizontal and near vertical (± 5°). Subjects were asked to look at the standard VK fixation target, to stare wide-eyed with their head positioned on the headrest to ensure minimal restriction of the VK image on the nasal side. After acquiring this first image, the subject was asked to fixate onto a small target positioned 10° from the VK fixation target on the nasal side. Our previous studies indicated that the corneal tilt was between 1° and 6° in a temporal direction. If we increased this tilt by a further 10° then some of our more peripheral rings would not produce images on the cornea. Indeed, this was a problem that we encountered. A 10° tilt in a nasal direction, on the other hand, means that the cornea will end up tilted only 4° to 9° in the typical eye, and in consequence all of the ring images that we wanted to measure will be present. The two captured images allowed calculation of the initial tilt using rings 7 to 12.

The contact lens was then inserted into the subject's right eye and the technique described above was repeated. The contact lens back surface possessed a steeper than average curvature, and the consequent steep fitting on the cornea encouraged the lens to sit centrally. This was further encouraged by using a lens with the relatively large total diameter of 9.80 mm. Good lens centration was important to prevent the contact lens front surface apex from being displaced from the corneal apex. The contact lens centration could be observed during image capture and was monitored to ensure that the image was captured only when the contact lens appeared to be well centered on the cornea. Once again the data from image rings 7 to 12 were analyzed and averaged to give a single result for an estimate of the initial tilt.

**Experiment 2: Mathematical Model for the Approximate Tilt**

The problem with the method described above for assessing the extent of the tilt is that two corneal images must be captured and analyzed. It is possible to acquire an approximate tilt by assuming that the acquired values for the \( P \) value and the apex radius are not affected by the tilt, and these values are used in the determination of the tilt from a single picture. It is obvious from Figure 1 that tilting the surface will alter the apparent apical radius and \( P \) value. A previous article indicated that the error in the apical radius is greatest for a \( P \) value around 0.5, but the error in the \( P \) value itself increases from zero with a circular section to an error approaching 0.2 for a parabolic section when the surface is tilted 5°. Therefore, if we are to use a single image, then the tilt calculated will be an approximation. Derivation of an equation from the geometry of the path of the light rays that result in a VK image is beset by yet more approximations. It was therefore decided to use the mathematical model described in a previous article to investigate the relationships between the tilt, the apical radius and the \( P \) value. A given asymmetry in the VK image of a tilted surface could be a result of a near spherical surface being tilted by a substantial angle or result of a substantially aspheric (near paraboloidal) surface being tilted by a small angle. The asymmetry can be quantified by comparison of distances \( D_a \) and \( D_b \) in Figure 2. These two distances will be equal when a rotationally symmetrical surface is measured with no tilt. We investigated the possibility of a relationship between the \( P \) value and...
the degree of apparent asymmetry as indicated by distances $D_a$ and $D_b$.

The mathematical model was used to consider surfaces with $P$ values from 0.2 to 0.8 with apical radii from 7.20 mm to 8.40 mm, tilted from 2° to 10°.

RESULTS

The distribution of the data were found to be not significantly different from that of a normal distribution using the Kolmogorov-Smirnov test. Parametric statistics were therefore used for analysis.

Experiment 1: Tilt Assessed from Two Captured VK Images

The front surface apical radius of the contact lens was measured as 7.56 mm and the $P$ value 0.77 according to the EyeSys VK in the absence of surface tilt (EyeSys Windows Workstation Version 2.00W).

The initial tilt of the contact lens when mounted on the lens holder was calculated to be 5.6° when the surface was tilted 5°.

The mean corneal tilt for the 24 subjects was 3.20°. The mean tilt with the contact lens in place was 2.80°. A t-test for dependent samples indicates no significant difference ($p = 0.430$) between the corneal tilt and the contact lens tilt. The relationship is shown in Figure 3.

A scatterplot of the difference in tilt (corneal tilt − contact lens tilt) versus the mean tilt ([corneal tilt + contact lens tilt]/2) is shown in Figure 4.

The mean difference in Figure 4, which indicates the bias, is 0.4°. The 95% confidence limits of the mean (95% confidence interval) are from −0.63° to 1.43°. The standard deviation of the difference is 2.44°.

Experiment 2: Approximate Tilt Assessed from a Single Captured Image

Mathematical Model. From the tabular display of the EyeSys VK, which indicates distances $D_a$ and $D_b$ (Fig. 2) for all of the ring images, scatterplots of $D_a/D_b$ versus tilt angle were obtained and found to be linear with the slope of the regression line changing as the $P$ value is changed, with no change in the intercept. The regression lines were identical for all values of apical radius considered, and so we concluded that the apical radius will have no influence on the results.

The linear relationship for the seventh VK ring was as follows:

$$\text{Tilt angle (degrees)} = \frac{D_a}{D_b} - 0.999$$

The gradient determined by the $P$ value was obtained by plotting a graph of the slopes acquired in the first set of scatterplots above versus the $P$ value. This was also a linear function which produced, for the seventh ring, the relationship:

$$\text{Gradient} = 0.016 - 0.017p$$

This whole exercise was repeated for each ring image (7–12) to produce the following equations:
The tilt angle recorded was the mean from the six rings. Equations (8) to (13) were confirmed using the mathematical model.

Measurements on Convex Conoidal Surfaces. Equations (8) to (13) were then applied to images acquired from nine plastic convex aspheric surfaces, used in a previous article, tilted at known angles. An additional problem encountered with actual measurements is that, when the surface is tilted, if the nasal part of the image is in focus, then the temporal image will be out of focus. Thus, the criteria for image capture cannot be achieved. The actual image captured in these circumstances was one where both the nasal and temporal images were simultaneously adjusted for best overall focus. Also the EyeSys accuracy deteriorates as the surfaces being measured become more aspheric. A final correction factor was applied to the tilt result to compensate for the difference between a theoretical and a measured result.

The nine plastic convex conoidal surfaces were used to assess the accuracy of the method when applied to the measurement of an EyeSys VK image. It was found that the bias in the error of the tilt angle was minimized by subtracting 0.4° from the mean of Eqs (8) to (13). In the case of the measured results, a correction factor is required because the accuracy of the VK varies with the asphericity of the surface being measured and it is not possible to have the entire ring image in focus with a tilted cornea.

It must be noted that a corneal meridian with a near circular section will need to be tilted through a considerable angle before any substantial asymmetry becomes apparent. This means that any small surface irregularities or deviation of the section from the assumed rotationally symmetrical...
FIGURE 6. A scatterplot of the difference in tilt (corneal tilt − approximate corneal tilt) versus the mean tilt ((corneal tilt + approximate corneal tilt)/2). The mean difference is −0.016°. This indicates the bias. The 95% confidence limits of the mean are from −0.525 to 0.556°. The SD of the difference is 1.187°.

Discussion

Figures 3 and 4 indicate that the measured tilts of the cornea and the contact lens are very similar. The mean corneal tilt for the group of 24 subjects was 3.3° and for the contact lens supported by the cornea was 2.8°. The spread of the values was greater for the contact lens than for the cornea. This was not entirely unexpected. It was stated in the Methods section that the contact lens was of a reasonably large diameter and was fitted steep to encourage good centration on the cornea. The subjects were nonwearers and in consequence tended to tear profusely. This made the contact lens mobile on the cornea, which contributed to some variability in the measurement that was not present when measuring the cornea alone. An investigation on a much larger number of subjects would help to ensure a representative mean because the variation in the contact lens position is likely to be a random variable that will tend to average out to zero as the number of measurements increases.

It must be noted that the analysis of the data assumed that the surfaces examined were rotationally symmetrical and conoidal in form. This is an appropriate assumption for the anterior surface of the contact lens. In the case of the anterior cornea it is possible that the surface is rotationally asymmetrical and this produces an appearance very similar to that produced by tilting a symmetrical surface. However, the results of this investigation indicate that the measured tilt of the contact lens, when supported by the cornea, is very similar to the measured tilt of the cornea itself. This agreement in the tilt angle suggests that if one surface (the contact lens) is rotation-
ally symmetrical then the other surface (the cornea) must be rotationally symmetrical also. This agreement in the tilt angle supports the notion that the apparent corneal asymmetry observed in the color coded maps of the cornea produced by the VK is mainly a result of the cornea being tilted in relation to the instrument optical axis when the subject looks at the instrument fixation target. The 0.4° difference in the tilt measured with and without the contact lens may possibly arise from an actual small asymmetry in the horizontal section of the cornea.

The tilt was of the order of 3° in the 24 subjects examined here. It will be useful to examine a greater number of subjects to determine the average tilt that may be used to set the position of an alternative fixation target at an appropriate angle to deal with the problem of corneal tilt.

Figures 5 and 6 indicate a reasonable agreement (within ±1°) between the tilt derived from two captured images and the approximate tilt derived from a single image in most cases. It must be noted, however, from Figure 6 that there are individual corneas in which the disagreement in the tilt angle is much larger.

The inability of the single captured image approach to deal with corneal meridians with \( P \) values greater than 0.9 is not considered to be a drawback because the presence of tilt in a circular section (\( P \) value = 1) has no effect on the ring images and will produce no asymmetry in the analyzed data.

The mean tilt for the second group of 24 subjects was 3.3° and that for the approximate tilt was 3.2°. The 95% confidence interval suggests that the approximate tilt will be within ±0.6° of the tilt derived from the capture of two VK images. A larger sample of subjects is needed to evaluate the usefulness of the approximate tilt approach, which requires only a single VK image. This study suggests that the derivation of the approximate tilt holds promise as a quick and convenient method for determining the appropriate position of the fixation target. This may be particularly useful for retrospective assessment of tilt in existing records, in which a single image is all that is required.

References