Location of the Major Corneal Reference Points

ROBERT B. MANDELL,* CHRISTINE SHIE CHIANG,† and STANLEY A. KLEIN‡
School of Optometry, University of California, Berkeley, California

ABSTRACT
Introduction. The two principal applications of corneal topography are those pertaining to corneal shape, such as contact lens posterior surface design, and those pertaining to corneal power, such as predicting power changes after refractive surgery. Corneal topography measurements for these applications have advantages when related to two major reference points, the corneal apex for shape and the corneal sighting center for power. Method. Simultaneous corneal power, toricity, and axis were measured by videokeratography in 20 right eyes using the standard instrument alignment and alignments at each of the 2 major reference points. Results. In comparing the central corneal measurements by videokeratography using the standard alignment to alignment at the corneal sighting center, there were minimal differences of less than 0.50 D for central power, toricity, and axis. In comparing the results for regular alignment to apex alignment there were significant differences for power (greater than 0.50 D) in 5 eyes, toricity in 3 eyes, and axis shifts of greater than 10° in 5 eyes. In comparing the results for the corneal sighting center to apex alignments there were significant differences for power in 4 eyes, toricity in 2 eyes, and axis in 5 eyes. Changes of greater than 1.00 D occurred in the corneal periphery. Conclusions. In comparing standard videokeratograph alignment to alignment at the corneal sighting center, there were statistically insignificant differences in videokeratography results for corneal power, toricity, and axis. Significantly larger differences were found in comparing standard alignment and alignment at the corneal apex, especially for measurements in the corneal periphery.

Key Words: videokeratography, videokeratoscopy, corneal apex, line of sight, corneal topography, corneal power, corneal sighting center, pupill, pupillary axis

designing the posterior surface of a contact lens to have a predetermined relation to the corneal front surface, we are concerned only with the corneal shape, which is a geometric problem. The selection of the contact lens power, however, is an optical problem with related but different considerations. Another example occurs in refractive surgery, where it is desired to produce a certain refractive change, a problem of corneal power, by making a certain geometric change in the cornea, a separate although related problem.

There are advantages to using two different major reference points for applications to corneal shape and power, the corneal apex for shape and the intersection of the line of sight with the corneal surface for power. The corneal apex is a highly useful reference point for describing the geometrical properties of the corneal shape. For example, the corneal apex may influence the riding position of a contact lens, which is a geometric problem that is independent of any optical considerations. An accurate measurement of the corneal toricity is also a shape problem, which requires an alignment with the videokeratograph with the corneal apex in order to avoid distortions of the keratoscope image, which can produce changes in both the power and axis of the toricity unless appropriate compensations are made in the instrument algorithm. Another example occurs in attempts to describe the corneal symmetry or asymmetry, which can be best be accomplished with respect to the corneal apex, again without consideration of the optical properties of the cornea. However, after the geometric properties of the cornea have been determined, it is then possible to apply the results to the calculation of the corneal optics.

The line of sight represents the principal axis for optical effects related to corneal and ocular refraction. It is defined by the chief ray of the bundle of light entering the eye and passing to the fovea. The intersection of the line of sight with the corneal surface (referred to here as the corneal sighting center) is the effective reference point for describing the optical properties of both the cornea and the entire ocular system. In addition, the pupillary axis plays an important secondary role as a reference for determining the direction of the line of sight. Another corneal reference point that has been used, the geometric...
centred, has the advantage of being a true anatomical landmark. However, it presents no advantages in describing either the shape or refractive properties of the cornea except in conjunction with one of the major reference points. For example, it may be of interest to know where the corneal apex lies with respect to the geometric centroid of the cornea but its relation to the corneal sighting center is usually of greater importance. A primary requirement for the corneal reference points is that they can be located accurately by practical clinical tests.

THE PUPILLARY AXIS

The pupillary axis is defined as the line from the center of the entrance pupil that is normal to the corneal surface, and hence passes through the center of curvature of the cornea (Fig 1). The entrance pupil is the image of the real pupil formed by the optics in front of it, consisting of the anterior chamber and cornea. ( Tears can be ignored here because their minimal thickness has negligible effect.) The pupillary axis is important because it represents an anatomical reference axis and also can serve as an optical reference axis. The pupillary axis can be used to reference the direction of the line of sight, which defines the primary axis for vision.

It is important that the position of the center of the entrance pupil remains relatively constant in order to achieve stability of the line of sight and the pupillary axis. It is known that small shifts of up to 0.5 mm occur in the position of the center of the entrance pupil with changes in pupil diameter induced either pharmacologically or by variations in illumination. However, for most practical ranges of illumination the shift is minimal and does not interfere with the use of the line of sight as the primary reference axis for vision.

LINE OF SIGHT

The bundle of light rays from the point of fixation that passes through the corneal surface and eventually reaches the retina is limited by the real pupil, serving as the aperture stop of the eye's optical system. If a light ray from the point of fixation is directed toward the center of the entrance pupil, it will be refracted by all the elements of the eye and strike the retina at the foveal position in a symmetrical eye, this is the chief ray or central ray about which the total ray bundle from the object point is dispersed, and determines the line of sight (Fig 1). The intersection of the line of sight with the anterior surface of the cornea is referred to as the corneal sighting center.

It is important to recognize that the line of sight accurately specifies only the beginning segment of the real light path that is refracted as it passes through the eye to the fovea, but is insufficient to locate where it intersects the corneal surface. The actual path of light within the eye is not needed.

Hence, the line of sight is the straight line segment from the fixation point to the center of the entrance pupil, E, and represents the beginning of the light path which, after refraction by all of the elements of the eye, reaches the fovea (Fig 1). The light path must strike the fovea because the subject is observing the fixation point.

Because the line of sight and the pupillary axis both pass through the center of the entrance pupil they form an angle that can be measured accurately in a real eye. This angle is known as angle lambda (Fig 1). Angle lambda must be distinguished from the more commonly used angle kappa, which is defined as the angle between the visual axis and the pupillary (or sometimes optic) axis. In a clinical setting it is angle lambda that is actually measured, even though it is commonly called angle kappa. It is important to distinguish the definitions of these angles clearly because their differences are clinically significant. Angle lambda generally has been measured in only the horizontal meridian, with average values reported varying from 1.4 to 9.8.

There are a number of other angles associated with the cornea, including angles alpha, kappa, and gamma. These have theoretical or experimental relevance but do not lend themselves to practical clinical measurements.

CORNEAL APEX

The corneal apex is defined as the point of greatest corneal curvature or shortest radius. If instead of a point, there is an area of greatest curvature, the apex will be represented by its
 centroid. This definition refers to the cornea in terms of its true shape only and is independent of the measuring method. In defining the apex we must use instantaneous radius of curvature (also known as tangential or true radius), which is intrinsic to the corneal shape. The normal to the apex defines the corneal primary axis with respect to shape.

ALIGNMENT OF VIDEokeratograph

Unfortunately, instruments that are used to measure corneal curvature, including keratometers and videokeratographs, are aligned on an axis that is not coincident with any intrinsic corneal point. The various commercial videokeratographs have alignment systems that may appear to differ but operate on exactly the same principle and align on nearly the same corneal point. A small but negligible variation occurs because of differences in the distance of the fixation point. However, all videokeratographs produce a corneal map that is centered with respect to whatever corneal point the optic axis of the videokeratograph is directed toward during a measurement.

In the standard method of videokeratography the optic axis of the instrument is aligned normal to the cornea at a point that is slightly displaced peripherally from the line of sight. This corneal position is sometimes called the vertex normal and is located at approximately twice angle lambda from the pupillary axis (Fig. 1, bottom). The corneal vertex normal must be distinguished from the corneal apex, as it actually relates to the corneal intersection of the optic axis of the videokeratograph, and not to any intrinsic corneal point. The position of the vertex normal varies in distance from the corneal sighting center for each eye. The relation between the videokeratograph optic axis and the position of the corneal apex is unknown for each patient unless measured.

METHODS

Measurements of corneal topography by videokeratography were made in the right eyes of 20 subjects (ages 24 to 40 years) using an EyeSys model 2 videokeratograph that was aligned first according to the regular method, second at the corneal sighting center, and third at the corneal apex. The measurements at the corneal sighting center and corneal apex were accomplished by having the subject view an eccentric fixation point on the videokeratograph target, after determining the correct position to place the fixation point for each eye. The fixation point consisted of a small luminous fluorescent dot on a wire that was held to the target face by double-sided tape. The wire was placed in a meridional direction so as not to interfere with the videokeratograph image processing.

The position of the fixation point for measurements at the corneal apex was determined as follows. For each subject a videokeratogram was taken using the regular alignment method. The corneal map was inspected and, if necessary, repeated until no central areas were missing; focusing was verified by noting the position of the reference crosses and the rings were well placed. The axis of corneal toxicity was determined from the computer display. The database for the steepest principal meridian was then examined to determine the position corresponding to the steepest instantaneous power, or the center of the region of steepest power. This provided the first estimate of the approximate position of the corneal apex. Using this position, we determined the angle and direction of the subject's eye rotation that would be needed in order to position the corneal apex so that it coincided with the optic axis of the videokeratograph. Another videokeratogram was then taken and the process repeated for two to five iterations until the corneal map appeared to have its greatest symmetry and maximum central power, indicating alignment with the apex. The distance of the apex from the line of sight was then calculated from the angle subtended by the fixation point at the center of curvature of the cornea. (This distance must be determined using the instantaneous radius values.)

The position of the fixation dot for the measurement at the corneal sighting center was determined by first measuring angle lambda, using an apparatus constructed for this purpose, and then calculating the location of the fixation point that would be needed to align the corneal sighting center with the optic axis of the videokeratograph. When aligned, the videokeratograph was normal to the cornea at the corneal sighting center, which fulfilled the basic

![Subject CS](image)

Figure 2. Reliability of 10 repeated videokeratographic measurements of a typical subject using regular fixation. SD is standard deviation.
alignment requisites for the instrument algorithm.

The reliability of the videokeratographic test method was determined on 5 subjects by repeating the test procedure 10 times.

The stability of the pupil position within the normal physiological range was measured in a second group of 20 subjects (some different from the first group) using a photographic slitlamp. A photograph was first taken with the slit beam at full illumination and directed parafoveally. A second photograph was taken with the slit beam turned off. The photographs were magnified 30X and the pupil position measured from the limbal border using a calibrated ruler.

Figure 3. Location of the major corneal reference points. Top: distance of the corneal sighting center from the videokeratograph optic axis. Center: distance of the apex from the videokeratograph optic axis. Bottom: distance of the apex from the corneal sighting center.

Figure 4. Relation between the central powers for the 3-mm chord-diameter measurement on the corneal maps for the corneal sighting center and apex, and the regular alignment positions.

RESULTS

Reliability of Test Method

Test reliability (repeatability) varied with the subject, the alignment position, and with the corneal position measured. Generally, it was found that the reliability, in terms of the standard deviation for 10 repeated measures, had the lowest variation at the intermediate ring positions, reaching a minimum value at ring numbers 6 to 10, where the standard deviation was ±0.02 to ±0.04 mm for 5 subjects. This placed the 95% confidence level for the worst case at 0.06 mm or approximately 0.50 D. The variation in repeated readings is somewhat greater for rings 1 and 2 and is greatest at the corneal periphery, where it may be twice as large (Fig. 2). Hence, for clinical purposes, a difference in two measurements was considered significant only if it exceeded 0.50 D for the central corneal readings (excluding rings 1 and 2) and 1.00 D for the peripheral corneal readings.

Location of Major Reference Points

The distance of the corneal sighting center from the videokeratograph optic axis (center of corneal map) for the right eyes of 20 subjects is shown in Fig. 3, top. The mean distance of the corneal sighting center from the map center was 0.38 mm (SD = 0.10). Fourteen of the 20 eyes had a corneal sighting center that was above the videokeratograph axis and 12 of the 20 eyes had a corneal sighting center that was temporal to the videokeratograph axis. The distance of the apex from the videokeratograph optic axis is shown in Fig. 3, center. The average distance of the apex from the map center was 0.62 mm (SD = 0.23). Fifteen of the 20 eyes had an apex that was below the videokeratograph axis. The position of the apex from the corneal sighting center axis is shown in Fig. 3, bottom. The mean distance from the corneal sighting center was 0.62 mm (SD = 0.57). Eighteen of the 20 eyes had an apex that was below the corneal sighting center.
Power at Major Reference Points

The central powers for the 3-mm chord-diameter measurements on the corneal maps for the corneal sighting center, apex, and regular alignment positions are shown in Fig. 4. The mean values were 43.55 D (SD = 1.36), 43.70 D (SD = 1.28), and 43.70 D (SD = 1.28), respectively. The powers at the apex and corneal sighting center alignments were not significantly different from those at the regular alignment position (paired t-test, p < 0.05).

The difference in mean central power in the flattest meridian between the corneal sighting center and regular alignments was 0.05 D (SD = 0.26), as shown in Fig. 5, top. There was not a detectable relation between the central power difference for the two alignment positions and the distance of the corneal sighting center from the corneal map center. The mean central power difference in the flattest meridian for the 3-mm chord-diameter measurement on the corneal map between the apex and regular alignments was 0.03 D (SD = 0.37) (Fig. 5, center). There was not a detectable relation between the central power difference for the two alignment positions and the distance of the apex from the corneal map center.

The mean central power difference in the flattest meridian for the 8-mm chord-diameter measurement on the corneal map between the corneal sighting center and apex alignments was 0.03 D (SD = 0.36) (Fig. 5, bottom). There was not a detectable relation between the central power difference for the two alignment positions and the distance of the apex from the corneal sighting center.

Peripheral corneal power readings for vision purposes are of interest only within the limits of the entrance pupil area and are determined with respect to the corneal sighting center as a reference. The peripheral corneal power differences between the regular and corneal sighting center alignments for the 3-mm chord-diameter zones are shown in Fig. 6 and were generally clinically insignificant when compared to the 3-mm zone.

**Figure 5.** Top: difference in mean central power in the flattest meridian between the corneal sighting center and regular alignments. Center: difference in mean central power in the flattest meridian between the apex and regular alignments. Bottom: difference in mean central power in the flattest meridian between the corneal sighting center and apex alignments.

**Figure 6.** Central power difference for the 3 and 5 mm chord-diameter zones.
Mean values for the 3-mm zone were 0.06 (SD 0.26) and 0.07 (SD 0.34) for the horizontal and vertical meridians, respectively. Mean values for the 5-mm zone were -0.08 (SD 0.23) and 0.07 (SD 0.26) for the horizontal and vertical meridians, respectively.

Peripheral corneal power readings for corneal shape purposes are of interest for the entire corneal periphery. The difference in the peripheral corneal powers for the regular and apex alignment positions was often much greater than the central difference and varied considerably for each subject. The individual variability was so high that group data were not considered relevant, as shown by four typical examples given to illustrate this variability (Fig. 7).

Toricity Difference at Major Reference Points

The mean corneal toricity (astigmatic) difference between the corneal sighting center and regular alignment positions was 0.02 D (SD = 0.33). There was no detectable relation between the corneal toricity difference for the two alignment positions and the amount of toricity for regular fixation (Fig. 8, top).

The mean corneal toricity (astigmatism) at the 3-mm chord-diameter measurement on the corneal map for the apex and regular alignment positions was 0.05 D (SD = 0.31) (Fig. 8, center). The mean toricity difference between the corneal sighting center and apex was 0.04 D (SD = 0.29) (Fig. 8, bottom). There was a slight trend toward a reduction of the toricity when the videokeratograph was aligned with the corneal apex.

Axis Shift

The mean axis shift at the 3-mm chord-diameter measurement on the corneal map between the corneal sighting center and regular alignment positions was 2.7° (SD = 7.1). The absolute shift (without regard to direction) was larger with a mean of 6.0° and SD of 5.9 (Fig. 9, top). The mean axis shift at the 3-mm chord-diameter measurement on the corneal map between the apex and regular alignment positions

![Figure 7. Examples of measurements in four meridians of four eyes, which illustrate the large variability of individual corneas.](image-url)
was 4.3° (SD = 13.5). The absolute shift (without regard to direction) was larger with a mean of 8.7° and SD of 11.0 (Fig. 9, center). The mean axial shift at the 3-mm chord-diameter measurement on the corneal map between the apex and corneal sightline center positions was 3.1° (SD = 9.8). The absolute shift (without regard to direction) was larger with a mean of 7.4 and SD of 6.7 (Fig. 9, bottom).

The results for all mean values are summarized in Table 1.

**Pupil Shift**

The mean pupil diameter was 5.1 mm dilated and 3.6 mm constricted. The mean shift in the center of the pupil for maximum to minimum luminance from the slitlamp was 0.01 mm (SD 0.02) nasally for the constricted pupil (Fig. 10).

**DISCUSSION**

The techniques described in this study for aligning a videokeratoscope with the corneal apex or corneal sightline center are laborious and not recommended as a clinical technique. It is anticipated that simpler methods of instrument alignment will be developed or that the videokeratoscraphs will be designed so as to transpose the
Table 1. Comparison of values measured at the major reference points.

<table>
<thead>
<tr>
<th></th>
<th>VK—CSC</th>
<th>VK—Apex</th>
<th>CSC—Apex</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance between points (mm)</td>
<td>0.38</td>
<td>0.62</td>
<td>0.62</td>
</tr>
<tr>
<td>Power difference (D)</td>
<td>0.05</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>Toricity difference (Δ K)</td>
<td>0.02</td>
<td>0.09</td>
<td>0.04</td>
</tr>
<tr>
<td>Axis shift (deg)</td>
<td>2.7</td>
<td>8.7</td>
<td>7.4</td>
</tr>
</tbody>
</table>

* VK, Intersection of the videokeratograph optic axis with cornea; CSC, corneal sighting center or intersection of line of sight with cornea; and Apex, corneal point of maximum curvature.

Figure 10. The shift in the center of the pupil for low to high illuminance.

results to a reference point based on either the line of sight or the apex. The results are important to the clinician in understanding the limitations of the instrumentation and the potential sources of error.

The ability to detect differences in corneal power and toricity for the three different alignment positions tested when measuring the central corneal shape is limited by the reliability of videokeratography, which has a 95% confidence limit of approximately 0.50 D. Hence, differences of less than 0.50 D may exist for the three alignment positions, which cannot be detected by present instrumentation. In the few eyes where differences exceeded 0.50 D, the results also may have been simply chance events.

The results for the corneal periphery are more definitive. Here the ability to detect differences in corneal power and toricity for the three different alignment positions is very large for some corneas and clearly significant.

While there are implications for videokeratographic measurements that are to be applied to both corneal shape and power, measurements for corneal power are only relevant to corneal areas intersected by light passing through the pupil and hence are limited to a diameter of less than 6 mm in most cases. Using the criterion of 0.50 D, there is no detectable difference between measurements at any of the three alignment positions. Measurements that are applied to corneal shape, however, will include the entire cornea. Measurements at the corneal periphery will certainly be affected by the alignment position.

The position of the corneal apex was below the corneal map center in 15 of 20 eyes and below the line of sight in 18 of 20 eyes. The mean difference was 0.82 mm, which is clinically significant. This has important implications for contact lens fitting because it has been suggested that the position of a rigid contact lens can be influenced by the position of the corneal apex.20-22

The basic principles described in this report would apply to videokeratographs produced by other manufacturers. The major difference in the various videokeratographs that might affect these results is the distance of the fixation target. It has been shown that this effect is negligible.17

In only one eye was the pupil shift from a maximum to minimum light stimulus significant. Hence, for normal physiological conditions the shift in position of the center of the pupil is less than 0.2 mm and probably not a factor in locating the line of sight with consistency under approximately the same lighting level. This does not exclude the need for an awareness of a possible pupil shift for some patients during extremes of illumination. Even with a pupil shift, however, it does not nullify the use of the pupil center as a reference point, but rather presents a new set of optical conditions. For purposes of refractive surgery the goal is to center the ablated or modified corneal area over the entrance pupil so that the limits of the modified zone include the entire effective light bundle that enters the pupillary area in order to avoid light flare. Hence, the line of sight should be determined under conditions of low illumination and maximum pupil physiological dilatation. A corneal ablation zone determined under these conditions would have the minimum diameter that would avoid flare and would likely cover any smaller pupil, even allowing for a maximum shift of the pupillary center.

The intersection of the line of sight and the corneal surface has been designated the corneal sighting center.19 This term is necessary because a distinction must be made between corneal measurements that are made along an axis that is normal to the cornea and measurements along the line of sight, which is usually not normal to the cornea. Although both measurements are centered with respect to the corneal sighting center, it is anticipated that significant power differences may occur in the corneal periphery even though they may be negligible for the central cornea. These measurements are yet to be obtained.

If a videokeratograph is not aligned with the corneal apex, it will be tilted and/or decentered with respect to the primary corneal axis, giving rise to irregular distortions of the corneal map, which are interpreted as an asymmetric bow tie shape.23 Therefore, corneas that appear to have asymmetric toricity (astigmatism) based on an...
asymmetric bow tie corneal map, are often simply artifacts resulting from a condition of misalignment of the videokeratograph from the corneal apex and the algorithm used for the calculation of the corneal power.23

REFERENCES

AUTHOR'S ADDRESS:
Robert B. Mandell
School of Optometry
University of California
Berkeley, California 94720-2020