Wide angle cornea-sclera (ocular) topography

Stanley A. Klein, John Corzine, School of Optometry, University of California, Berkeley

Jacob Corbin, Sheldon Wechsler, Thom Carney, Neurometrics Institute, Berkeley, CA

ABSTRACT

Most corneal topographers are slope-based instruments, measuring corneal slope based on light reflected by the cornea acting as a mirror. This mirror method limits corneal coverage to about 9 mm diameter. Both refractive surgery and contact lens fitting actually require a larger coverage than is obtainable using slope-based instruments. Height-based instruments should be able to measure a cornea/sclera area that is twice the size (four times the area) of slope-based topographers with an accuracy of a few microns. We have been testing a prototype of a new model height-based topographer manufactured by Euclid Systems. We find that single shots can produce a corneal coverage of up to 16 mm vertical and 20 mm horizontal. The heights and slopes in the corneal region have good replicability. Although the scleral region is noisier, it is the only topographer available able to measure scleral topography that is critically important to contact lens fitting. There are a number of improvements to the Euclid software and hardware that would enable it to fill an important niche in eye care and eye research.

1. THE NEED FOR WIDE ANGLE OCULAR TOPOGRAPHY

During the period from 1992 to 1999 corneal topography became a major focus for cornea researchers and instrument makers. There were numerous new instruments and journal articles on corneal topography. There were two principal reasons for the interest in corneal shape: screening candidates for refractive surgery and fitting contact lenses. However, the enthusiasm for corneal topography has subsided and many of the corneal topography instrument makers are now out of business. We will argue that an important reason for the decline of interest is that most of the topographers available in the past did not have a sufficiently large coverage to be adequate for the task. Ocular topography that includes the peripheral cornea and sclera is needed rather than topography limited to central cornea.

1.1 Refractive surgery.

Refractive surgery blossomed in the past decade and was closely connected with the development of corneal topography. There are several uses of corneal topography for refractive surgery, including:

(i) The topographic map with computerized analysis reveals any distortions of the cornea, such as keratoconus or corneal scarring. Although wide angle coverage isn't essential for detecting anomalies problematic for refractive surgery, this use is limited for future sales of topographers because refractive surgery centers already have their corneal topographers.

(ii) Corneal topography has been used to guide the refractive surgery ablation pattern[1], but Shack-Hartmann instruments are now replacing corneal topographers for this purpose since they measure the full aberrations of the eye.

(iii) The preoperative peripheral corneal shape may influence the dioptric outcome of the surgery. It is plausible that the shape of the peripheral cornea near the limbus gives an indication of corneal collagen structure and this structure may be important to how the stromal shape is readjusted following refractive surgery. Past topographers had insufficient corneal coverage to be fully useful for this task. Mandell et al.[2] showed that there is a large variation in preoperative peripheral corneal shape. The mild corneal flattening from the apex peripherally over the central 8 mm is relatively similar across the population. The peripheral cornea, on the other hand, shows dramatic differences. Mandell, et al.[2] measured peripheral cornea by using Placido based topographers with the subjects shifting their gaze away from primary position. Some subjects showed extremely low curvatures near the limbus. (see Figure 8 for an example of a subject with negative limbal curvature) while the curvatures of other subjects never went below +20 D.

Ophthalmic Technologies XII, Fabrice Manns, Per G. Soderberg, Arthur Ho, Editors, Proceedings of SPIE Vol. 4611 (2002) ©2002 SPIE • 1605-7422/02/$15.00

(iv) Another need for wide coverage corneal topography is related to hyperopic ablation. Myopes need to have their cornea flattened by removing tissue from the corneal center. Hyperopes, on the other hand need their corneas steepened by removing tissue from the corneal periphery. To get a smooth ablation profile, hyperopic ablation needs to have a wider diameter than myopic ablation. Further details on the corneal shape following hyperopic ablation are considered in Section 2.1 (see Figure 1) discussing limitations of Placido topographers. Wide coverage topography is needed for hyperopic ablation in order to build up knowledge of the healing process in order to improve the ablation profile.

1.2 Contact lens fitting

The big hope of corneal topographer manufacturers was that most eye care providers who fit contact lenses (optometrists, ophthalmologists, opticians) would purchase a corneal topographer. Between 1992 and 1999 contact lens trade journals were filled with articles[3,4,5] and advertisements showing the wonders of topographers in reducing the trial and error aspect of contact lens fitting. Although most soft lens wearers are not difficult to fit, there are a substantial number that are difficult and these are the individuals that take up much of the time of the contact lens specialist. Difficult to fit patients are increasing now that toric soft lenses are more common. All topographers had fancy contact lens software modules that were advertised as reducing the time needed for fitting lenses. The problem was that the software wasn't that great. A decent clinician could do a better job[6]. It isn't surprising that the contact lens software had limited success. The motion, centration and stability of rigid lenses depend on peripheral corneal shape and for soft lenses they depend on limbal and scleral shape as well as on peripheral corneal shape[7,8].

We anticipate that the next few years will see a dramatic increase of interest in ocular (cornea, limbus and sclera) topography rather than corneal topography. The new interest will be generated by problems with the new silicone hydrogel extended wear contact lenses. These new lenses have sufficiently high oxygen transmission so that corneal health is much better than with previous extended wear lenses. Extended wear lenses are extremely important to the eye care industry because the idea of leaving the lens in the eye for a month appeals to many individuals. These new lenses appear to be powerful competition to refractive surgery. There are, however, three problems with these lenses: (a) On some individuals the lenses do not have sufficient motion to generate the tear exchange needed to clean out the debris that collects under the lens. (b) In the future, toric designs and custom aberration correcting extended wear designs will be available. These lenses, especially those correcting aberrations, will require greater rotational stability than past lenses. The eyelid action during blinks causes the contact lens to rotate and shift position. The shape of cornea, limbus and sclera provide the restoring forces needed for lens stability, (c) We believe that a spike of high contact pressure in the corneal periphery[9] is responsible for the corneal abrasions that have been reported for a substantial fraction of soft contact lens wearers. Our colleague. Henry Tran, has been doing finite element calculations of soft lenses on eyes. He found that the lens causes a spike of high contact pressure on the cornea about 1.5 mm in from the limbus. This is just inside of the point where there is a gap between the lens and the eye. Tran finds that the magnitude of the pressure spike depends on ocular shape and on the contact lens flexibility. We believe that this spike of high contact pressure is likely to be the etiological factor for the corneal abrasions (superior epithelial arcuate lesions or SEALS) frequently reported by eye care practitioners who prescribe silicone hydrogel lenses. The lesions are in the position on the cornea where the spike in contact pressure is found in our finite element modeling. We believe that knowledge of the topography of peripheral cornea and sclera will be important for choosing a lens design for a given ocular shape that can reduce the likelihood of abrasion or for screening candidates susceptible to abrasion.

2. PROBLEMS WITH PREVIOUS TOPOGRAPHERS

2.1 Slope (Placido) topographers

Slope based topographers, presently the most common design, treat the eye as a mirror. Typically a concentric set of rings (called Placido rings) is flashed and the reflected image is captured. Because of their use of Placido ring targets, these topographers are often called Placido instruments. The location of the reflected image is very sensitive to the corneal slope and has a minor sensitivity to corneal height. The main advantage of Placido topographers is their high accuracy in measuring corneal slope, as will be discussed in Section 2.3. The main drawback of these topographers is their limited corneal coverage. Consider a point 4 mm from the axis of a cornea with an 8 mm radius, corresponding to a corneal normal that makes an angle of 30 deg relative to the optic axis. Light enters the camera fairly parallel to the optic axis so the Placido ring that is visible at the point 4 mm from the axis is the ring at 60 deg from the optic axis, based on the property of mirrors that the reflected angle equals the incident angle. It is difficult for Placido rings at angles larger than 60 deg to be seen since they are typically occluded by the nose, eye brows and eye lashes.

In the past the exquisite slope information was needed for estimating the refractive aberrations of the eye. This is no longer much of an advantage since instruments such as Shack-Hartmann devices measuring the full aberrations of the eye are now commercially available. The need for accurate corneal slope measurements has diminished.

Placido instruments are not ideal for measuring corneal height because to calculate height one must integrate slope[10]. Slight errors in slope estimation can be cumulative in producing height errors. In addition, the standard height reconstruction algorithm used by Placido ring topographers introduces a skew ray error because it is incorrectly assumed that the corneal normal lies in the meridional plane[11]. Although one can compensate for this error[12] this is not typically done. These errors in corneal height are important because we anticipate the main future uses of corneal topography to be in contact lens fitting and refractive surgery improvement where it is height, not slope or curvature, that is important.

In order to provide greater insight into the operation of slope-based topographers it is useful to examine the extreme case of the image of a hypothetical hyperopic ablation as seen by a Placido topographer. The shape we choose to investigate is the hyperopic test shape recommended by the recent American National Standards Institute (ANSI) standards. One of our motivations for discussing this shape is to alert interested parties about the existence of these recently developed standards. Further details of the ANSI standard are given by Klein[13].

The ANSI standard specifies several shapes, including spheres and ellipsoids, so that the accuracy of the instruments could be quantified. The most challenging of the proposed shapes was that of a hyperopic ablation. The shape consisted of an inner and outer sphere with radii of curvatures of 7.34 and 8.04 mm. The hyperopic ablation makes the inner curvature steeper than the outer curvature. The inner sphere has a 6 mm diameter, and the outer sphere begins at a 9 mm diameter. Between the two spheres is a transition zone consisting of two toric shapes. The inner torus has a radius of curvature of -5.51 mm in the radial direction and the outer torus has a radius of +5.51 mm. The transition between the two tori occurs at a diameter of 6.667 mm. We also consider a second hyperopic ablation (not in the ANSI standard) in which the transition zone is flat with an infinite radius of curvature. Both shapes are designed to have continuous height and slope. There will be discontinuities in curvature at the transition points. The details of the two shapes are listed in the following table.

Name	inner diameter	outer diameter	inner radius of curvature	transition radius of curvature	outer radius of curvature
hyperopic PRK1	6	9	7.34	-5.51,+5.51	8.04 (fix central height)
hyperopic PRK2	6	6.61	7.34	infinite	8.04 (float central height)

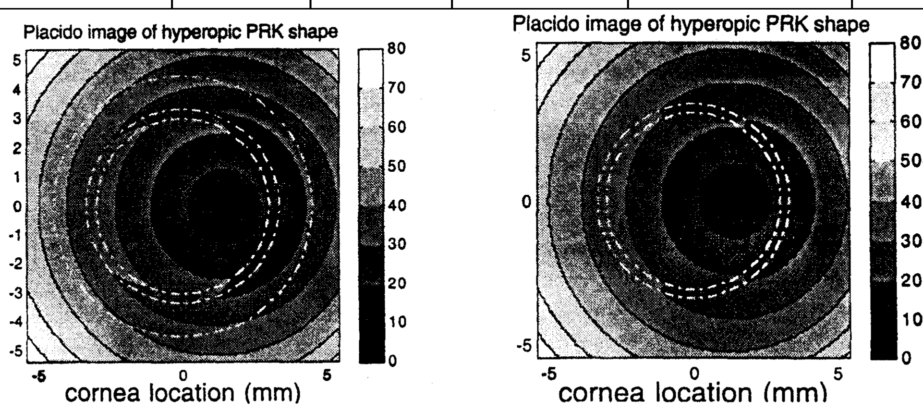

Fig. 1 Placido image for two axially symmetric hyperopic ablation test shapes with a rotated corneal topographer.

The two panels in Fig. 1 show the Placido image rings for the two hyperopic ablated shapes. For ease of reading the plot we have selected contour lines every 10 deg of corneal slant (the Placido target rings are at twice the indicated angle). To make the images more interesting the corneal topographer (CT) has been rotated 0.2 radians to the right while leaving the shapes unrelated. The transition zones are indicated by the dot-dashed white circles. The symmetry axis of the shapes is the center of the white circles. The CT axis is at the center of the inner and outer contours.

The plots were produced by the standard Matlab function 'contourf(angle)' where 'angle' is the angle the corneal normal makes with the CT axis:

$$\text{angle} = \text{acos}(\cos(.2)\cos(sl) - \sin(.2)\sin(sl)\cos(phi)) \quad (1)$$

where 0.2 and 'sl' are the CT axis tilt and the corneal slope with respect to the corneal symmetry axis (the plot axis), and phi = atan2(x,y) is the azimuthal angle of the corneal point at location x, y. The simplicity of Eq. 1 is based on the assumption that the corneal radius of curvature is small compared to the distance from the cornea to the Placido rings and from the cornea to the camera.

Present Placido CT algorithms would fail for the ANSI hyperopic shape. For the tilted shape shown in Fig. la present algorithms fail at the early step of tracing the jagged rings because in the region of negative curvature the Placido ring lines have opposite slope. The algorithms would also have trouble with specifying ring radius as a function of angle since there are regions where the function is triple valued (rather than single valued). Even if that shape weren't tilted the algorithms will have problems since the rings in the negative curvature zone will be triplicates of the rings in the central zone. Height topographers, to be discussed next, would not have problems measuring shapes with negative curvature. A less extreme shape is that shown in Fig. Ib where (bottom row of Table 1) the transition zone has zero curvature. It produces the Placido image shown in Fig. Ib. Since there are no negative curvatures, the ring locations as a function of angle are single valued (except at a few discrete points). The outer transition diameter is calculated by $r_{outer}*d_{inner}/r_{inner}= 8.04*6/7.34 = 6.61$ mm. The center of the outer sphere must be shifted along the symmetry axis for continuity. In the ANSI shape (row 1 of the Table) the center of the outer zone was fixed at a distance of 8.04 mm from the vertex as would be expected of a minimal ablation. A side benefit of the second test shape (row 2 of the Table) is that the flattening to zero curvature is quite similar to the rapid flattening of normal corneas near the limbus.

2.2 Height topographers

Height topographers measure corneal height directly. These instruments work on the slit lamp principle whereby a slit of light is projected on the eye from an offset light source. The light that is scattered from the eye is then photographed by a central camera. Suppose the slit of light is coming in at a 45 deg angle with respect to the optic axis. Then if the intersection of the light with the cornea is displaced a distance *d* (compared to a cornea with zero curvature) the corneal depth is a distance *d* below the plane of the corneal vertex where the displacement is zero. These instruments have the advantage that height is measured directly, so there is no cumulative error of the sort found in slope-based topographers. The Orbscan height-based topographer has the additional advantage that corneal thickness can be measured since the scattered light comes from the full corneal thickness. Refractive surgeons are pleased with corneal thickness maps, even though ultrasound measurements of thickness may be adequate for refractive surgery purposes.

The Orbscan topographer uses a moving slit to obtain coverage across the cornea. The slit moves relatively slowly, so eye movements introduce noise into the data. An additional problem is that since scattered light from the full corneal thickness measured it hasn't been possible to measure the limbal or scleral region since the scattered light is too strong and the camera is driven to saturation.

The Euclid topographer is based on a similar principle; however, rather than using a moving slit, a multiplicity of about 40 slits are projected onto the cornea simultaneously. Fluorescein is instilled in the eye so that rather than looking at a thick band of light coming from the full corneal thickness, the scattered light comes from the corneal surface. The advantage of this instrument is that it is possible to measure the full cornea, limbus and near sclera in a single shot. The disadvantage is that the latest model of the instrument is not yet commercially distributed. We have been using a prototype of the latest model of the Euclid topographer and will discuss some of its properties in Section 3 of this paper. In Section 4 we discuss possible future improvements that may be useful.

2.3 Accuracy of slope and height instruments

In calculating the ideal, best case accuracy of corneal topographers we will assume that the topographer covers the full 20 mm eye and that there are 1000 pixels across the CCD camera. Therefore each pixel covers 20 microns of the eye. We further assume that a subpixel edge finder gives about 1/10 pixel precision, or 2 microns. For a height topographer where the angle between projector and camera is 30 deg, a 2 micron lateral shift corresponds to a 2/tan(30) = 3.5 micron depth. Thus we expect that the optimal height accuracy of the Euclid topographer is about 3-4 microns. This accuracy is sufficient for contact lens fitting.

For Placido instruments the angle, 9, that the corneal normal makes with the CT axis is given by:

$$\sin(\Theta) = y/r \qquad (2)$$

where y is the axial distance of the corneal point and r is the corneal radius of curvature. Since the measurable increment in y is about 2 microns and since r is about 8 mm, the derivative of Eq. 2 shows a measurable increment in 9 to be:

$$\Delta\theta\cos(\theta) = \Delta y/r = 2/8000. \qquad (3)$$

Thus $\Delta\theta$is slightly less than 1 minute of arc. This seems like a remarkably small value, but it is precisely the accuracy needed for accurate corneal measurements relevant to the refractive aberrations of the eye. A similar calculation is relevant to the required accuracy of Shack-Hartmann devices.

3. PRELIMINARY RESULTS USING EUCLID TOPOGRAPHER

3.1 Output from Euclid

Figure 2 shows the raw image produced by the Euclid topographer. The upper panel shows an array of slits projected from the right onto the subject's left eye. The eye has been instilled with a small amount of fluorescein. The curvature of the lines indicates the curvature of the cornea. The bottom panel is a height profile along the horizontal meridian. Note that this shot has a horizontal coverage of 17 mm, about twice that of Placido instruments. In the vertical direction the coverage is limited by the eyelids. Notice that very close to the eyelids the slit reflections abruptly change slope. This is because of the tear meniscus near the lids. The meniscus region gives illusory estimates of corneal height, so the data very close to the eyelids needs to be removed from the analysis. Section 4 discusses methods that we will use to gain extended coverage in the vertical direction.

Another item to look at in the raw image is that on the sclera the image quality is degraded. The background is quite light and mottled, possibly due to roughness of the conjunctival tissue. The non-uniform scleral region produces errors in accurate localization of each projected line. There is also a possibility of bias in the limbal region where the intensity increases due to a greater amount of fluorescein. These topics will be discussed in Section 4.

Figure 3 shows the height map produced by the Euclid software. In order to accurately show the nuances of ocular height, the best fitting sphere is subtracted off. The precision of this single shot can be estimated by examining the smoothness of the contour lines that are separated by 12.5 microns. The smooth contours in the central region where the height is fairly flat indicate that the precision is quite good. The bright white band at around a 10 mm diameter is an artifact of the color-map being displayed in black and white. The white band represents yellow, the central and outer regions are shades of green and red in the original Euclid display. The lower panel of Figure 3 shows the height along a horizontal meridian. It is seen that outside a 4 mm radius the corneal curvature begins to flatten

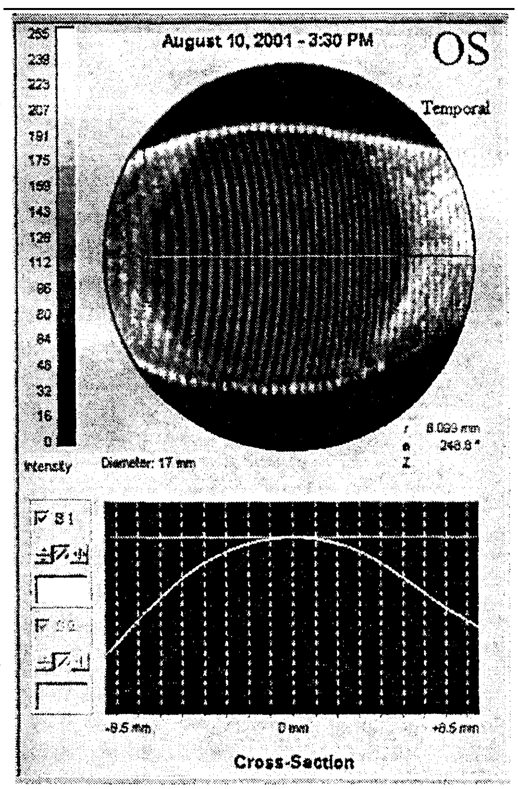

Figure 2

rapidly. Within the central region a sphere is a good approximation to the shape. The dramatic flattening is of critical importance to the centration, motion and stability of contact lenses.

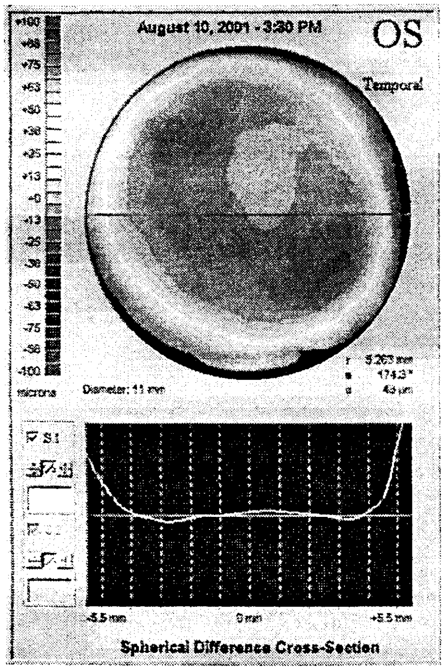

Figure 3

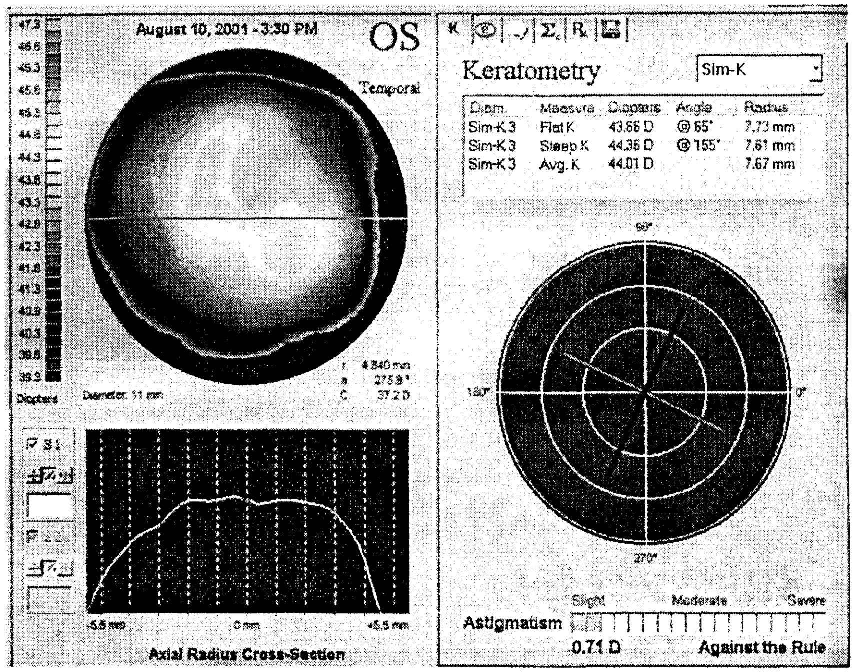

Figure 4

The left panel of Figure 4 shows the axial curvature for the same eye as shown in Figs. 2 and 3. Axial curvature is based on the slope of the cornea[14]. It is the quantity that is directly measured in Placido topographers. Height topographers must calculate axial power by taking the gradient of the height map. Since the gradient is based on taking differences, it is expected to be somewhat noisier than what is obtained with Placido topographers. One can judge the precision of the algorithm for the single shot by looking at the raggedness of the contour lines. The contour lines are separated by 0.25 D. Since the contours are quite smooth it is seen that the algorithm does a good job of presenting smooth data. The coherent features of the axial curvature map also indicate that excessive smoothing is not being done. One of the questions that we explored (see Figure 6) was the replicability of corneal slope across multiple shots.

The right panel of Figure 4 provides a summary of the left panel in language familiar to the contact lens fitter. The maximum and minimum curvatures in the central 3 mm (Sim-K) are calculated. The maximum curvature (steep meridian) is found to be 44.36 D at the 155 deg meridian. The minimum curvature (flat meridian) is found to be 43.66 D at the 65 deg meridian giving a central corneal toricity of 0.70 D. The Euclid software is thus adequate for the conventional uses of corneal topography.

3.2 Processing the Euclid raw data

The Euclid topographer is able to export the raw height data from each shot. We developed Matlab software to process the raw height data and display it in different ways. We were especially interested in estimating the extent of coverage of the Euclid topographer and its test-retest reliability when minimal smoothing of the raw data is done.

Figure 5 shows the height map of a single shot of an individual who is able to open his eyes widely. The coverage of the topographer, 20 mm horizontal and 16 mm vertical is impressive. The dark circle drawn on the picture has a diameter of 14 mm to indicate the size of a typical soft contact lens. Notice that near the top and bottom of the picture the contour lines are no longer circular. The contours bend outward because of the tear meniscus near the eyelids. The meniscus produces a sharp increase in the height of the measured surface. The meniscus was also seen in Figure 2 on the raw image for a different eye where the eyelids are not as separated as in Fig. 5. Figure 5 shows the potential of height instruments for obtaining a large corneal coverage.

Contact lens motion tends to be vertical because of the action of the opening and closing eyelids. In order to predict contact lens motion we will need more information about the topography in the vertical direction. One method for extending the ocular coverage is to take multiple shots with subjects directing their gaze in different directions. A second method based on extrapolating information from a single shot will be mentioned in Section 4.

Figure 6 shows the horizontal meridian of 10 shots that were taken with each of three gaze directions: nasal, primary and temporal gaze. The gaze shift was about ±15 deg corresponding to ±2 mm for a cornea with an 8 mm radius. Five rows (200 microns) of data were averaged. No averaging was done horizontally. Several items are worth noting in the figure. First, in the central 10 mm of the primary and temporal gaze shots the repeatability of the height was excellent. The repeatability for the nasal gaze was good except for a region around -3 mm where about half the shots showed a little upward bump and half showed a downward bump. This feature will be clearer in Figure 7 showing the slope. It is apparent that the quality of the picture in the central region of the cornea is much better than the quality in the limbal and scleral regions. This will be discussed in Section 4. The temporal gaze shot didn't enlarge the coverage because of the poor quality of the scleral region. The nasal gaze showed consistency in the temporal scleral region enabling us to estimate scleral curvature.

Figure 7 presents the slope of curves in Figure 6. The left side of the figure corresponds to the region of Figure 6 where the height is increasing, so the slopes are positive. The top and lower group of curves representing temporal and nasal gaze have been offset from the primary gaze lines for ease of viewing, just as in Figure 6. The ten shots of primary gaze data have excellent replicability. It should be emphasized that no smoothing was done in generating this plot. The nasal gaze shots show a little variability at -3 mm, as discussed in connection with Figure 6. Further study is needed to understand the origin of this noise. We are especially interested in the righthand region of the nasal gaze set of shots since this is the limbal and scleral region. Even though the scleral region is noisy, we are able to estimate the scleral curvature.

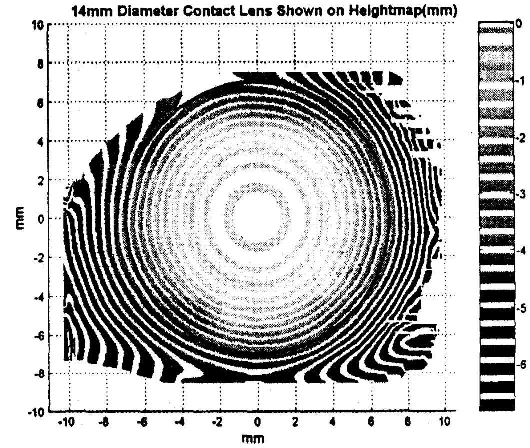

Figure 5

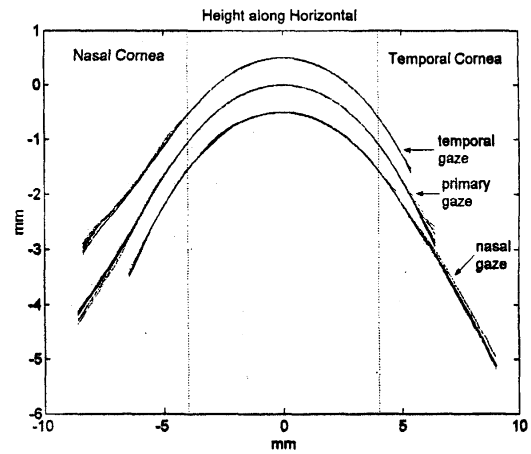

Figure 6

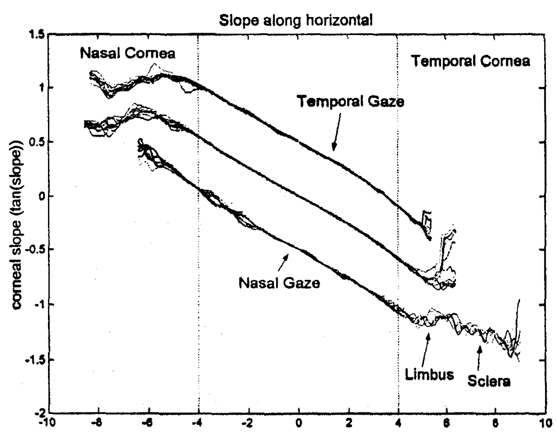

Figure 7

Figure 8 is the curvature obtained from Figure 7 according to the formula

$$\text{Curvature} = 337.5\ ds/dx\ (1+s^2)^{-3/2}$$

where s is slope from Figure 7 and x is corneal position in mm. Some smoothing was done for this plot because of the noise in the temporal and nasal gaze shots. This picture is remarkable because it may be the first picture showing scleral curvature taken with an ocular topography instrument. Figures 7 and 8 show that this eye has a limbal region with a negative curvature. The scleral curvature is around 20 D corresponding to a 17 mm radius of curvature, a reasonable value. Not all eyes have negative limbal curvature. As was discussed in Section 1 the limbal and near scleral regions are regions that control soft lens stability. The large variability of curvature in this region is a major factor for why we think expanded range topographers such as the Euclid instrument are needed.

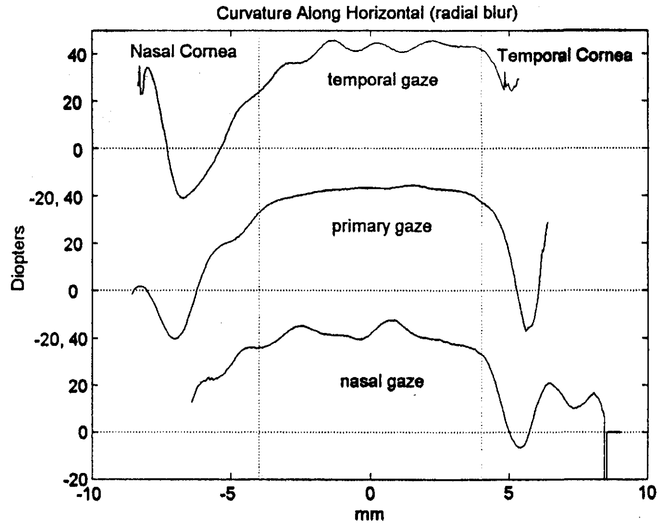

Figure 8

4. FUTURE WORK

Three years ago it seemed clear to us that slope-based corneal topographers are the topographers of choice. Their high accuracy allows one to predict slopes accurate to minutes of arc, thereby allowing accurate estimation of the contribution of the cornea to refractive aberrations. Times have changed. The availability of commercial wavefront analyzers such as those based on the Shack-Hartmann method has lessened the need for knowing corneal slope accurately. We believe that for contact lens fitting and for improved refractive surgery planning, wide coverage, height-based topographers are the topographers of the future. We have been working with a prototype Euclid topographer and it shows good promise. In this section we discuss a number of improvements we plan to make to the instrument. Some of these improvements will be done in collaboration with Euclid Systems Corporation.

4.1 Improve scleral topography-Use available CCD bits

We found that often the scleral region loses information because the image is saturated. This can be seen in Figure 2 showing the raw Euclid image with portions of the scleral region washed out. One way to improve the quality of the signal is to make full use of the Euclid hardware. The Euclid CCD camera presently puts out 10 bits of data per pixel in the original image. The present software only makes use of 8 bits. It should be fairly straightforward to modify the software to adjust the camera gain and make use of the extra two bits.

4.2 Improved filter to enhance fluorescein.

An additional method to enhance the scleral signal contrast is to use colored filters to enhance the fluorescent signal. A filter on the projector that passes short, but not long, wavelength light, and a filter on the camera that does the reverse, should improve the contrast of the slit pattern. We may also need to increase the gain of the camera.

4.3 Improved algorithm for calculating height from raw image

Presently the Euclid instrument uses a Fourier method for calculating the phase shift of the image and from the phase shift it calculates height. We are working on algorithms where the identity of each slit in the raw image is tracked across the image and then the position is used to calculate height[15]. This should increase the accuracy of height estimation.

4.4 Averaging and splicing multiple shots

Averaging multiple shots will reduce the noise. We need to determine the correlation of noise across shots to be able to estimate how many repeated shots are useful. In addition we will continue our research on splicing multiple shots. As shown in Figure 5, the primary gaze shot provides adequate horizontal coverage. However, in the vertical direction it may be necessary to take additional shots with gaze up and gaze down. Alternatively, the primary gaze shot might not be needed and the splicing of gaze up and gaze down shots might be fully adequate for giving a large picture of ocular topography.

4.5 Use horizontal sclera to estimate vertical sclera

Figure 2 shows that the horizontal coverage is wider than the vertical coverage. We plan to carry out studies to determine whether we can adequately predict scleral shape in the vertical direction from that in the horizontal direction. Our past studies have shown that there is a large variability across subjects of curvature in the limbal region. We plan to study within-individual variability in scleral shape. We suspect that there is enough information in the ocular region shown in Figure 2 to be able to do an adequate job of predicting scleral height in the vertical direction. The information gained from the single primary shot is so much more than that available from previous topographers, that it may be fully sufficient for contact lens fitting purposes.

4.6 Determining cause of scleral noise.

One of our short-term goals is to explore the various possibilities that could be the cause of the ragged scleral topography. A contributing factor to the noisy scleral topography is that the conjunctival tissue comprising the scleral surface is highly unstable. It is like very loose skin that keeps moving around in response to blinks. Another possibility is the image degradation discussed in items 4.1 and 4.2. Before extended topography is fully useful we need to determine the cause of the scleral inconsistency. If it turns out the non-repeatable height measurements are due to the loose conjunctival tissue, then we will explore using a very thin large diameter, low Young's modulus contact lens impregnated with fluorescein as a covering for the ocular surface. The thin lens will drape over the eye and allow us to estimate the true corneal surface. The soft lens will not drape perfectly in the limbal region of negative curvature. This is not a problem because the thicker, stiffer actual contact lens will drape even less perfectly. Our research using finite element analysis will be useful for learning how to use knowledge of the topography of the thin, draping lens to calculate the ocular topography that is relevant to fitting of commercial soft lenses.

ACKNOWLEDGMENTS

This research was supported by grant R43 EY 012924-01 from NIH.

REFERENCES

1 G. Alessio, F. Boscia, M.G. La Tegola and C. Sborgia, "Topography-driven photorefractive keratectomy," *Ophthalmology,* **107,** pp. 1578-1587, 2000.

2. R.B. Mandell, J.C. Corzine and S.A. Klein, "Peripheral corneal topography and the limbus", *Investigative Ophthalmology & Visual Science* **39** (suppl),S1036, 1998.

3. N. Maeda and S.D. Klyce, "Videokeratography in contact lens practice," *International Contact Lens Clinic,* **21,** pp. 163-169, 1994.

4. L.B.Szczotka, "Corneal topography for residual astigmatism prediction in computer-assisted rigid contact lens fitting," *International Contact Lens Clinic,* **21,** pp. 175-179, 1994.

5. J.Pole and G.E.Lowther, "Comparison of simulated K's measured by computerized videokeratographers to keratometer measurements," *International Contact Lens Clinic,* **21,** pp. 180-184,1994.

6. S.F.Lester, M.G.Harris, S.Keller and D.Larsen, "Clinical applications of corneal topography," *International Contact Lens Clinic, **21,*** pp. 170-174,1994.

7. P.J.Caroline, M.P.Andre and C.W.Norman, "Corneal topography and computerized contact lens-fitting modules," *International Contact Lens Clinic,* **21,** pp. 185-195, 1994.

8. T. Reddy, L. Szczotka and C. Roberts, "Peripheral corneal contour measured by topography influences soft toric contact lens fitting success. *Journal of the Contact Lens Association of Ophthalmologists.* **26,** pp. 180-185, 2000.

9. GM.T. Funkenbusch and R.C. Benson, "The conformity of a soft contact lens on the eye," *Journal of Biomechanical Engineering,* **118,** pp. 341-348, 1996.

10. S.A.Klein and R.B.Mandell, "Shape and refractive powers in corneal topography," *Investigative Ophthalmology,* **36,** pp. 2096 - 2109, 1995.

11. S.A.Klein, "Axial curvature and the skew ray error in corneal topography," *Optometry and Vision Science,* 74, pp. 931-944,1997.

12. S.A.Klein, "Corneal topography reconstruction algorithm that avoids the skew ray ambiguity and the skew ray error," *Optometry and Vision Science,* 74, pp. 945-962, 1997.

13. S.A. Klein, "Corneal topography: A review, new ANSI standards and problems to solve," OSA *Trends in Optics and Photonics* 35. *Vision Science and its Applications,* Vasudevan Lakshminarayanan, ed (Optical Society of America, Washington DC), pp. 174-177, 2000.

14. S.A.Klein and R.B.Mandell, "Axial power and instantaneous power in corneal topography," *Investigative Ophthalmology,* **36,** pp. 2155 - 2159, 1995.

15. S. Dastmalchi and T. Carney, "Tracking irregular peripheral image rings in videokeratography," *Proceedings of the SPIE* "Biomedical Diagnostic, Guidance, and Surgical-Assist Systems II" Ed. Vo-Dinh, T., Grundfest, W.S. and Benaron, D. A., **3911,** pp. 314-321, 2000.