Methods of Analysis of Corneal Topography

STEPHEN D. KLYCE, PhD and STEVEN E. WILSON, MD

ABSTRACT: The visual inspection of photokeratoscope images permits the diagnosis of advanced anomalies in corneal shape and is an extremely useful adjunct to keratometry and slit-lamp microscope examination. However, corneal distortions too small to be appreciated by visual inspection of keratographs can seriously degrade visual acuity. In this article, an outline of the problems involved and the steps necessary to accomplish modern quantitative corneal topography is given. [Refractive and Corneal Surgery 1989; 6:368-371.]

Almost 90% of corneal dioptic power arises from refraction at the anterior corneal surface. Hence, the quality of vision is greatly dependent on the topography of the cornea. The growing development and practice of corneal refractive surgery have provided renewed impetus for improvements in the analysis of corneal topography, since existing tools have not provided sufficiently detailed information. The keratometer is routinely used to measure the shape of the cornea in the clinical practice of ophthalmology, but this instrument measures corneal curvature from the reflection of mires from only four positions along two meridians at right angles. While this method achieves an accuracy of better than 0.25D, clinical keratometers cannot be used to measure irregular astigmatism or corneal asphericity. For example, the keratometer cannot be used to assess the size of the central zone of uniform power following radial keratotomy.

A variety of keratographs also have been used clinically to assess corneal shape. Generally, keratograph photographs (keratographs) have been interpreted by visual inspection of the mires. With keratoscopy it is possible to detect and diagnose many forms of corneal distortion, and, importantly, relatively inexpensive hand-held keratoscopes can be used intraoperatively to correct gross amounts of astigmatism. However, direct reading or visual inspection of keratographs takes a great deal of training, and even seasoned topography experts cannot detect low amplitude or complex corneal surface distortions. Help in the form of computer transformation of the keratographs to amplify corneal distortions can be used to overcome this deficiency.

IMAGING THE CORNEAL SURFACE

There are several technologies that might be used for the determination of corneal topography using the analysis of either the virtual or real image of a target projected onto the corneal surface. The most commonly used target in keratoscopy is geometrically similar to the Placido disk with evenly spaced concentric circles of light or mires. This form of target has the advantage of having the same symmetry as the cornea, guaranteeing that data points can be obtained along as many corneal meridians as desired. With reflection keratoscopes, like the Nidek PKS 1000 or the keracorneascope for example (see below), a virtual image of the target is formed behind the corneal surface, and this virtual image is used in the reconstruction of corneal topography. Automated reflection keratoscopy, as is used by the Corneal Modeling System for example (see below), is currently the most proven technology in the field. Rasterstereography relies upon analysis of the real image of a target projected onto the corneal surface. This image is obtained by projecting a calibrated grid onto the fluorescein-stained tear film followed by computerized analysis. The geometry of this grid makes it possible to collect a mesh of equally spaced data points from the corneal surface, in contrast to the circular keratoscope mires used by the reflection keratoscope which provides...
data from corneal meridians that are equal angles apart. Finally, there has been commercial interest in the utilization of wave interference techniques (eg, laser holography) to measure corneal topography. The major advantage of such an approach is the ultrahigh precision with which such measurements could be made (less than a wavelength of the probing wave). The potential for such technology is exciting, but devices using this approach have not yet been made clinically available; perhaps their resolution is too great, providing so much detail it becomes both clinically irrelevant and too difficult to comprehend.

**ACQUISITION OF THE CORNEAL IMAGE**

Before three dimensional reconstruction of the corneal surface can occur, the image must be translated from observation space to storage medium, which can be either a photograph (keratograph) or a video frame in computer memory. Reproducibility has been a problem with methods utilizing photographs because of the film and paper's dimensional instability. Analog video cameras built with the old style videocam vacuum tube detector also introduce errors because they are inherently unstable. Therefore, digital video cameras that capture their image on a semiconductor circuit array have been a tremendous boon to image processing because dimensional stability is guaranteed by fixed optics and sensor by comparison to an electronically scanned electron beam.

Once the image has been captured with a camera, the next step is generally the digitization of the image, either manually or automatically. The LSU Corneal Topography System, for example, uses manual digitization of a photographic enlargement of the Nidek PKS 1000 photokeratoscope image. Although considerable care is taken to ensure accurate enlargement of the original, certain errors are inherent with dimensionally unstable photographic paper and the manual digitization process itself. Automatic densometric scanning of keratoscope photographs is used in the Keratron Keracan unit, but a limited number of semimeridians are analyzed. Automatic digitization can also occur when an entire video image is digitized with a frame grabber, which permits the storage of one video frame at a time in computer memory. This is the method used by the rastereographic system, as well as the Computed Anatomy Corneal Modeling System. The digital cameras used in these machines are able to convert images into a 512 by 512 array of numbers representing the intensity of light at corresponding points in the original image, and it is this array of so-called pixel values which must be evaluated automatically by computer if the reconstruction of the corneal surface is to occur automatically.

**CORNEAL IMAGE FEATURE EXTRACTION**

With the image of the target projected onto the cornea stored in computer memory, the next task is to identify the positions of all of the projected target features, which in the case of keratographs, involves finding the mires. This is the process of image feature extraction. With the LSU Corneal Topography System method the position of each of the 11 keratoscope mires is traced carefully with the digitizing pad. The mires are traced sequentially from the innermost to the outermost so that the program "knows" which set of mire image data is associated with which target mire. With the rastereographic method, which projects a series of parallel vertical lines on the cornea, each row of the image is scanned from one side to the other in order to identify the position of each image line within the captured image; this has been described in detail elsewhere. Basically, as an image is scanned from left to right, an optical density scan is obtained, with peak intensities corresponding to the presumptive position of the target image on the corneal surface. The object of the feature extraction algorithm for that methodology then becomes finding and storing the position of the brightest place in the scan, which corresponds to the assumed position of a given mire. Such positions found for 360° of all mires become the data that are used subsequently for surface reconstruction.

With the Corneal Modeling System, feature recognition and data capture can be thought to proceed in a fashion similar to that of the rastereographic method after the central fixation light in the image is automatically located. This estimated central position is used to convert the picture into polar coordinates, which has the effect of turning the nearly circular mires into nearly straight lines, which are then more easily identified and captured with image analysis technology. Some of this technology must be derived specifically for the field of corneal topography analysis to accommodate corneas with a broad range of distortions. Automatic computer recognition of image features is in its formative years—highly distorted patterns (eg, from advanced keratoconus or from early postoperative keratoplasty) may not be correctly digitized. Hence, it is important, if not essential, that instruments that automatically identify target image features provide a means for the operator to check the accuracy of the process. The Corneal Modeling System, for example, displays the video image of the keratoscope frame and overlays each mire with the position determined by the computer programs. When grossly distorted corneas cause errors in identification of the mires, the analysis can be aborted. In any case, the net result is that the instrument contains the coordinates of all relevant features in the captured image for corneas that are analyzable.

The density and location of data obtained from images of the corneal surface determines the
dimensions of the smallest features that can be revealed; in general, the more points that are analyzed on the corneal surface, the closer they will be to each other, and the higher will be the transverse spatial resolution. For example, an instrument that collects data from several points on, for instance, eight hemimeridians, would not provide enough transverse spatial resolution to depict the local circumferential corneal distortion in the vicinity of a radial keratotomy incision. There is a trade-off between the number of surface points analyzed and the speed of analysis. Obviously, a device that finds and uses 64 points on the corneal surface will calculate the data 128 times faster than a device (like the Corneal Modeling System) that uses 8192 points. For some applications, fewer points and faster speed may be appropriate. However, as faster computers become available, the corneal surgeon may be able to have the best of both worlds: high transverse resolution and real time data acquisition and presentation.

RECONSTRUCTION OF THE CORNEAL SURFACE

So far we have covered the production and acquisition of data by corneal topography instrumentation, and we have pointed out that these data, which are extracted from images, represent a transformation of the actual shape of the cornea. In order to retrieve the actual three dimensional original from this transform, equations unique to the optical principles and employed by a given device must be derived.

For the photokeratoscope class of instrument, several approaches and refinements have been reported. However, a major drawback to accurate corneal shape analysis by photokeratoscopy is that an exact solution is not possible from the data of the virtual image of the projected target. Hence, all of the solutions rely upon the adequacy of assumptions necessary to form a set of solvable equations. Wang et al.11 considered this problem and concluded that current algorithms used to reconstruct corneal topography from keratography analysis probably underestimate the magnitude of peripheral corneal asphericity such as occurs in radial keratotomy, for example. The analysis of spherical calibration surfaces can be quite accurate with photokeratoscopy algorithms, but few corneas requiring topographical analysis are spherical.

For the rasterstereographic approach to topography, an exact and efficiently calculated solution for the reconstruction of the cornea is available from the data captured. This has such a great potential advantage to the various numerical solutions and approximations that have been offered for photokeratoscope analyses that additional comment is merited. First, the accuracy of a given approach to measuring corneal topography is inherited from the specific methods used for imaging and reconstruction. For example, the reflection approach used in photokeratoscopy, which utilizes a virtual image, is more sensitive to corneal distortion than is the real image used by rasterstereography. The position of the virtual image of the target reflected from the cornea is principally a function of the slope and the displacement of the cornea from the target whereas the position of the real image is principally a function of the surface displacement alone. With wave interference methods, direct or nearly direct analytical methods appear to be available to reconstruct a cornea. However, serious deficiencies in this technology have yet to be overcome. It isn’t often that one is faced with a yardstick that is too accurate for its own good, but this appears to be the problem with using interference techniques for measuring corneal shape. These methods can provide rapid, highly precise estimates of corneal position, but may not be able to do so for a sufficiently large number of data sites on the cornea. With interference techniques, it is easy to ascertain whether a given cornea is identical to a given model (used to produce a wavefront), but for any deviation from a known model, the resulting pattern becomes indecipherable far more rapidly than the photokeratoscope image on the distorted cornea (vide infra).

CORNEAL PRESENTATION SCHEMES

As difficult as it might seem to achieve the three-dimensional reconstruction of the corneal surface from two-dimensional images, presentation of the resultant data in a meaningful fashion is more of a challenge. Itoi was the first to our knowledge to publish a wire mesh representation of corneas reconstructed from photokeratoscope analyses.12 This form allowed the observer to appreciate rather gross distortions of the cornea surface and was later refined with wire mesh presentations of corneal distortions from a sphere rather than presentation of the corneal shape alone.6 Unfortunately, such presentation schemes failed to be easily interpretable. However, this beginning led to the development of the color-coded contour mapping scheme that is used in an increasing number of instruments. We need not belabor description of this modality here, as it is apparently accepted internationally and is used extensively throughout this thematic issue of Refractive and Corneal Surgery. Color coding per se is not adequate in and of itself. The depiction of corneal topography using a color-coded mapping scheme must convey corneal shape information. To do so, it must be based on accurately obtained shape data, and interpretation of the presentation scheme must be straightforward and obvious to the clinical audience.

The color-coded contour map of corneal surface power13 is one step in the presentation of corneal topography. This modality should provide a
platform for launching even more useful presentation schemes in addition to the more quantitative analytical data needs as dealt with by the Dingeldein et al article in this issue.14 To a great extent, advances in the field of corneal topography have paralleled advances in the field of digital computers. When Mandell15 performed his classic experiments to determine corneal shape with his microkeratometer, he could only dream that someday inexpensive computer power would be available to permit a more accurate and more detailed analysis of the corneal shape. But, with the advent of modern analysis of corneal topography, coupled with the current color-coded presentation scheme of corneal surface power distribution, corneal surgeons finally have a tool that they can bring to practical clinical use.16-18

VALIDATION OF CORNEAL TOPOGRAPHY DEVICES

After all of the above discussion regarding the methods for the computerized reconstruction of the corneal surface from various automated approaches, it is essential to mention the importance for the validation of instruments. We cannot emphasize too strongly or too often the need for prospective customers of corneal topography equipment to insist upon validation data to verify the utility of the equipment for the measurement of corneal shape. The Food and Drug Administration (FDA) is very strict about devices that purport to yield clinical data. Unfortunately, the FDA cannot police the entire field, and while one device is being examined in minute detail, several other devices competing in the same market can be offered and sold without the FDA’s knowledge, let alone inspection. Validation of corneal topography analysis systems is slow to appear, primarily because the best data are gathered by independent research laboratories and the publication process is lengthy by nature. The validation of a corneal topography instrument might proceed with demonstrations of accuracy in analyzing manufactured calibration or reference surfaces. Such a demonstration must include not only precision spherical surfaces, but aspherical surfaces as done by Wang et al.11 One of the major difficulties encountered is that current corneal topography analysis instruments have the potential to be more accurate than traditional methods used for the production of accurately defined aspherical surfaces and this has the potential to confound validation studies. Perhaps the validation of corneal topography instruments for the purposes of FDA acceptance, as with clinician acceptance, should be judged on the basis of accuracy in permitting diagnosis of clinical shape anomalies.

SUMMARY

Several different methodologies may be applied to the clinical analysis of corneal topography. Photokeratoscopy-based methods are currently the most highly tested and validated of the commercially available approaches. Other methods are under development. However, rasterstereography may not have the accuracy necessary for the presentation of clinically significant corneal surface distortions. While the wave interference approach could substantially improve the accuracy of corneal surface reconstruction over photokeratoscopic methods in one dimension, this method will probably be unable to provide a large number of accurate points on the surface to be collected.

REFERENCES