Corneal topography using computer analyzed rasterstereographic images

Joseph W. Warnicki, Paul G. Rehkopf, Diane Y. Curtin, Stephen A. Burns, Robert C. Arffa, and John C. Stuart

This paper describes a new method for determining corneal surface detail utilizing a modified Zeiss photo slit lamp. This system projects a grid onto the cornea through a cobalt blue filter. The tear film is stained with fluorescein, causing the projected grid pattern to be visible on the corneal surface. A video image of the grid is then digitized by an image processor which calculates surface detail by evaluating the distortion of the grid lines. Information on curvature and surface detail is obtained across the full corneal surface, both the central optical axis and peripherally beyond the limbus.

I. Introduction

In recent years there has been increased interest in both qualitative and quantitative measurements of corneal topography, particularly related to keratorefractive procedures. Since keratorefractive procedures correct the refractive error of the eye by altering the curvature of the corneal surface, topographic measurements of the corneal curvature are important in planning, performing, and assessing the effect of these procedures. Corneal topography has proved of value in predicting the result of radial keratotomy,[1] evaluating the design of epikeratophakia for myopia,[2] diagnosis and staging of keratoconus,[3] and guiding suture removal after corneal transplantation.[4]

Previously reported photographic methods[3,5] are based on the keratoscopic disk system described by Antonio Placido and further refined by Gullstrand.[6] This keratoscopic system consists of a series of black and white concentric rings on a circular disk. When this disk is placed in front of the eye, the rings are reflected by the corneal surface and their position, size, and spacing in the reflected image are determined by the corneal shape. Current commercial systems utilize illuminated concentric circular rings surrounding a viewing port through which photographs are taken. If the cornea is spherical, the rings appear round and regularly spaced [Fig. 1(a)]. If the cornea is oval or astigmatic, the rings are oval and the spacing varies in different axes [Fig. 1(b)].

These techniques, while providing a visual representation of the corneal surface, do not provide quantitative information. Doss et al.[7] has described a computer program which calculates the corneal profile and the optical power distribution on the corneal surface from placido disk images. Klyce[8] has developed computer analyzing techniques for deriving quantitative information about the corneal shape from keratoscope photographs and displaying the results both numerically and graphically in easily understood forms.

Placido disk techniques for recording and quantifying the corneal surface have certain limitations which reduce their clinical usefulness. They do not extend to the corneal periphery or do they provide information about the most central portion of the cornea. In addition, they will not work on corneas which do not have the necessary qualities to reflect an image of the disk due to conditions such as epithelial defects, scarring, or highly irregular shape.

The current computer methods being used to obtain quantitative measurements utilize photographic images acquired with the commercially available Placido disk keratoscopes and are, therefore, subject to the same limitations discussed above. The data are entered into the computer by hand digitizing from these photographs, requiring a considerable amount of time, and the possible introduction of error during the digitization process.

We have adapted and refined a rasterstereographic method[9,10] which obviates some of these problems. Rasterstereography is a method of obtaining contour or topographic information where one of the cameras

The authors are with Eye and Ear Institute, Ophthalmology Department, 203 Lothrop Street, Pittsburgh, Pennsylvania 15213.

Received 26 June 1987.
0003-6935/88/061135-06$02.00/0.

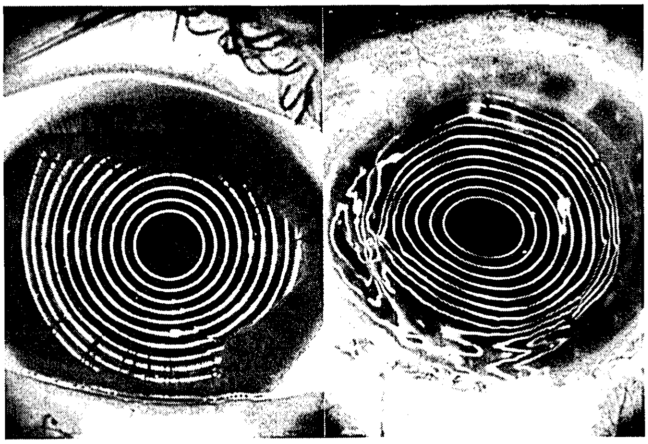


Fig. 1. (a) Placido disk photograph of a normal spherical cornea photographed with the sun photokeratoscope model PKS-1000. (b) Corneal transplant patient with astigmatic central cornea.

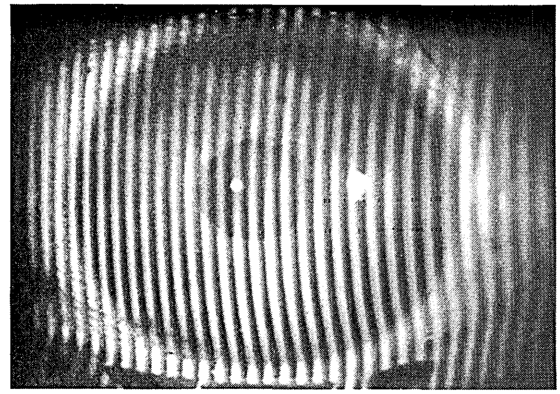


Fig. 2. Vertical grid projected on eye. Horizontal lines of black dots are an artifact from a bad memory chip in the image processor.

in a stereophotogrammetric pair is replaced with a light source which projects a grid of vertical parallel lines onto a subject. Previously, rasterstereography has been used for measuring large body surfaces, curvature of the back, and reconstructive plastic surgery.

II. Methods and Results

In our method an image is projected onto the corneal surface (Fig. 2) rather than reflected by it and thus is not affected by surface defects and irregularities. Also, the projected image covers the full cornea, including the central optical zone and the limbus. The image of the corneal surface is acquired electronically, then digitized and analyzed by a computer imaging system. The data obtained from analysis of these images are displayed in easily understood formats.

A. Optical System and Computer Image Acquisition

The optical system consists of a Zeiss stereo photo slit lamp which has been modified to be both a camera and projection system (Fig. 3). This modification requires that two cine elbows be mounted on the beam splitter. Attached to one of these elbows is a black and white video camera and to the other elbow a coaxial illuminator/flash normally used with the slit system but modified so that the illumination and flash project through a Ronchi ruling mounted at the focus of the optical system.

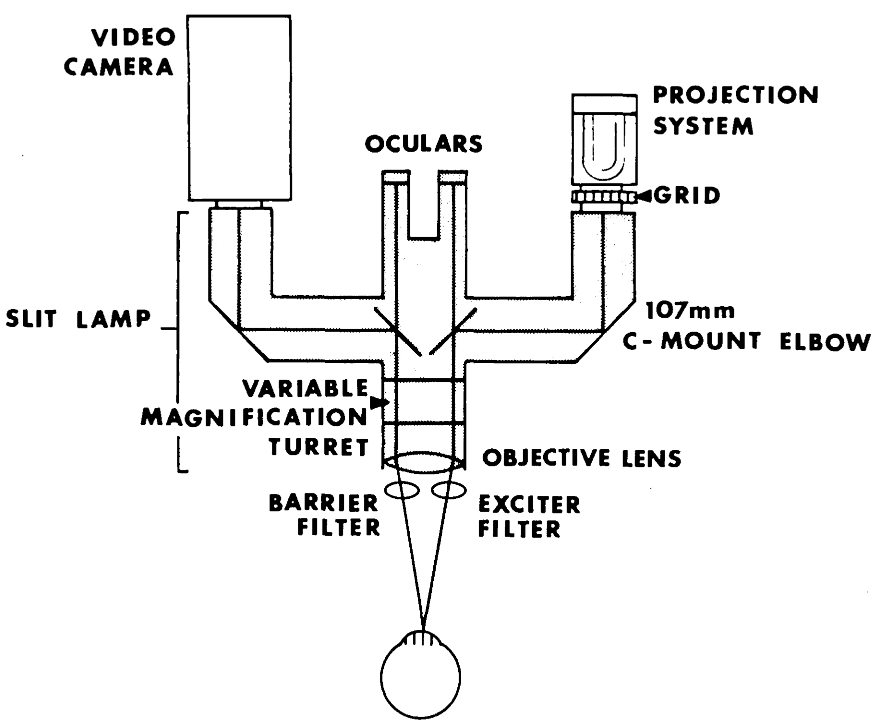


Fig. 3. Schematic diagram of Zeiss microscope with beam splitter and projection system attached.

When acquiring rasterstereographic images of the cornea, the operator focuses the slit lamp in the same manner as when taking photographs. The illumination required for focusing is provided from the illuminator/flash unit through the cine elbow, beam splitter, and internal slit lamp microscope optics and is projected onto the cornea. When the system is in focus, the operator triggers the flash, which follows the same optical pathway. The flash provides sufficient light intensity to acquire an image of the grid on the corneal surface.

Because the cornea is a transparent nondiffusing surface, the projected grid is not visible unless a diffusing material is used to provide a surface on which an image can be visualized. Bonnet[11] in 1962 sprayed talcum powder on anesthetized corneas to obtain stereo photographs of the cornea. We have substituted fluorescein to stain the tear film. The flash illuminator passes through a cobalt blue excitation filter (Zeiss SE40) causing the stained corneal tear film to fluoresce in an alternating light and dark grid pattern produced by the Ronchi ruling. This image is then viewed by the video camera through a yellow barrier filter (Zeiss SB50) and digitized by the image processor (PAR IS2000)[12–15] for storage and analysis.

1. Computer Analysis

The position and spacing of the grating lines on the cornea provide information for determining the corneal topography. The computer calculates the corneal surface elevation trigonometrically by comparing the horizontal displacement of the projected grid lines on the cornea to the position of the grid lines when projected onto a flat plane. A 2-D matrix of elevation points is created from these data. Horizontally the number of data points is equal to the number of projected grid lines, while vertically the number of points is limited only by the resolution of the video system. To limit computer processing time we use a vertical scaling which is proportional to the horizontal scaling. When calculating elevations on a full cornea and sclera, the spacing between matrix analysis points is 0.4 mm. Using higher magnification this distance can be reduced to 0.1 mm. The matrix size is ~35 horizontal by 45 vertical for a total of >1500 elevation points across the corneal surface.

The following computer programs have been developed to normalize the image, identify the grid lines, calculate elevation data, and display the results. The image of the grid varies widely over the eye (Fig. 4) with low contrast areas, typically over the sclera, and high contrast areas, over the iris and pupil. We first normalize the intensity across the image. To do this the maximum and minimum pixel intensity value is computed over a width of neighboring pixels slightly larger than one cycle of the grating. The minimum intensity for the pixels measured is then subtracted from the original pixel. Pixels in the vertical direction are not used, since in a small section it would not aid in contrast measurement and would only increase the processing time.

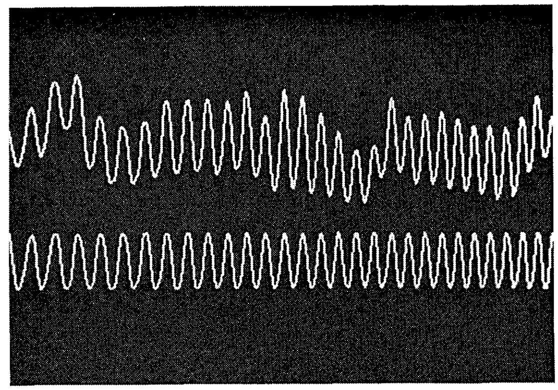


Fig. 4. Intensity plot of center line across cornea on top, normalized below.

Similarly a localized contrast range for each pixel is computed. Using this contrast, each pixel is then scaled, as follows, to make a uniform intensity plot across the entire line:

$$\text{new value} = (L_{prev} - L_{min}) \times (256/L_{max} - L_{min}),$$

where L_{prev} is the original value of pixel, L_{min} is the lowest value in the processing region, L_{max} is the highest value in the processing region, and 256 is the desired contrast range.

High values along the resulting intensity profile represent the center of each grid line. The precise location of this point is determined by finding the horizontal position of a sine wave (the image of the grating contains only small amounts of the higher harmonics), which provides the minimum root mean square error. This technique locates the center of each projected line to better than a single pixel. The computer displays a red dot at the nearest pixel to confirm its interpretation of the center of each grid line.

B. Detection of Elevation Matrix

Any section of the grid line can be used as the reference point for elevation calculations. A reference plane is then placed through this point perpendicular to the optical axis of the stereo optics. The apex of the cornea was chosen as the reference point because clinically the central cornea is the region of most interest.

Grid spacing on a flat plane is a known constant[16] (SP), any elevation or depression from this plane will deviate the grid line according to the formula

$$\text{deviation of grid} = (\text{lines shifted} \times \text{SP}) - \text{horizontal distance},$$

where lines shifted is the number of grid lines, positive or negative from the reference line to the line to be measured, SP is the grid spacing constant as projected on a flat plane, and the horizontal distance is the distance measured on the horizontal plane from the reference point to the point on the line to be measured.

The trigonometric solution to calculate the elevation at each of the matrix points from deviations of the grid line is given schematically in Fig. 5 using the formula

$$\text{elevation} = [(\text{deviation of grid/sine } \alpha) \times \cos \beta]/\text{magnification ratio},$$

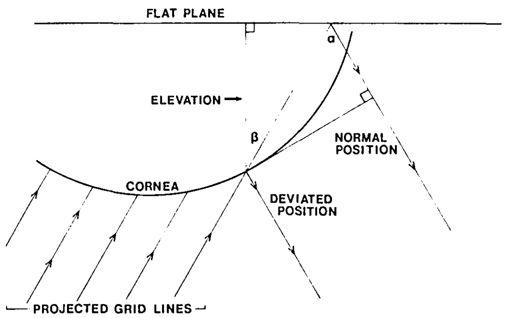


Fig. 5. Schematic diagram showing grid lines displaced on cornea from assumed normal position and trigonometric solution for elevation.

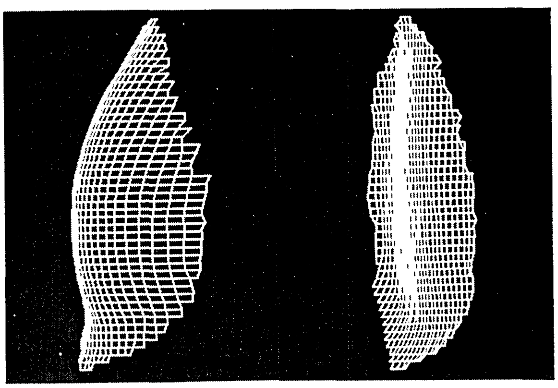


Fig. 6. Orthogonal view of normal cornea on left; same cornea with common curve removed on right.

where α equals the angle between the projected grid and viewing optics, β is one-half of the angle of α, and the magnification ratio is the number of pixels per millimeter of the original image.

The greater the elevation of the cornea (the closer it comes to the projection and imaging lens) the greater a grid line deviates toward the projection lens side, or to the left in this case. The matrix point elevations that are calculated from that line are also moved proportionately to the left. This matrix can then be stored for future use or processed for further image analysis.

C. Curvature Calculations

The computer displays a cross-sectional view of the cornea along any axis by plotting the elevation points of the matrix along any particular line. The radius of curvature is calculated by using the simplex computer algorithm[17] to best fit an arc to the elevation points. Using the same method, curvatures can be determined for any axis, either for the average across the full cornea or for a small portion of it.

D. Display Methods

Using the matrix file, the image can be represented in several forms. Standard graphics processing techniques[18] can be used to rotate the cornea around the X or Y axis. Figure 6(a) shows the cornea rotated 80° to the right to view the corneal shape across the bridge of the nose. Here one can see the tear film curve up to the

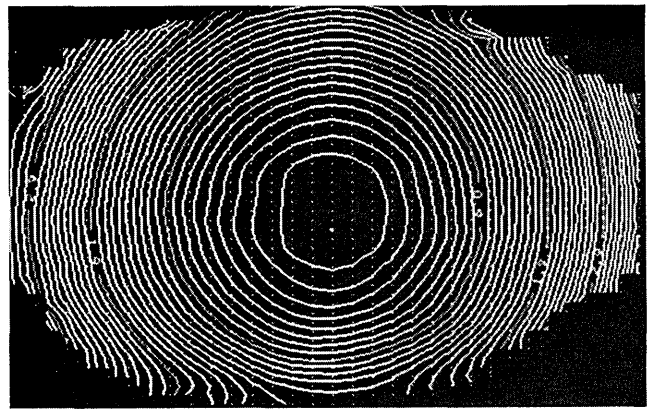


Fig. 7. Contour plot of cornea. Each line represents an elevation change of 0.1 mm.

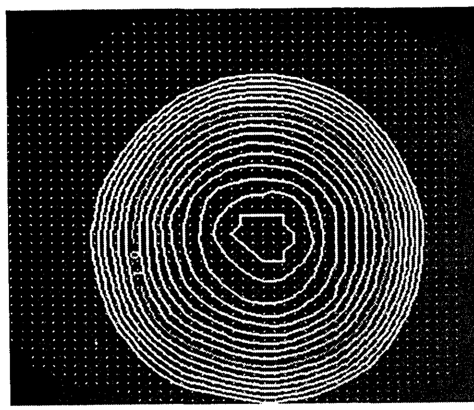


Fig. 8. 2.5× optical magnification of the center of the cornea before processing. Each contour line represents 0.0125 mm in elevation.

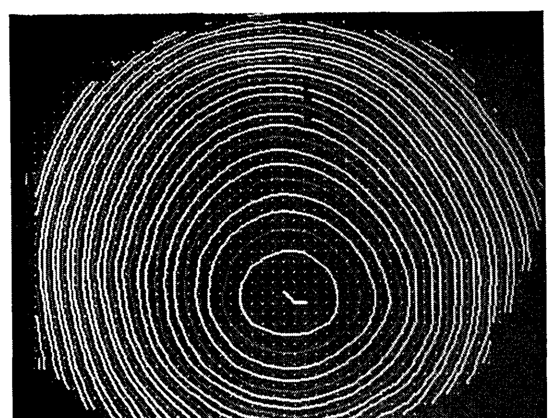


Fig. 9. Contour plot of a cornea with astigmatism.

lower lid. Figure 6(b) shows the same cornea from the same angle, but the common curve of the cornea has been subtracted out to accentuate distortions from a spherical shape, as reported by Klyce.[8]

Contour plots of the cornea are shown in Figs. 7, 8, and 9. Although they appear similar to placido disk photographs, these are maps of equal height areas of the cornea. The numbers represent the height in millimeters between points along that line and the highest point on the cornea. In Figs. 7 and 8 the difference between each contour line is 0.1 and 0.0125 mm respectively.

The image used to obtain the data in Fig. 8 was magnified 2.5× the image used for Fig. 7. Thus only the central 3 mm of the cornea is shown. However, the detail of the elevation changes has been increased proportionately. Figure 9 shows a full cornea of a patient with astigmatism.

E. Calibration

The system was calibrated using four steel balls as a standard. The balls were spray painted to provide a nonreflective surface and then measured with a micrometer. To determine the accuracy and reliability of curvature measurements, the balls were photographed 4 times each using the projected grid. The images were then processed to find the radius of curvature, and the resulting data are plotted in Fig. 10. The average error of the sixteen measurements was 0.060 mm with a range of +0.11 to −0.16. For the balls of larger radius the image processor tended to overestimate the true curvature, while it tended to underestimate the curvature of the smallest ball. For each ball the range of measurements was 0.10 mm or less.

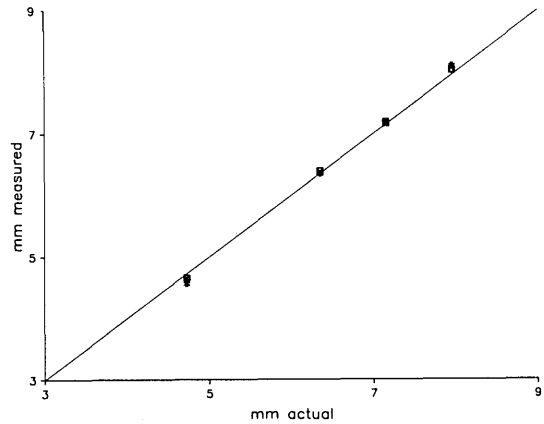


Fig. 10. Graph comparing grid curvature measurements with micrometer readings; four points plotted for each steel ball.

III. Discussion

The accuracy of this method is dependent on several variables: system resolution; magnification; the angle between the projected image and the viewing optics; and the number of projected lines. The smallest portion of a digitized image is the pixel. As the magnification of the corneal image increases, or the resolution of the video system increases, the change in depth represented by each pixel is reduced, increasing the accuracy of the measured displacement of the grid.

The accuracy of the topographic measurement is proportional to the angle of separation between the projected image and the viewing optics. As the angle of separation between the projected grid and the camera increases, so does the sine of the angle, which is used to determine corneal surface elevation, making the depth represented by a 1-pixel change in displacement of the grid smaller. However, at the same time, increasing the angle of separation causes more of the grid lines to fall on the projection side of the cornea, possibly diminishing the accuracy of the system on the total cornea. This effect is exaggerated for demonstration purposes in Fig. 5. Due to these contrasting effects, at this time it is not certain whether changes in the angle of separation would be beneficial. Also, the advantage of working with well-proved stable equipment such as the Zeiss slit lamp or operating microscope outweighs small increases in accuracy that might be achieved with these alterations.

Increasing the number of lines projected onto the cornea could easily be achieved by changing the etched grid in the projection system (Fig. 2). Doubling the density of the grid lines would result in an increase in the number of elevation points in the matrix from 1500 to 6000. It is not yet clear how much resolution is necessary or whether further detail would provide clinically useful information.

Occasionally the tear film was insufficient or the fluorescein stain dispersed too rapidly, making it impossible to obtain an image. To overcome this problem, the fluorescein was then mixed with a solution of methylcellulose and artificial tears; this mixture persists long enough to acquire images of the corneal surface.

IV. Conclusions

Determining corneal topography using rasterstereographic images is a new technique that has several advantages over the more traditional systems currently being used. Full corneal measurements are obtainable as well as more detailed measurements of the central cornea or other areas. Images can be obtained from corneas with irregular or nonreflective surfaces. Quantitative measurements of curvature appear to be accurate to within 0.10 mm over a wide range of curvatures from 4.6 to 8.0 mm. However, the deviation is greatest at the extremes of this range. For an average sized eye, with a radius of curvature of 7 mm, the accuracy is 0.04 mm, which is equivalent to ~0.3 diopters.

The system currently utilizes the optics of a Zeiss slit lamp for grid projection and image acquisition. The camera and projection system is mounted on the standard beam splitter normally used for photography. This system adapts easily to a Zeiss operating microscope making it possible to obtain images intraoperatively without cumbersome attachments.

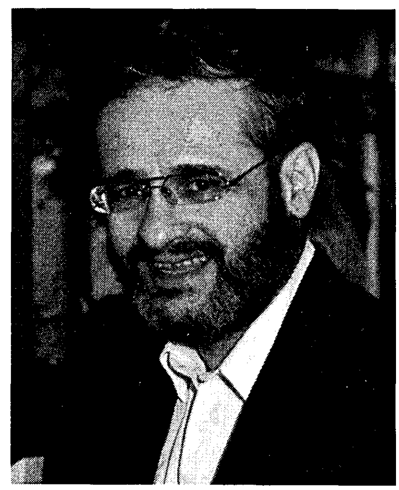
This research was supported in part by The Pennsylvania Lions Sight Conservation and Eye Research Foundation, Inc., and by Research to Prevent Blindness and by NIH NEI EYO-4395 (S. Burns)

References

1. J. J. Rowsey, H. Gelinder, J. Krachmer, P. Laibson, et al., "PERK Corneal Topography Predicts Refractive Results in Radial Keratometry," Ophthalmology 93 (8) (Suppl.), 94 (1986).

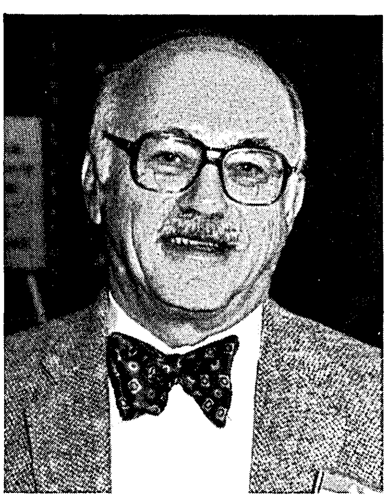
2. L. J. Maguire, S. D. Klyce, D. E. Singer, et al., "Corneal Topography in Myopic Patients Undergoing Epikeratophakia," Am. J. Ophthalmol. 103, 404 (1987).
3. J. J. Rowsey, A. E. Reynold, and R. Brown, "Corneal Topography," Arch. Ophthalmol. 99, 1093 (1981).
4. P. S. Binder, "Selective Suture Removal Can Reduce Postkeratoplasty Astigmatism," Ophthalmology 92, 1412 (1985).
5. B. A. J. Clark, "Autocollimating Photokeratoscope," J. Opt. Soc. Am. 62, 169 (1972).
6. Sr. Stewart Duke-Elder and D. Abrams, "Chapter III The Dioptic Imagry of the Eye," Syst. Ophthalmol. Ophthal. Opt. Refraction 5, 128 (1970).
7. J. D. Doss, R. L. Hutson, J. J. Rowsey, and D. R. Brown, "Method for Calculation of Corneal Profile and Power Distribution," Arch. Ophthalmol. 99, 1261 (1981).
8. S. D. Klyce, "Computer-Assisted Corneal Topography. High-Resolution Graphic Presentation and Analysis of Keratoscopy," Invest. Ophthalmol. Vision Sci. 25, 1426 (1984).
9. W. Frobin and E. Hierholzer, "Rasterstereography: A Photogrammetric Method for Measurement of Body Surfaces," J. Biol. Photogr. 51, 11 (1 Jan. 1983).
10. J. W. Koepfler, "Moire Topography in Medicine," J. Biol. Photogr. 51, (1 Jan. 1983).
11. R. Bonnett, "New Method of Topographical Ophthalmometry—Its Theoretical and Clinical Applications," Am. J. Opt. 39, 227 (1962).
12. M. R. Nelson, J. L. Cambier, S. I. Brown, P. G. Rehkopf, and J. W. Warnicki, "System for Acquisition, Analysis, and Archiving of Ophthalmic Images (IS 2000), " Proc. Soc. Photo-Opt. Instrum. Eng. 12, 72 (1984).
13. P. G. Rehkopf and J. W. Warnicki, "Clinical Experience with the Ophthalmic Image Processing System (IS 2000)," Proc. Soc. Photo-Opt. Instrum. Eng. 13, 282 (1985).
14. P. G Rehkopf, J. W. Warnicki, M. R. Nelson, J. Cambier, and S. I. Brown, "Image Processing in Opthalmology. A New Clinical Noninvasive Diagnostic Modality," in *Technical Digest, Noninvasive Assessment of the Visual System* (Optical Society of America, Washington, DC, (1985), paper WA2.
15. J. W. Warnicki, P. G. Rehkopf, J. L. Cambier, and M. R. Nelson, "Development of an Imaging System for Ophthalmic Photography," J. Biol. Photog. 53, 9 (1985).
16. Grid lines were projected onto a calibration object with a flat surface. The spacing between the lines has been measured and the distortions occurring from off-axis projection analyzed and quantified. Images are then normalized using this analysis.
17. M. S. Caceci and W. P. Cacheris, "Fitting Curves to Data," Byte (May 1984).
18. J. D. Foley and A. Van Dam, *Fundamentals of Interactive Computer Graphics* (Addison-Wesley, Reading, PA, 1982).

1987 OSA ANNUAL MEETING



Vincent J. Corcoran
Potomac Synergetics, Inc.

Girish Agarwal
Hyberabad University



Erwin G. Loewen
Milton Roy Co.

photos
F. S. Harris, Jr.