1040-5488/95/7211-0828$03.00/0
OPTOMETRY AND VISION SCIENCE

Vol. 72, No. 11, pp. 828–837

PAR Corneal Topography System (PAR CTS): The Clinical Application of Close-Range Photogrammetry

MICHAEL W. BELIN*

Division of Cornea, External Disease and Refractive Surgery, Lions Eye Institute, Albany Medical College, and Stratton Veterans Administration Medical Center Surgical Service, Division of Ophthalmology, Albany, New York

JAMES L. CAMBIER†
JOHN R. NABORS‡

PAR Microsystems Inc., PAR Vision Systems Corp., New Hartford, New York

C. DEREK RATLIFF§

Division of Cornea, External Disease and Refractive Surgery, Lions Eye Institute, Albany Medical College, Albany, New York

ABSTRACT

The PAR Corneal Topography System (CTS) is a computer-driven corneal imaging system which uses close-range photogrammetry (rasterphotogrammetry) to measure and produce a topographic map of the corneal surface. The PAR CTS makes direct point-by-point measurements of surface elevation using a stereo-triangulation technique. The CTS uses a grid pattern composed of horizontal and vertical lines spaced about 0.2 mm (200 μm) apart. Each grid intersection comprises a surface feature which can be located in multiple images and used to generate an (x,y,z) coordinate. Unlike placido disc-based videokeratoscopes, the PAR CTS requires neither a smooth reflective surface nor precise spatial alignment for accurate imaging. In addition to surface elevation, the PAR CTS computes axial and tangential curvatures and refractive power. Difference maps are available in all curvatures, refractive power, and in absolute elevation.

Key Words: topography, photogrammetry, rasterphotogrammetry, stereogrammetry, triangulation, videokeratoscopes, placido, structured lighting, fluorescence, elevation, tangential, keratoconus, "forme fruste" keratoconus, photorefractive

The PAR Corneal Topography System (CTS) is a computer-driven corneal imaging system which uses close-range photogrammetry (rasterphotogrammetry, rasterstereography, stereogrammetry) to measure and produce a topographic map of the corneal surface. Rasterphotogrammetry is a standard method of extracting object information by projecting a known pattern onto an object and recording the distortion when viewed from an oblique angle. This technique has been used in a variety of medical (e.g., optic nerve head analysis) and nonmedical applications, and was initially adapted for corneal topography by Warnicki et al.[1] The CTS determines distortion in a projected two-dimensional grid with a point density spacing of 0.22 mm, resulting in approximately 1700 data points on the cornea.[2] This information is then fed into a proprietary elevation detection algorithm along with calibration data to compute a true topographic map (elevation detection). The PAR CTS makes direct point-by-point measurements of surface elevation using a stereo-triangulation technique. Because the system defines elevation points, not angle of reflection, mathematical modeling is easily accomplished without the shape assumptions necessary in placido-based systems. Unlike placido disc-based videokeratoscopes, the PAR CTS requires neither a smooth reflective surface[3] nor precise spatial alignment[4] for accurate imaging. It is capable of imaging irregular corneas, such as de-epithelialized corneas, and has been integrated both onto an operating microscope and an optical bench refractive laser.[5] The system can be adapted to measure over 12 mm on the corneal surface (limbus to limbus).

Received March 6, 1995; revision received August 22, 1995.
* M.D., F.A.C.S., Paid Consultant to PAR Technology.
† Ph.D.
‡ M.S.
§ M.D.

TECHNOLOGY

The CTS uses a form of stereo-triangulation, a standard photogrammetric method of extracting three-dimensional object information using two or more overlapping photographs or views of the object taken from different vantage points. Typically some feature of interest is located in each photograph and, using geometric information about the camera position associated with that photograph, a ray is constructed in three-dimensional space, which extends from the camera to the feature. Multiple rays from multiple cameras are constructed and their intersection point, which defines the location of the feature, is calculated. The result is an (x,y,z) coordinate for the feature.

Adaptation of the stereo-triangulation technique to the cornea requires some special steps. First, the cornea is effectively featureless; there are no landmarks which can be identified and located by multiple cameras and used to perform the ray intersection. This is overcome by a special illumination technique called structured lighting. Structured lighting involves projecting a regular light pattern onto the cornea which will produce unique identifiable features on the surface.[3] The PAR system uses a grid pattern composed of horizontal and vertical lines spaced about 0.2 mm (200 μm) apart. Each grid intersection comprises a surface feature which can be located in multiple images and used to generate an (x,y,z) coordinate.

In order for the triangulation technique to work, the surface features used must emit light in multiple directions so they can be observed by multiple cameras at once. In most imaging applications the surfaces being measured scatter incident illumination in all directions, and the images can be formed using this scattered light. This is the mechanism used in standard photography. Because the cornea is nearly transparent and does not effectively scatter light, the image we see looking into the eye is generated almost entirely by light scattered from the iris. In order to produce light emissions from the surface of the cornea, the PAR system uses a small amount of fluorescein placed in the tear film, with the images collected using standard fluorescence-based photography. The fluorescence from the dye is emitted in all directions, just as scattered light would be, so it can be imaged from multiple locations. The grid pattern is projected through a blue excitation filter, and the imaging is performed using a yellow barrier filter so only the fluorescence is observed (Fig. 1).[6]

The CTS approach could be implemented by using one optical system to project the grid pattern onto the cornea and create the surface features to be measured, and two or more camera systems to measure the locations of the features. A significant simplification can be achieved by recognizing that the grid projection system is mathematically equivalent to a camera, with the physical grid (a precision silver-chrome pattern deposited on a glass substrate) corresponding to the image. The system can then be reduced to two optical systems, one projecting the grid onto the cornea and the other imaging it from another vantage point (Fig. 2). Each grid intersection is projected along a ray PO from the grid to the surface of the cornea, and is imaged along a ray OI by the camera. From the known geometry of the projection and imaging systems, the two rays can be intersected in three-dimensional space to compute the (x,y,z) coordinates of the surface point O. The process is repeated for each grid intersection. The coordinates are referenced to an

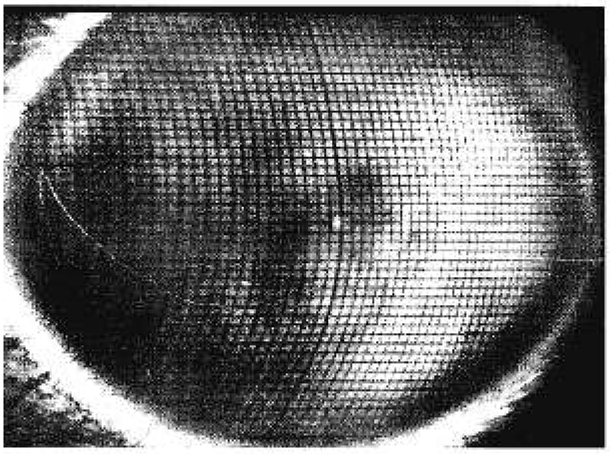


Figure 1. Standard grid projection on cornea. The central box is used for aligning "line of sight fixation." The two empty mid-peripheral blank rectangles are used by the system for processing. The grid is captured by the video camera after staining the tear film with fluorescein.

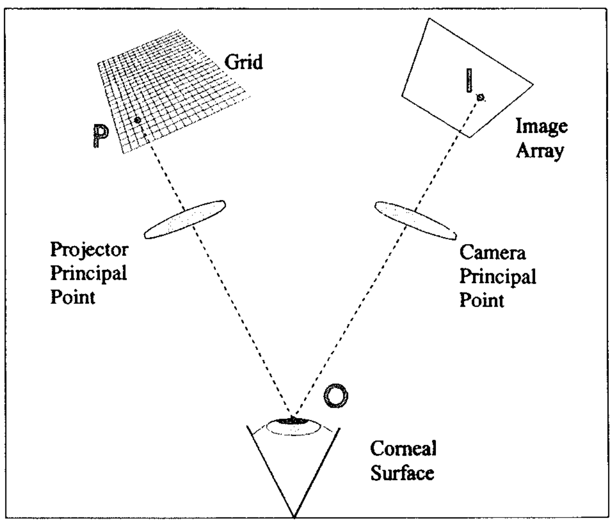


Figure 2. CTS triangulation geometry. Each grid intersection is projected along a ray PO from the grid to the surface of the cornea, and is imaged along a ray OI by the camera.

imaginary plane orthogonal to the optical axis of the eye to compute the elevation data. The elevation data represent the true topography of the anterior corneal surface. The corneal curvature is then calculated from the elevation data.

HARDWARE

A typical hardware configuration for the CTS consists of a Windows-based PC with video digitizer and system interface boards, a flash power supply, the CTS optical head that mounts on a slitlamp (Fig. 3) or operating microscope, and a color printer. The hardware can be adapted to an existing slitlamp or operating microscope by use of the appropriate mechanical fixtures and optical components to obtain the proper working distance and magnification.

The standard slitlamp system views the cornea through the two optical paths, which are oriented at a fixed angle of 24.6° relative to each other (Fig. 4). In theory, larger angles of separation create greater grid distortion and increased system sensitivity. In practice, however, angles greater than 30° are not useful because of shadowing by the nose and brow. In addition, larger angles of separation demand greater depth of field (see below).[5]

Successful image acquisition is dependent on the depth of field and working distance, both of which are hardware-dependent. Because the system projects a grid pattern from an oblique angle onto a nonplanar surface, the distance from the objective lens to points on the corneal surface is not constant. As with any camera or video system, depth of field is controlled by the f stop of the lens. Smaller apertures (greater f stops) yield increased depth of field. Greater f stops require boosting the sensitivity of the video camera or increasing the intensity of the light source (projector). The working distance of the system is variable and controlled by the focal length of the video lens. As the working distance is increased (larger objective lens) the variation in cornea to objective distance decreases, effectively increasing the depth of field.[5] All three factors, focal length, light intensity, and camera sensitivity are amenable to modification, making the system adaptable to different working environments.

DISPLAYS

As noted above, the elemental data produced by the CTS consist of an array of elevation values, which define the height of each surface point relative to an imaginary plane located behind the cornea. Although this topographic information (raw data display) provides an accurate representation of the corneal shape, it is difficult to display

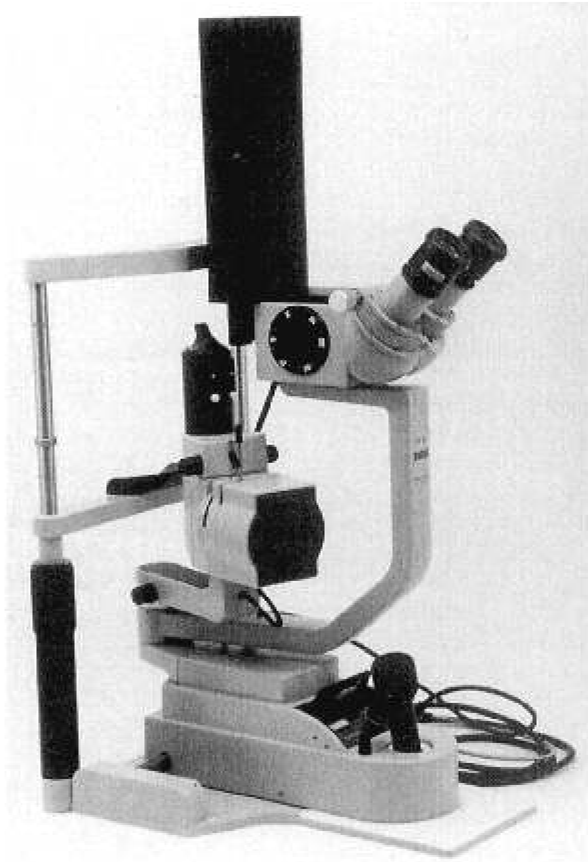
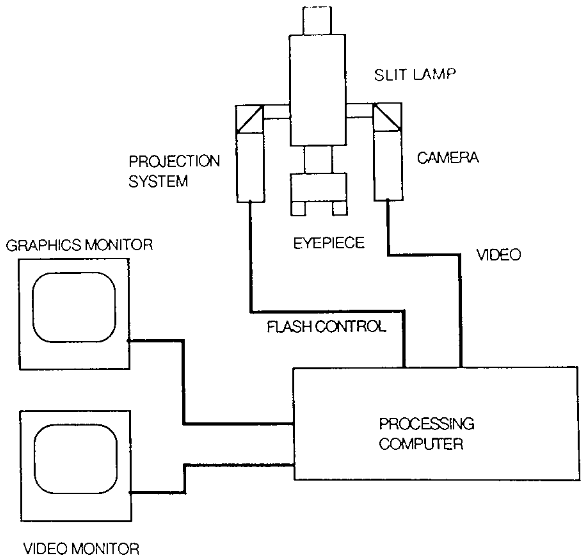


Figure 3. CTS Slitlamp configuration. The CTS housing mounts on a standard slitlamp and encloses the video camera and the projector.



CTS BLOCK DIAGRAM

Figure 4. PAR CTS schematic. The system can be broken down into two converging optical paths. Neither path has to be normal to the cornea, allowing integration with other diagnostic or therapeutic devices.

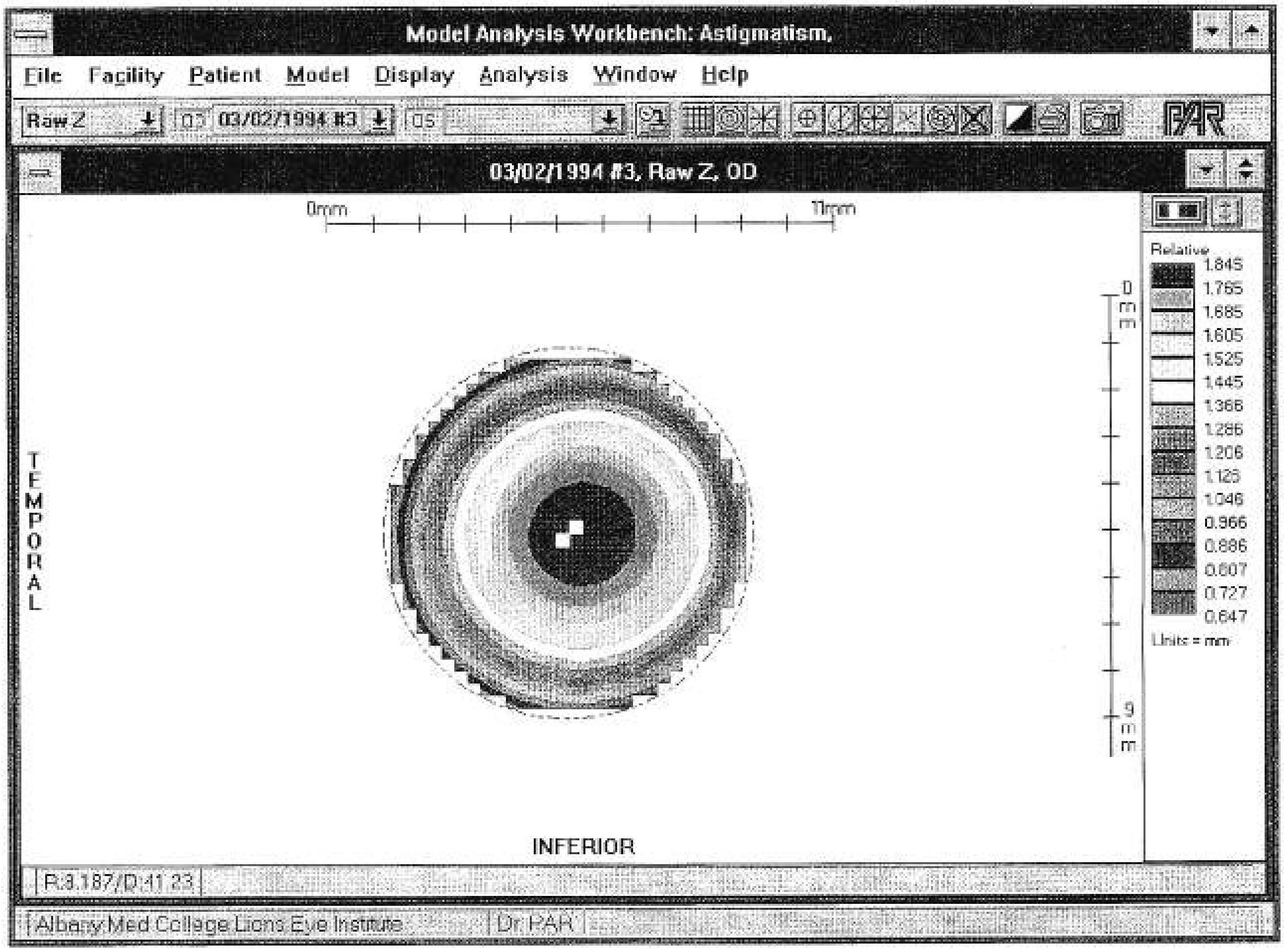


Figure 5. Raw data. The raw elevation data (as measured from the imaginary plane).

these data in a manner which shows the subtle variations in corneal shape (Fig. 5).

Because the cornea is approximately spherical, it proves useful to calculate an average or best fit sphere for the corneal surface, and display the actual surface with this sphere as a reference. Elevation deviations, both positive and negative (above and below), from this sphere can then be color-coded and displayed (elevation display).[3] This display shows how the cornea deviates from a best fit sphere, and thus reveals subtle corneal abnormalities (Figs. 6 and 7).

A "sagittal" (more correctly axial) curvature map (sagittal curvature display) is obtained by computing the distance from the surface along the normal to where it intersects the optical axis and using this as the radius of curvature (Fig. 8). Other authors have pointed out that use of the term sagittal to describe this curvature calculation is incorrect,[7, 8] and that placido disc-based systems have a fundamental inability to measure either sagittal curvature correctly.

The tangential map (tangential curvature display) is obtained by computing the local or instantaneous radius of curvature along the meridian from the second derivative of the elevation function. Tangential maps are typically more sensitive to local changes in curvature (Fig. 9).[9, 10]

The refractive power map is obtained by applying Snell's law of refraction to the known shape. Difference maps are available in elevation, sagittal, tangential, and refractive power.

The Windows-based environment allows for multiple displays to be opened simultaneously. As with other systems, a number of overlays and/or computed indices are available: (1) 1-mm grid overlay; (2) 3–5-7-mm optical zone overlay; (3) simulated keratometry (either 3- or 4-mm optical zone); (4) astigmatic indices (operator-selected optical zone, nonorthogonal axis); (5) 3–5-7-mm optical zone astigmatic indices (hemi-meridians); and (6) astigmatic flow.

The refractive properties of the cornea at a particular point can be described accurately only by determining how an incident ray is bent either toward or away from the normal to the surface, in accordance with Snell's law. The direction of the normal at a point can be determined only from knowledge of the true topography, i.e., elevation data, at that point. The PAR system is able to

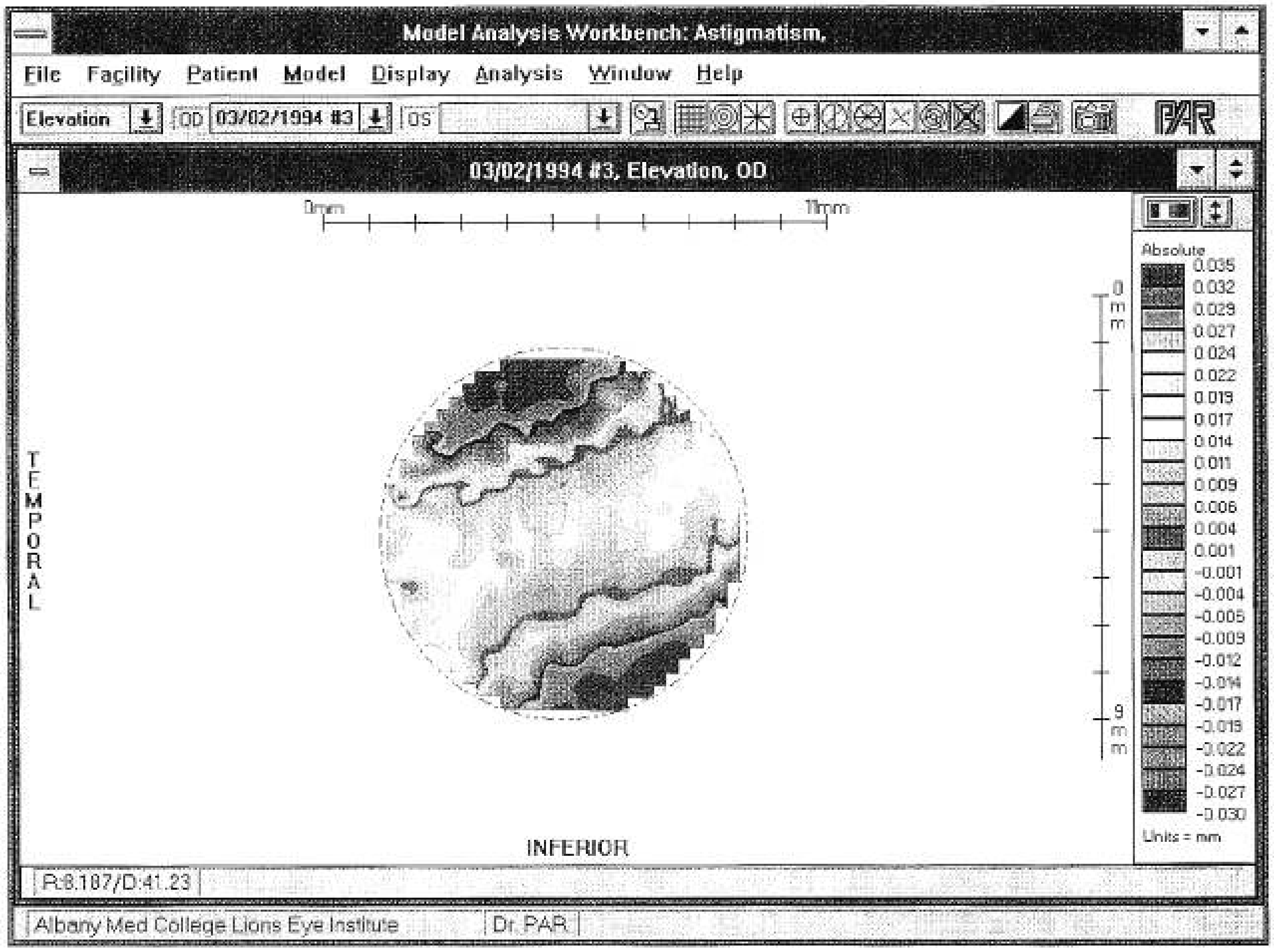


Figure 6. Elevation map (astigmatism). The elevation map shows the deviation from the best fit sphere. This cornea is highly astigmatic. The "high" or "elevated" areas represent the flat portion of the cornea (hot colors), and the "low" or "depressed" areas represent the steeper axis (cool colors).

produce accurate elevation data, and offers a potential for generating more accurate characterizations of corneal refractive properties than is currently available.

PREVIOUS STUDIES

Previous studies have shown the system's accuracy, reproducibility, resistance to defocusing error, and unique clinical properties. Accuracy has been reported in 2 studies by analyzing test objects calibrated by a Taylor-Hobson contact profilometer (37.5, 42.25, 58 D in study 1; 33.55, 42.21, 55.76 D in study 2). Error values of 0.08 ± 0.09, 0.06 ± 0.08, and 0.14 ± 0.18 D[2] and 0.07 ± 0.01, 0.00 ± 0.02, and 0.03 ± 0.0 D[3] were obtained, respectively. To determine the reproducibility of the system 3 investigators measured 3 noncalibrated balls (20, 18, and 12 mm). The optical system was purposely decentered after each reading, dictating refocusing. Maximum intra-observer variability was 0.09, 0.06, and 0.11 D, respectively. Inter-observer variability measured 0.18, 0.12, and 0.16 D.[3] This compares favorably to the early published reports of videokeratoscopes' accuracy (placido disc-based) of ±0.37 D[11] and reproducibility error greater than 0.50 D.[12] More recently, Koch and co-workers demonstrated improved accuracy (greatest mean error 0.10 D) and reproducibility (greatest SD 0.07) for the EyeSys Corneal Analysis System model 1 on similar test objects but without a system defocus.[13]

The sensitivity of the PAR CTS to a focusing error was evaluated by keeping the system stable (not refocusing) and decentering the test objects (55.76, 48.05, 42.21, 37.49, and 33.55 D) by 0.5 mm along the X, Y, and Z axis. This corresponds to imaging 8 points in space at each corner of a 1-mm cube. The PAR CTS was both accurate (greatest error recorded 0.09 D) and reproducible (greatest SD 0.03 D) in imaging calibrated balls within a defined zone in space.[4]

Because the PAR CTS computes individual point data independently and does not depend on

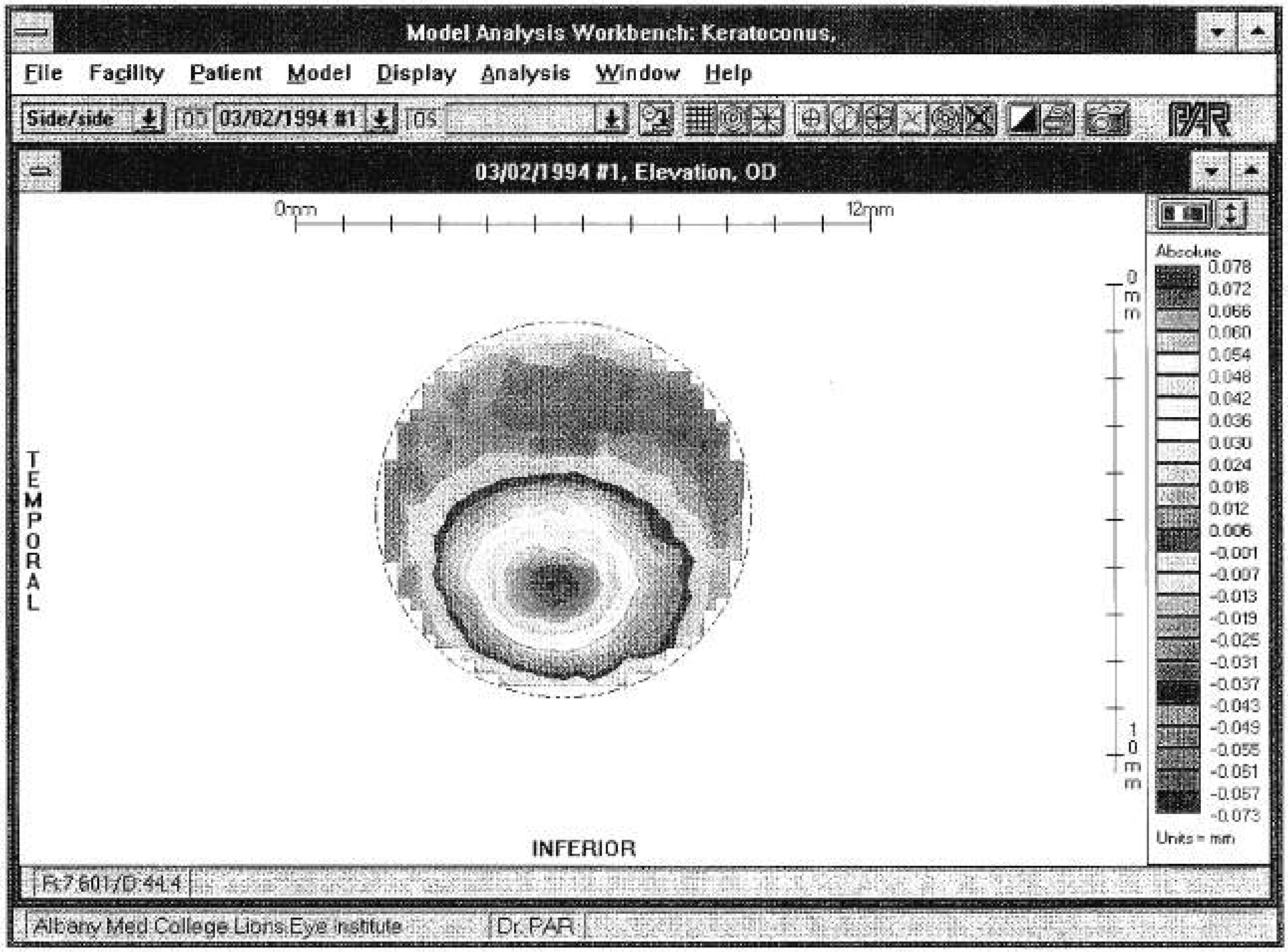


Figure 7. Elevation map (keratoconus). The elevation map showing the deviation from the best fit sphere. The elevated portion of the cornea represents the ectatic portion of the cornea.

a reflective surface, abnormal and irregular corneas, not analyzable by placido systems, can be imaged. Corneas devoid of corneal epithelium and bare stroma have been successfully captured (Fig. 10).[5] On highly irregular corneas, such as advanced keratoconus, the PAR system has shown greater corneal coverage than placido-based systems.[14] In the detection of early "forme fruste" keratoconus, the combined use of both elevation maps and curvature maps has reduced potential false positives and may be a better indicator of true cone morphology (Fig. 11).[15]

The PAR CTS can be adapted to work in conjunction with other diagnostic and/or therapeutic devices. Because the system does not need to be coaxial, integration with an operating microscope or photorefractive laser is possible. The ability to vary the working distance and angle of separation also assists in adaptation. A modified CTS has been integrated into an experimental photoablative laser. The CTS successfully imaged corneas both before, after, and during laser photoablation. The ability to image nonreflective surfaces, and integrate the CTS into other optical systems, may make the system suitable for intraoperative photorefractive monitoring.[5]

CLINICAL APPLICATIONS

Computerized corneal topography has established itself as a valuable diagnostic tool. Its use has been advocated in screening and managing keratoconus,[16] in the fitting and design of contact lenses, in all aspects of refractive surgery, in suture management after corneal surgery, and in the evaluation of unexplained visual loss.

As previously discussed, the CTS's combined use of elevation and curvature maps appears to be a more specific indicator of early corneal ectasia than systems that rely on curvature alone.[15] In photorefractive surgery, the ability to image over absent epithelium or bare stroma is an advantage. In automated lamellar keratoplasty, the PAR CTS can read the keratectomized base and determine the operative refractive change. In photorefractive surgery, the CTS can analyze the cornea after the epithelium is removed and im-

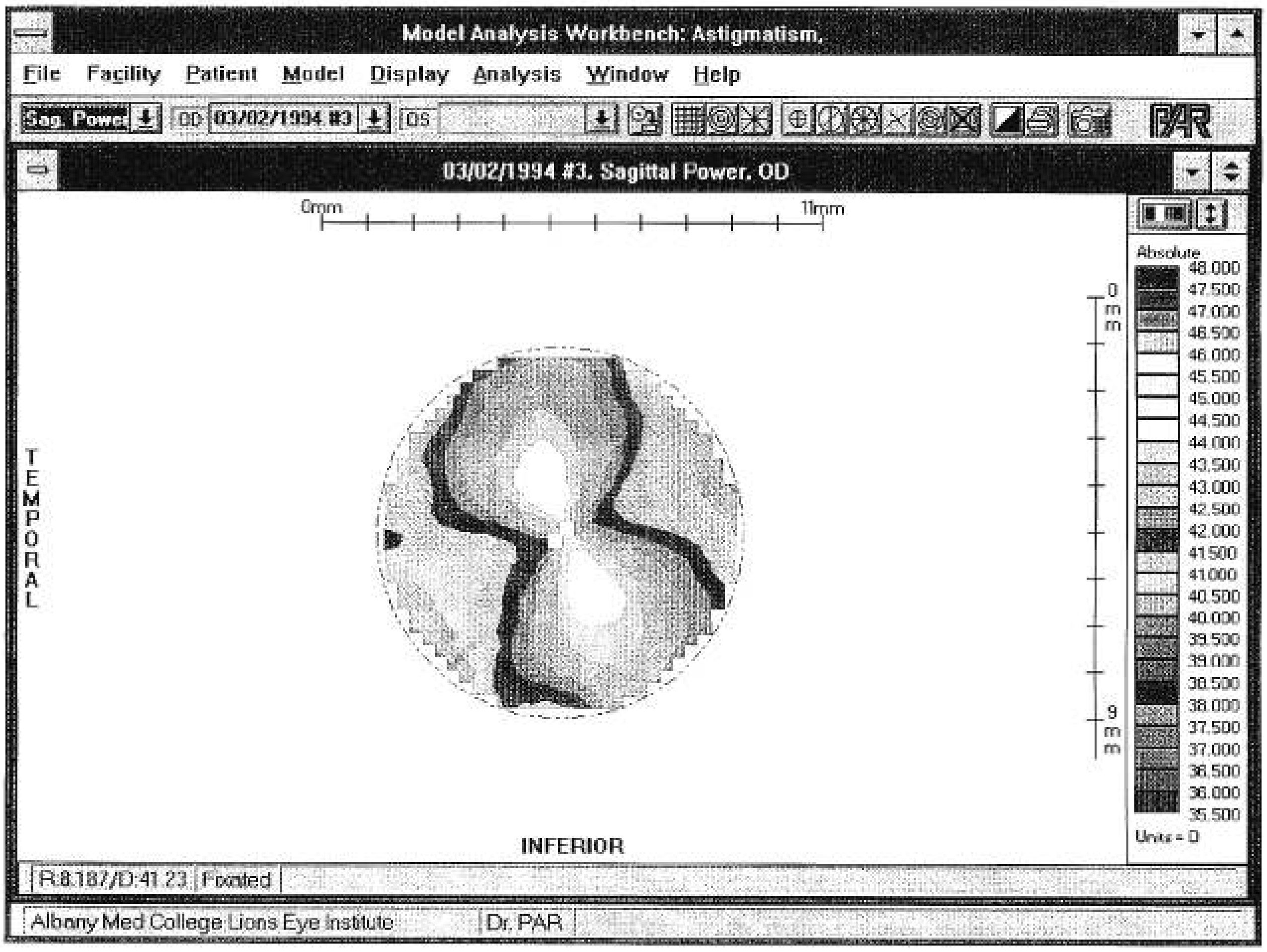


Figure 8. Sagittal (axial) curvature display. Sagittal curvature map of same astigmatic cornea in Fig. 6. The color display (hot-steep; cool-flat) is similar to other placido-based systems.

mediately after the laser ablation, showing the true laser effect. Placido-based systems rely on a preprocedure image and a postepithelialization image, and subsequently merge epithelial removal, laser effect, and healing into the "surgical result."

Currently, topography is being advocated as an aid in the fitting of contact lenses. The use of topography as both a fitting aid and as a supplier of data for computer aided design/manufacture is limited by the fact that most systems cannot supply information beyond the 8.0-mm optical zone[14] and the accuracy of the data declines rapidly in the periphery. The PAR system is capable of greater corneal coverage and the independent computation of data points may increase accuracy in the corneal periphery.

CONCLUSION

Computer-assisted videokeratography has emerged as a useful clinical and research tool. All of the other currently available commercial units use a modified placido disc image (Eye Technology CLAS-1000 uses laser interferometry) and require a smooth reflective corneal surface for analysis. These systems produce a color-coded map that depicts the "curvature" of the cornea. The PAR CTS is unique in its image acquisition and processing and has a number of theoretical advantages over placido-based corneal imaging systems.

1. Measuring the "topography" of the cornea by a reflected placido image can yield errors and incomplete results when the cornea has sudden topographic changes encountered in patients with severe scarring, ulcerations, sutures, or who are immediately postoperative from photoablative or photorefractive procedures. Under these circumstances the image mires or reflected rings of a placido disc system will tend to merge into one another and become indistinguishable.

2. Placido disc-based videokeratoscopes measure the surface normal and derive the corneal curvature. True topography requires the determination of elevation. The PAR CTS projects a positive image onto the cornea and measures surface elevation instead of the surface normal. This al-

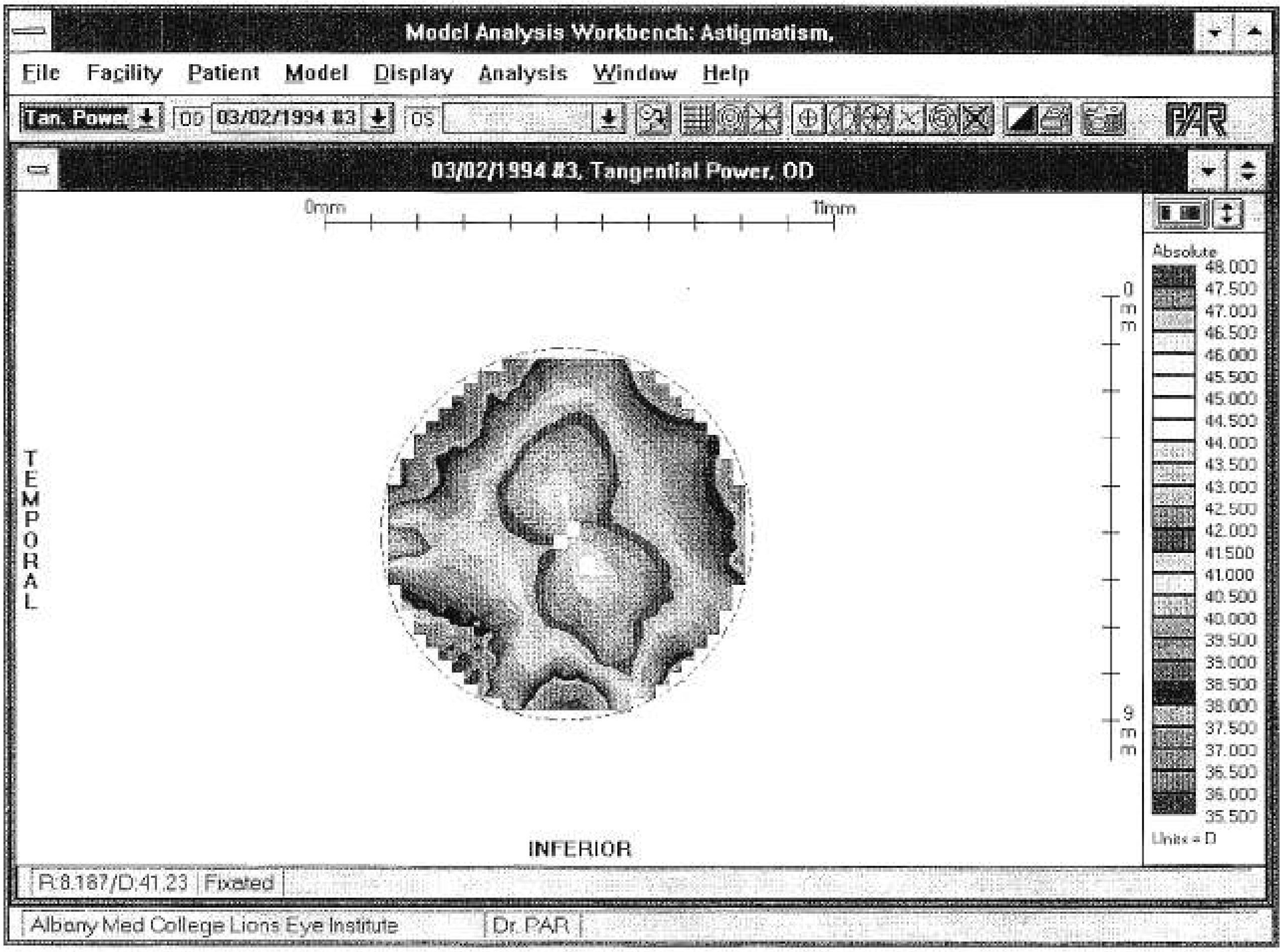


Figure 9. Tangential curvature display. Tangential curvature map of same cornea as in Figs. 6 and 8. Tangential maps are derived by computing the second derivative of the elevation function.

lows the system to measure much larger surface deviations than traditional placido disc-based systems. This departure from using reflected light enables the CTS to be used on corneas that do not reflect well because of scaring, epithelial defects, or irregular shape.

3. The PAR CTS can measure the surface topography of the cornea regardless of the cornea's orientation relative to the instrument. Proper use of placido-based systems requires that the rings be coaxial to the cornea. Improper positioning of placido-based systems will yield erroneous results. (Although PAR topographic data are independent of orientation, curvature by definition is orientation-dependent.)

4. Because the PAR CTS initially determines elevation, the data are more amenable to the mathematical computations necessary to determine ablation depths and optical zones for future photorefractive surgery or computer-added design for contact lens manufacture.

5. The combined use of elevation "true topography" and curvature maps may be a more sensitive indicator of corneal shape abnormalities (e.g., early ectasia).

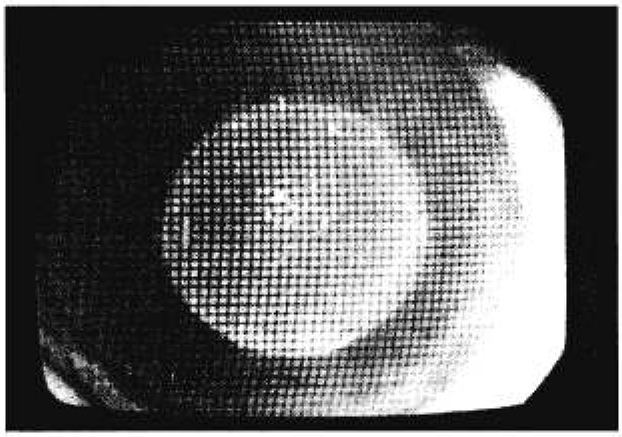


Figure 10. Deep keratectomy. Grid projection on a cadaver eye after a partial thickness keratectomy demonstrating the ability to analyze both intact epithelium and bare stroma concurrently.

6. The PAR CTS may be incorporated into various ophthalmic devices. Neither of the optical paths (projector or camera) needs to be coaxial, making integration into other optical devices

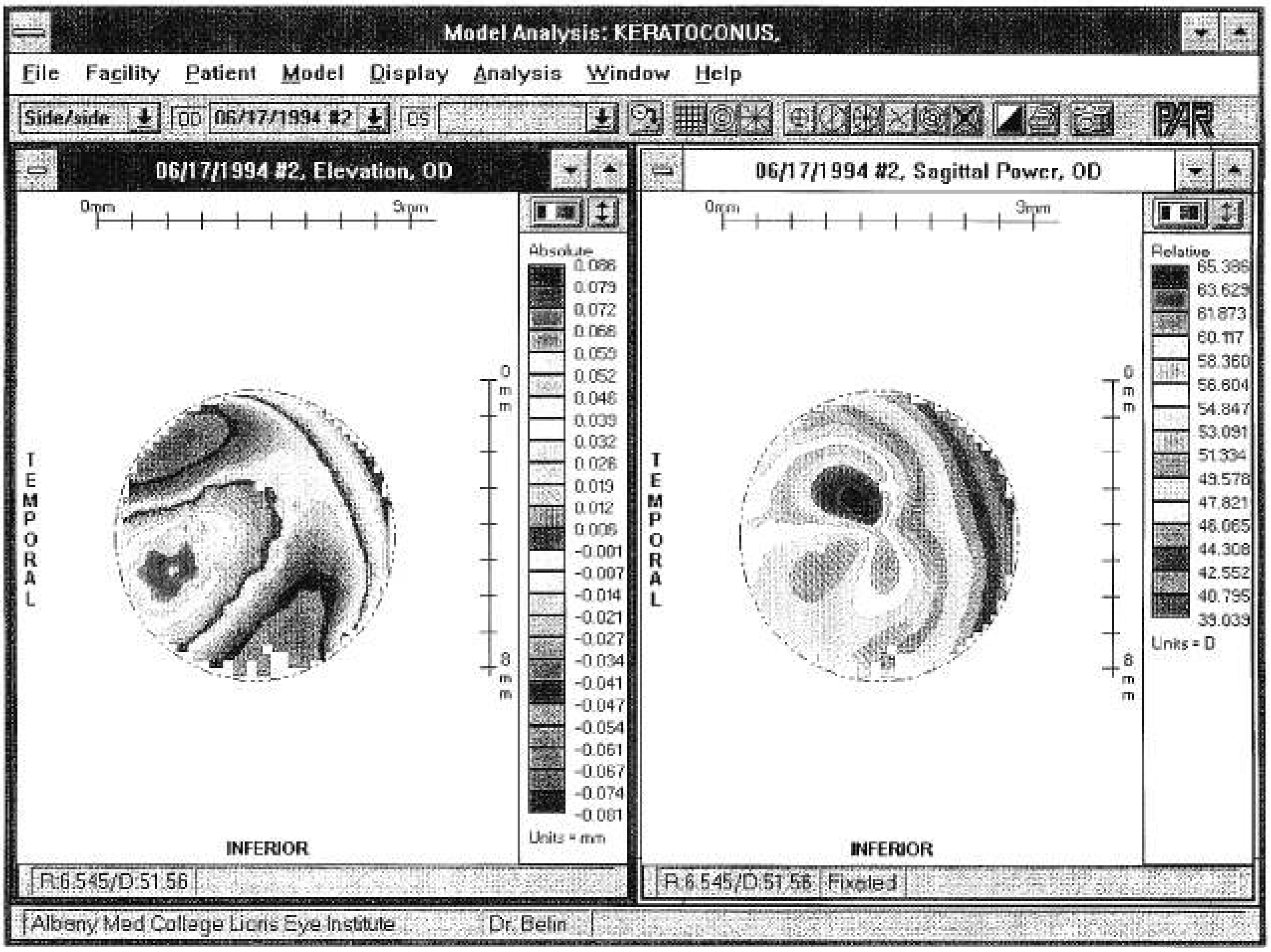


Figure 11. Keratoconus combined elevation and curvature maps. This shows the distinction between curvature and shape (ectasia). The sagittal curvature map locates the maximum curvature ("cone") superiorly ("atypical keratoconus"), whereas the true ectasia is located inferiorly.

(e.g., operating microscope, photoablative laser) relatively easy.

Computerized corneal analysis has become an integral part of refractive surgery and corneal diagnosis. The addition of elevation maps to complement curvature maps appears to enhance topography's clinical usefulness.

REFERENCES

1. Warnicki JW, Rehkopf PG, Curtin SA, Burns SA, Arffa RC, Stuart JC. Corneal topography using computer analyzed rasterstereographic images. Appl Opt 1988;27:1135–40.
2. Littoff D, Belin MW, Winn SS, Smith RS. PAR Technology Corneal Topography System. Invest Ophthalmol Vis Sci 1991;32(Suppl):922.
3. Belin MW, Litoff D, Strods SJ, Winn S, Smith RS. The PAR technology corneal topography system. Refract Corneal Surg 1992;8:88–96.
4. Belin MW, Zloty P. Accuracy of the PAR Corneal Topogaphy System with spatial misalignment. CLAO J 1993;19:64–8.
5. Belin MW. Intraoperative raster photogrammetry—the PAR corneal topography system. J Cataract Refract Surg 1993; 19(Suppl):188–92.
6. Arffa RC, Warnicki JW, Rehkopf PG. Corneal topography using rasterstereography. Refract Corneal Surg 1989;5: 414–7.
7. Roberts C. The accuracy of power maps to display curvature data in corneal topography systems. Invest Ophthalmol Vis Sci 1994;35:3525–32.
8. Applegate RA. Characterization of the inherent error in a spherically-biased corneal topography system in mapping a radially aspheric surface. Refract Corneal Surg 1994;10: 113–4.
9. El Hage SG. A computerized corneal topographer for use in refractive surgery. Refract Corneal Surg 1989;5:418–23.
10. Mandell RB. The enigma of the corneal contour. CLAO J 1992;18:267–73.
11. Hannush SB, Crawford SL, Waring GO, Gemmill MC, Lynn MJ, Nizam A. Accuracy and precision of keratometry, photokeratoscopy, and corneal modeling on calibrated steel balls. Arch Ophthalmol 1989;107:1235–9.
12. Hannush SB, Crawford SL, Waring GO, Gemmill MC, Lynn MJ, Nizam A. Reproducibility of normal corneal power measurements with a keratometer, photokeratoscope, and video imaging system. Arch Ophthalmol 1990;108:539–44.
13. Koch DD, Wakil JS, Samuelson SW, Haft EA. Comparison of the accuracy and reproducibility of the keratometer and the EyeSys Corneal Analysis System Model 1. J Cataract Refract Surg 1992;18:342–7.
14. Belin MW, Ratliff CD, Ditkoff J. Comparison of color topometry, rasterphotogrammetry and standard black and white videokeratography in the analysis of severely distorted corneas. Cornea 1995;14:117.

15. Belin MW, Ditkoff J, Ratliff CD. "Use of combined elevation and curvature maps in the detection of keratoconus" (presentation). International Society of Refractive Keratoplasty (ISRK) Annual Meeting, San Francisco, CA, 1994.
16. Rabinowitz YS, McDonnel PJ. Computer-assisted corneal topography in keratoconus. Refract Corneal Surg 1989;6: 400–8.

AUTHOR'S ADDRESS:
Michael W. Belin
Albany Medical College
Department of Ophthalmology
One Pinnacle Place, McKown Road
Albany, New York 12203