Is Keratoconus a True Ectasia?

An Evaluation of Corneal Surface Area

Michael K. Smolek, PhD; Stephen D. Klyce, PhD

Background: Keratoconus has long been considered to be an ectasia produced by stromal stretching. Although stretching should result in increased corneal surface area, previous observations of topography during progression of keratoconus have suggested that surface area may actually be conserved. A novel objective surface area measurement based on corneal topography was tested and applied to data from actual corneas under various conditions for comparative analysis.

Setting: The LSU Eye Center clinic videokeratography archives.

Methods: TMS-1 videokeratography files (Tomey Corp, Cambridge, Mass) were obtained from 6 groups of corneas: normal (n=29), keratoconus from mild to severe states (n=51), topographically judged keratoconus-suspect conditions (n=10), postoperative photorefractive keratectomy for myopia (n=39), with-the-rule corneal astigmatism (n=17), and keratoglobus (n=1). Additionally, 3 different spherical test surfaces were analyzed to verify the accuracy of the process. Only maps with no missing data out to ring 29 were used. The cumulative surface area from center to periphery was determined by calculating and summing the area of individual patches along consecutive annular rings. Mean surface area with respect to mean chord radius was plotted for each corneal condition, and curve fitting was used to extend each result to a 5.85-mm limbus. Means, SEs, and 95% confidence intervals were calculated at intervals for statistical comparisons among all groups. Computer-generated surfaces helped to evaluate the relationship between shape and surface area.

Results: When videokeratographic test targets were used, surface area error was less than 2%, which was deemed acceptable. Normal corneas had a mean ± SE surface area of 120.3 ± 2.2 mm², whereas all keratoconus corneas combined had a mean ± SE surface area of 116.2 ± 3.4 mm². The difference was not significant at any chord radius (analysis of variance, P<.05). The keratoglobus cornea was found to have a surface area of 129.9 mm², which was 7.98% greater than normal. An individual with progressive keratoconus exhibited no appreciable trend toward increasing surface area during a 76-month period. The corneas in the other groups resembled normal corneas in their total surface area.

Conclusions: With the exception of the single case of keratoglobus, corneal surface area tended to be conserved near a value of 120 mm² for all groups in the study, including corneas with keratoconus. Surface area is remarkably insensitive to curvature change near the vertex. Flattening seen in the periphery of corneas with keratoconus suggests that biomechanical coupling compensates for any increase in curvature occurring in the region of the cone itself. Thus, it seems that keratoconus is not a true ectasia as is keratoglobus, but rather a specialized type of warpage, at least in mild to moderate forms of the disease.


Keratoconus is a degenerative corneal disease characterized by a localized region of stromal thinning that is spatially associated with a cone-shaped deformation of the surface. It has been inferred that keratoconus is an ectasia resulting from stromal stretching. The term ectasia is defined as a dilation, expansion, or distension, all of which invoke the notion of an increase in surface area by a process of stretching. Despite wide acceptance that keratoconus represents a true ectasia, it has never been confirmed by objective measurements, nor have any accurate corneal surface area measurements been made from living corneas (Table 1).

We hypothesized that total corneal surface area during the progression of keratoconus remains essentially identical to that of normal corneas. The reasons for this counterintuitive hypothesis are 2-fold. First, simple mathematical calculations reveal that the total surface area of a hemisphere is not appreciably increased by the addition of a region of localized steepening. Second, the corneal periphery covers a proportion-
MATERIALS AND METHODS

SURFACE AREA ALGORITHM

A computer algorithm was derived to calculate the surface area of a 3-dimensional conic section surface modeling the cornea, a videokeratographically acquired test surface, or a videokeratographically acquired surface of a living cornea. Using this algorithm, the surface was divided from center to periphery into concentric rings of known elevation, with 256 patches distributed at equal meridional angles along each ring. A value of 256 patches per ring was chosen to comply with the data acquisition format of the TMS-1 videokeratoscope (Tomey Corp, Cambridge, Mass).

The surface area of each patch was calculated by first determining its axial radius of curvature using the following relationship: $r = y^2/2s + s/2$, where $s$ is the sagitta determined for a chord radius, $y$ (Figure 1).16 We define chord radius as the distance from the axis of rotation of a conic section or the videokeratographic axis to a point on the surface that defines the location of the patch. The sagitta and chord radius values can be generated from equations describing a theoretical surface, or in the case of videokeratography, using data contained in the RAD and HIT files of the TMS-1. Note that values for radius of curvature also can be back-calculated from the DIO file. However, this approach was tried and found to generate increasing, albeit minor, inaccuracies in surface area measurements toward the periphery. These inaccuracies may be consistent with the minor peripheral curvature inaccuracies reported previously.17

Given an elevation height ($h$) and radius of curvature ($r$) for each patch, the equation $A = 2\pi rh$ was applied to determine the total surface area ($A$) of a segment of height $h$ for a sphere of radius $r$ (Figure 1).16 The surface area ($A$) of the segment was then divided by 256 to determine the effective surface area of a single patch. The process was repeated for each patch on the surface. Using this approach, the surface area of any complex surface could be determined. When modeling a theoretical surface in a patchwork fashion, $h$ was given a constant height of 50 µm, but when deriving area from TMS-1 videokeratographic data, $h$ was determined from the HIT file by obtaining the mire inter-ring elevation height. Only the first 29 rings were used in the analysis of videokeratographic data. Although there were more patches (the total number depending on the shape) measured for a modeled surface, compared with 7424 patches when using a videokeratograph, the modeled surface patches were proportionately smaller and this difference was found to have no effect on the total surface area measurement. Although the surface area of each patch tended to increase from center to periphery, individual patch areas were, on average, only 0.016 mm² when videokeratographic data were used.

The area of each patch was added to a running total for each ring. The total surface area of each ring was then added to a cumulative total surface area out to a chord radius of at least 6 mm for modeled surfaces or out to ring 29 of the videokeratograph. Because chord radius varies for each patch and is dependent on the shape of the surface, the mean chord radius for each ring was determined in order to plot surface area as a function of chord radius.

MATHEMATICAL MODEL TESTING

The computer algorithm was tested by generating a wide variety of spherical and ellipsoidal surfaces of the following formula: $x^2/a^2 + y^2/b^2 + z^2/c^2 = 1$, where $x$, $y$, and $z$ are coordinates of surface points and $a$, $b$, and $c$ are the axis intercepts of the surface along the $x$, $y$, and $z$ directions. Spheres of various sizes as well as both rotationally symmetric and asymmetric ellipsoids can be modeled by choosing the appropriate axis intercept values. The surface areas of theoretical shapes (or any portion of the shapes) were then computed using a noniterative approach,19 and the results compared with the iterative approach of the computer algorithm to confirm the validity of the algorithm.

TMS-1 VALIDATION TESTING

Before analyzing the corneas of living eyes, we assessed the ability of the TMS-1 system to generate height and chord radius values that could provide accurate area measurements, ately greater surface area than the central cornea, such that a minimal amount of peripheral flattening might compensate for the emergence of a cone elsewhere on the surface. Because of its subtle nature, peripheral flattening is a rarely recognized sign of keratoconus.14 An example of superior peripheral flattening of corneas with inferiorly located keratoconus has been shown with cinemakeratography, an animated form of videokeratography that enhances visualization of curvature change.14,15

This study describes a novel method for the objective measurement of surface area using data obtained from videokeratography. During the first part of the study, a computer algorithm was designed and tested using mathematical formulas relating surface area to radius of curvature, elevation height, and location on spherical surfaces. The method was extended by an iterative, patchwork approach to measure surface area on a variety of closed surfaces representing theoretical corneal shapes, including spheres and rotationally symmetric and asymmetric ellipsoids. Next, surface area measurements using the algorithm were validated with known test surfaces imaged using videokeratography. Finally, the surface areas of normal, astigmatic, keratoconus-suspect, keratoconus, keratoglobus, and surgically altered corneal groups were calculated using the algorithm in conjunction with patient videokeratographs. Averaged results from each group were compared with results from the normal group or with modeled surfaces of similar shapes. Surface area for keratoconus progression during a 76-month period was also measured to determine if any trends toward increasing surface area were present.

RESULTS

MATHEMATICAL MODEL VERIFICATION

As expected, there was no difference in surface area measurement between the iterative approach of the com-
as well as the algorithm’s ability to convert those data into surface area measurements. Videokeratography maps for 3 spherical test surfaces having vertex radii with curvatures of 9.3 mm, 7.8 mm, and 6.5 mm were provided by Computed Anatomy Inc (New York, NY) and subsequently analyzed for surface area by comparing the results with models of spheres with the same radius of curvature. Maps of more complex test surfaces were not available at the time of this study.

CORNEAL MAP ANALYSIS

TMS-1 videokeratography maps were obtained from adult patient records at the LSU Eye Center, New Orleans, La. Videokeratography had institutional review board approval at the LSU Eye Center and informed consent was obtained from all patients undergoing this procedure. Maps were obtained for normal corneas (n=29); clinically diagnosed keratoconus corneas that included 17 mild, 24 moderate, and 10 severe cases (n=51); topographically judged keratoconus suspects (n=10); postoperative photorefractive keratectomy for myopia cases (n=39); with-the-rule corneal astigmatism cases (n=17); and a keratoglobus cornea (n=1). It is important to note that there were as many moderate and severe keratoconus examples as mild forms, and our dataset was not skewed toward early forms of the disease. We specifically included as many severe cases of keratoconus as possible to detect any effects of the disease on corneal surface area. Normal corneas exhibited less than 1.5 diopters (D) of cylinder power measured by simulated keratometry. Astigmatic corneas had 1.5 D to 4.5 D of regular cylinder power. Keratoconus corneas were diagnosed by an ophthalmologist using traditional clinical signs such as corneal thinning and the Munson sign; our sample included mild, moderate, and severe forms of the disease as defined in a previous study.15 Keratoconus-suspect corneas were defined as those that could not be clinically classified as keratoconus, although they showed topographic patterns resembling mild keratoconus.20 The photorefractive keratectomy cases were randomly selected from videokeratography acquired at 1, 3, 6, 12, 18, or 24 months after the surgical procedure was performed using the VISX 20/20 excimer laser system (VISX Inc, Santa Clara, Calif). None of the corneas in the study had a history of contact lens wear.

As each TMS map was analyzed by the surface area algorithm, the chord radius and the computed surface area for each patch of the surface were written to a SigmaPlot 4.0 (SPSS Inc, Chicago, Ill) database file. If interpolated or missing values were encountered for any of the 7424 chord radius values from ring 1 to 29, the map was not used for surface area analysis. The dataset size of each category as described in the preceding paragraph indicates the final numbers of cases where TMS maps met the criterion of interpolation-free data.

By averaging surface area and chord radius plots obtained for each cornea in a group, a single best-fitting function to describe the mean surface area as a function of mean chord radius was determined for each corneal group, including the subgroups of the 3 levels of keratoconus severity (TableCurve 2D; SPSS Inc). Additionally, the mean ± SE surface area was evaluated at every 0.5 mm of chord radius and at a theoretical limbus of 5.85 mm, except for keratoglobus, for which n=1 (SigmaStat; SPSS Inc). All corneal groups except the single case of keratoglobus were curve-fitted with the following equation:

\[
X = a + bY^2
\]

where X signifies surface area and Y is the chord radius. The keratoglobus data were fitted better by the power function:

\[
X = aY^b
\]

The goodness of fit and predictive ability were demonstrated by a large overall F value and a coefficient of determination (R²) near the value of 1.

It was necessary to extrapolate the mean surface area plot for each group out to a chord radius of 5.85 mm to facilitate comparisons and calculate the total corneal surface area for a typical cornea. With the exception of rare cases of megalocornea, microcornea, and congenital glaucoma, corneas have an average diameter of 11.7 mm at the limbus.21-23 To facilitate comparisons and emphasize differences, we plotted the residual difference between the mean surface area for each keratoconus group and the normal group (which served as a control), as a function of chord radius.

MEAN SURFACE AREA BY CORNEAL CONDITION

Results for all corneal conditions are shown in Table 2. Normal corneas had a mean surface area of 120.3 ± 2.22 mm², which was 8% to 25% less than previous estimates based on spherical, ellipsoidal, or complex shape models6-10 and 13.6% greater than a flat plane-projection area estimate (Table 1).12 When the normal cornea group was compared with other groups, the surface area difference ranged from −3.41% to +1.58% (−4.1 mm² to +1.9 mm²) of that of the normal cornea with the exception of keratoglobus, which was estimated to be 7.98% (+9.6 mm²) greater than normal (Table 2). Because of the rarity of keratoglobus, caution should be used when assuming our result is typical. Likewise, extrapolation for a single set of data to the theoretical limbus may induce some inaccuracy.

The surface area difference plots for the corneas with keratoconus and keratoglobus as compared with nor-
mal corneas are shown in Figure 3. The keratoglobus data were consistently greater than those of the normal group, whereas the keratoconus data, subdivided by severity, tended to exhibit increasingly less surface area toward the periphery and were distributed such that mild keratoconus corneas were most similar to normal corneas and the most severe cases were most different from the normal cases. However, a 1-way analysis of variance comparing normal and keratoconus surface area for each of the subcategories of keratoconus at the 5.85-mm chord radius and at every 0.5-mm chord radius step indicated no significant difference among any pairs of points at any chord radius (P = .5–1.0). It is interesting to note that although the results are not significant, the tendency toward the reduction in surface area in the periphery in keratoconus is entirely consistent with our hypothesis that subtle peripheral flattening has an important influence on the surface area measurement. It seems to follow that the greater the severity of the cone, the greater the peripheral flattening, and the lower the total surface area. With only a single case of keratoglobus, it is impossible to know if the result is typical. However, this example does estimate a much larger surface area than was measured for either the normal or the keratoconus groups, and the value is well above the 95% confidence interval for either of the other 2 groups (Table 2).

**SURFACE AREA CHANGE DURING KERATOCONUS PROGRESSION**

We analyzed 8 videokeratography maps obtained during a period of 76 months from the left cornea of an individual with clinically diagnosed keratoconus situated in the inferior periphery. The disease progressed from a mild to a moderate state with as much as an 8-D increase in curvature at the steepest point on the topography map (Figure 4). The vertex curvature also increased to a lesser extent, but a point in the superior hemisphere directly opposite the steepest point of the cone was shown to decrease in curvature over time. In fact, the appearance of flattening covered a relatively large region of the superior hemisphere, but the visual impact was minimal when static images of the color-coded contours were viewed. The keratoconus prediction index (KPI) for this patient increased from 0.18 at month 0 to 0.36 at month 46, whereupon it remained stable to month 70 and then decreased to 0.33 at month 76. Although KPI is not specifically a severity index, it does correlate with keratoconus severity (R = 0.892; P < .001). The surface area at the limbus was plotted as a function of time (Figure 5). Despite the obvious trend toward worsening of keratoconus in this patient during a 6-year period, there was only a minor trend toward increasing corneal surface area, and this trend may be insignificant because over time; the data appeared to fluctuate about a mean value in a sinusoidal-like fashion. There was no statistical difference between the mean of the normal group and the mean of this patient’s surface area measurements during the 76-month period (Figure 5). However, there was considerably more variance in this patient’s data.

**SURFACE AREA AND CORNEAL ASTIGMATISM**

Maps from the TMS-1 of corneal astigmatism with 1.8 D, 3.4 D, and 3.5 D of cylinder oriented at various axes were modeled using nonrotationally symmetric ellipsoids, and then compared with the measured surface areas. Simulated keratometry values from the TMS-1 examinations were used to model the curvature of the cornea in the x and y directions, while the TMS-1 vertex radius of curvature provided the z-axis shape parameter. Table 3 shows that the 3 shape parameters (a, b, and c) of the theoretical ellipsoid models varied among the 3 examples. The surface area plots (Figure 6) were virtually identical in profile, however.

The fitted ellipsoid surface area functions (Figure 6) tended to slightly overestimate surface area toward the limbus because the ellipsoid data were generated solely with simulated keratometry and vertex powers and these parameters tend to describe curvature of the central cornea. Fitting curves to all the data (as was performed in

---

**Table 1. Previously Published Corneal Surface Area Values**

<table>
<thead>
<tr>
<th>Surface Area Estimate, mm²</th>
<th>Study</th>
<th>Method Used</th>
</tr>
</thead>
<tbody>
<tr>
<td>130</td>
<td>Maurice⁴</td>
<td>Sphere geometry</td>
</tr>
<tr>
<td>150</td>
<td>Ehlers⁷</td>
<td>General shape estimate</td>
</tr>
<tr>
<td>132</td>
<td>Kwok³⁹</td>
<td>Ellipsoid geometry</td>
</tr>
<tr>
<td>136.3</td>
<td>Hannam et al⁴⁰</td>
<td>Lotmar¹¹ aspherical cornea</td>
</tr>
<tr>
<td>104</td>
<td>Watsky et al²⁰</td>
<td>2-Dimensional plane</td>
</tr>
</tbody>
</table>

---

©2000 American Medical Association. All rights reserved.

Downloaded From: by a Non-Human Traffic (NHT) User on 10/30/2018
During the course of fitting models to corneas of various shapes, we realized that only certain ellipsoids appeared to be suitable models of the basic shape of the central cornea while simultaneously fulfilling a conservation of surface area principle. In other words, a corneal shape that is relatively steep in one meridian must be compensated either by flattening in another meridian (typically the orthogonal meridian) or by altering the eccentricity of the overall shape to the extent that surface area remains near a value of 120 mm². Corneas apparently do not exist in an infinite variety of shapes, but tend to exist only in forms that conserve surface area. This observation is analogous to the biomechanical concept of coupling, in which steepening in one meridian can induce flattening of the orthogonal meridian. Similarly, if surface area is conserved, then corneal volume must tend to remain constant.

Table 2 for all astigmatic corneas) would have resulted in a better solution. Our surface area data support the observation that the cornea is indeed flatter in the periphery than a true ellipsoid. The fact that corneas are not true ellipsoids also accounts for our normal corneal surface area calculation being approximately 12 mm² less than the theoretical corneal surface area estimated by an aspherical.

<table>
<thead>
<tr>
<th>43.84-D Sphere (Theoretical)</th>
<th>Normal Group</th>
<th>Keratoconus Group</th>
<th>Keratoconus Suspect Group</th>
<th>Corneal Astigmatism Group</th>
<th>Photorefractive Keratectomy Group</th>
<th>Keratoglobus Case</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of cases</td>
<td>1</td>
<td>29</td>
<td>51</td>
<td>10</td>
<td>17</td>
<td>39</td>
</tr>
<tr>
<td>Mean surface area</td>
<td>129.1</td>
<td>120.3</td>
<td>116.2</td>
<td>118.9</td>
<td>119.8</td>
<td>122.2</td>
</tr>
<tr>
<td>95% Confidence interval</td>
<td>. . .</td>
<td>±2.2</td>
<td>±3.4</td>
<td>±6.9</td>
<td>±6.5</td>
<td>±1.9</td>
</tr>
<tr>
<td>Percent from normal</td>
<td>+7.32</td>
<td>. . .</td>
<td>+3.41</td>
<td>−1.16</td>
<td>−0.42</td>
<td>+1.58</td>
</tr>
<tr>
<td>R²</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>F statistic</td>
<td>2 × 10⁻³</td>
<td>3 × 10⁻⁴</td>
<td>1 × 10⁻⁶</td>
<td>4 × 10⁻⁶</td>
<td>7 × 10⁻⁶</td>
<td>4 × 10⁻⁶</td>
</tr>
<tr>
<td>b Fit SE</td>
<td>0.216</td>
<td>0.086</td>
<td>0.428</td>
<td>0.076</td>
<td>0.178</td>
<td>0.235</td>
</tr>
<tr>
<td>a</td>
<td>−1.7 × 10⁻³</td>
<td>−9.1 × 10⁻⁴</td>
<td>0</td>
<td>−8.1 × 10⁻⁴</td>
<td>−9.7 × 10⁻⁴</td>
<td>−6.4 × 10⁻⁴</td>
</tr>
<tr>
<td>b</td>
<td>0.325</td>
<td>0.316</td>
<td>0.304</td>
<td>0.316</td>
<td>0.319</td>
<td>0.302</td>
</tr>
<tr>
<td>Mean vertex radius-of-curvature</td>
<td>. . .</td>
<td>±2.2</td>
<td>±3.4</td>
<td>±6.9</td>
<td>±6.5</td>
<td>±1.9</td>
</tr>
<tr>
<td>Percent from normal</td>
<td>+7.32</td>
<td>. . .</td>
<td>+3.41</td>
<td>−1.16</td>
<td>−0.42</td>
<td>+1.58</td>
</tr>
<tr>
<td>R²</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>F statistic</td>
<td>2 × 10⁻³</td>
<td>3 × 10⁻⁴</td>
<td>1 × 10⁻⁶</td>
<td>4 × 10⁻⁶</td>
<td>7 × 10⁻⁶</td>
<td>4 × 10⁻⁶</td>
</tr>
<tr>
<td>b Fit SE</td>
<td>0.216</td>
<td>0.086</td>
<td>0.428</td>
<td>0.076</td>
<td>0.178</td>
<td>0.235</td>
</tr>
<tr>
<td>a</td>
<td>−1.7 × 10⁻³</td>
<td>−9.1 × 10⁻⁴</td>
<td>0</td>
<td>−8.1 × 10⁻⁴</td>
<td>−9.7 × 10⁻⁴</td>
<td>−6.4 × 10⁻⁴</td>
</tr>
<tr>
<td>b</td>
<td>0.325</td>
<td>0.316</td>
<td>0.304</td>
<td>0.316</td>
<td>0.319</td>
<td>0.302</td>
</tr>
</tbody>
</table>

*S* indicates diopters; *R*², the coefficient of determination; *a* and *b*, the parameters for all curves described in the table, corresponding with the equation $X = a Y^b$, where $X$ is the surface area and $Y$ is the chord radius.

**SURFACE AREA AND SPHERICITY**

The mean vertex radius-of-curvature of the normal cornea group was 7.70 mm (43.84 D), which amounts to a surface area of 129.1 mm² at a limbus radius of 5.85 mm for a perfectly spherical cornea (Figure 3, Table 2). This value is only 0.69% less than the often-cited estimate of 130 mm² reported by Maurice, but is 7.32% larger than the measured surface area of the living cornea, which is aspherical.

Spheres have relatively greater surface area in the periphery for a given chord radius, compared with actual corneas, particularly beyond 3.5 mm into the periphery. Nevertheless, the periphery contains a significantly greater proportion of the actual corneal surface;
approximately 50% of the total surface area of the cornea is located within a 1.5-mm-wide annulus and adjacent to the limbus (Figure 6, Right scale). Therefore, centrally located deformations that invoke any increase in localized surface area could be totally compensated by a decrease in surface area produced by a flattening in the far periphery. Simultaneous cone steepening and peripheral flattening is known to occur in keratoconus.3,13–15 We have shown that the most severe form of keratoconus may have a greater than normal surface area within the central 4 mm, but this is offset by a tendency for relatively less area toward the far periphery (Figure 6). Simultaneous cone steepening and peripheral flattening may arise out of a localized steepening elsewhere on the surface of the cornea. A slight peripheral flattening may arise out of a localized steepening elsewhere on the surface of the cornea.

Based on our results, our hypothesis that keratoconus and normal corneas have virtually identical surface areas seems to be correct. We conclude that several factors contribute to this condition: (1) The closer a region of localized steepening is to the corneal vertex, the less effect it has on total surface area. (2) A localized region of steepening such as is seen with a well-defined cone tends to contribute to only a small portion of the total surface area. (3) Steepening in one localized region can produce flattening elsewhere on the cornea through biomechanical coupling. (4) A 2-dimensional map of the corneal surface greatly deemphasizes the contribution of the corneal periphery to surface area. (5) In an absolute color-contour map, a subtle, peripheral flattening effect producing only one color contour step or less spread over a large corneal area may be barely noticeable when com-
pared with a well-defined cone exhibiting several color contour steps; however, the effects of flattening and steepening may counterbalance one another and produce no significant change in total surface area.

Thus, the concept of a cone produced primarily by stromal stretching seems to be an entirely intuitive construct used to explain keratoconus deformation and the illusion of an increased surface area. Any stretching that does occur is probably highly localized and relatively insignificant when compared with the total area of the surface. Stromal thinning, which has often been associated with stretching, may be a direct result of the degenerative process, rather than linked to a stretching process.

To emphasize that the topographic appearance of shape change is not necessarily linked to stretching, consider an example of contact lens–induced corneal warpage. It is well known that corneal curvature can change dramatically with contact lens–induced warpage, so much so that it can on occasion resemble early keratoconus. However, a warped cornea typically regains a normal topographic appearance after cessation of lens wear. It is difficult to conceive of a process whereby contact lens wear increases cornea surface area by stretching, and then returns it to a completely normal shape in a matter of days. It seems more reasonable that the topographic appearance is related not to stretching, but rather to deformations acting under the principle of surface area conservation.

A literature review of the past 33 years indicated that more than 75% of corneas with keratoglobus spontaneously ruptured prior to treatment, but fewer than 1% of corneas with keratoconus were reported to have ruptured. This result may be indicative of differences in treatment for these conditions, but perhaps a better explanation is that corneas with keratoconus rarely burst simply because surface area is conserved and the stroma’s elastic limit is never reached. Edmund compared the elastic modulus of normal corneas and corneas with keratoconus reported in several previous studies, and found no difference in the immediate elastic response of the tissue, although viscoelastic tissue properties differed with keratoconus. Even if elasticity does increase in keratoconus, there is no conflict with the results of our study. Increased elasticity alone does not imply that the surface area must increase by stretching, provided that strain-inducing stresses are controlled. It is important to note that acute hydrops occurs in about 6% to 8% of all keratoconus cases; however, microscopic tears of the Descemet membrane alone would not be expected to significantly increase corneal surface area, even though they do suggest biomechanical events occurring throughout the corneal structure.

In a simplistic sense, the decreasing radius-of-curvature of an emerging cone may act as a stress-reducing mechanism that also counteracts the effects of a diminishing cross-sectional thickness of a shell according to the following well-known relationship: $S = P (r/2t)$, where $S$ is the stress tension in the corneal shell, $P$ is the intraocular pressure, $t$ is the thickness of the tissue, and $r$ is the radius of curvature. Similarly, the increasing amount of flattening (ie, a larger radius of curvature) in thicker corneal regions distant from the cone should allow higher stresses to be tolerated without requiring any concomitant increase in surface area from stress-induced stretching.

On the other hand, untreated corneas with keratoglobus tend to rupture because the entire corneal surface is involved in the disease, which means that no other region can be recruited to deform in a way that will minimize stress and thus conserve surface area. Once the elastic threshold is reached in this completely thinned tissue, it can stretch no further and the tissue ruptures. From this standpoint, surface area measures may have some clinical benefit as a means of assessing structural integrity in these diseases, differentiating keratoglobus from keratoconus, and establishing a surface area threshold beyond which rupture is imminent.

In conclusion, the normal human corneal surface area was found to be approximately 120 mm² by measurements made on living eyes, and this value appears to be conserved in a variety of corneal shapes, including
that of corneas with keratoconus. Whenever corneal surface area remains constant, the possibility to remodel the surface into an optically useful shape remains feasible.

Accepted for publication March 21, 2000.

This work was supported in part by US Public Health Service grants EY03311 (Dr. Klyce) and EY02377 (LSU Eye Center core grant) from the National Eye Institute, National Institutes of Health, Bethesda, Md.

Presented in part at the annual meeting of the Association for Research in Vision and Ophthalmology, Fort Lauderdale, Fla, May 14, 1997.

Corresponding author: Michael K. Smolek, PhD, LSU Eye Center, 2020 Gravier St, Suite B, New Orleans, LA 70112 (e-mail: msmole@lsuhsc.edu).

REFERENCES


From the Archives of the ARCHIVES

A look at the past . . .

According to Leber and Krahnstover the appearance of choroidal sarcomas in eyes already phthisical is merely due to chance, their appearance after tracoma not having been sufficiently proven. Phthisis bulbi however is frequently the result of sarcoma, being brought about through irido-cyclitis. The development of the latter is favored by the tumor, since microorganisms which have been carried there find favorable conditions for development in the dead cells of the tumor and total necrosis of the tumor is brought about. The inflammation then, in consequence of disturbances in secretion, proceeds to phthisis.