Progression of Keratoconus Assessed by Fourier Analysis of Videokeratography Data

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Objective: To quantitatively document changes in corneal refractive parameters in relation to the progression of keratoconus over years.

Design: Retrospective observational case series.

Participants: Eighty-five eyes of 64 patients with keratoconus who had undergone videokeratography examinations at least twice with an interval of 1 year or longer between each examination.

Methods: By means of Fourier series harmonic analysis, topography data were decomposed into spherical component, regular astigmatism, decentration component, and higher order irregularity.

Main Outcome Measures: Change rate of each parameter per year was calculated by use of the least squares method.

Results: All four refractive parameters were significantly larger in the keratoconic eyes than in the age-matched normal controls (P < 0.001, Student’s t test). The yearly rate of change was significantly positive for spherical component (P = 0.008) and higher order irregular astigmatism (P = 0.015) but not for the regular astigmatism and decentration component. In eyes that showed apparent progression on color-coded maps, spherical component showed a significantly positive change rate per year (P = 0.002), but other parameters did not. In eyes without apparent progression, the yearly change rate of higher order irregular astigmatism was significantly larger than zero (P = 0.049).

Conclusions: Keratoconus progression over years was quantitatively described. It was indicated that spherical equivalent is a manifest indicator for the apparent progression of keratoconus, and irregular astigmatism increases along with the natural course of the disease. Ophthalmology 2002;109:339–342 © 2002 by the American Academy of Ophthalmology.

Keratoconus is a progressive, asymmetric, noninflammatory disease of the cornea characterized by steepening, distortion, and apical thinning of the cornea. This disease process results in mild to marked impairment of the quality of vision. In the past, the progression of keratoconus was evaluated clinically on the basis of indicators such as contact lens failure, development of acute hydrops, and progression to penetrating keratoplasty. The advent and widespread use of videokeratography made those judgments more sophisticated and systematic. A videokeratoscope is a computer-assisted device to analyze the contour of the anterior corneal surface, enabling precise and sensitive evaluation of the changes in corneal topography.

In practice, the progression of keratoconus can be best evaluated by analyzing the serially acquired corneal topography. Reports of serial analyses of the topography in keratoconic eyes, however, have been confined to a few case presentations, and a quantitative analysis of keratoconus progression in a large sample size has not been conducted. To detect and diagnose keratoconus, several quantitative indices have been devised on the basis of videokeratography measurements and hard contact lens fitting. These descriptors, however, have been used for the segregation analysis of keratoconus, and a longitudinal study on keratoconus progression using such quantitative parameters has not been reported. Because patients and physicians are greatly interested in what to expect regarding the rate and severity of visual malfunction, an objective way to address the progression and natural course of keratoconus is important. This study aimed to quantitatively analyze progression of keratoconus over the years.

Subjects and Methods

Eighty-five eyes of 64 patients with keratoconus who had undergone videokeratography examinations at least twice with an interval of 1 year or longer between each examination were retrospectively evaluated. They were diagnosed clinically; they had at least one clinical sign other than the topographic appearance of the map, which included, among others, slit-lamp findings of stromal thinning, Vogt’s striae, Fleischer ring, and Munson’s sign. Eyes were included only if a well-focused, smooth topographic image was obtained. Those with previous history of any ocular surgery including penetrating keratoplasty were excluded from the subjects. The age range of the subjects was 14 to 65 years old (28.3 ± 8.4 years old, mean ± standard deviation). There were 45 males and 19 females. The study adhered to the tenets of the Declaration of Helsinki.

Videokeratographic data were obtained with computerized...
videokeratography (TMS-1, Computed Anatomy Inc., New York, NY). For each eye, measurements were repeated at least three times to obtain a well-focused, properly aligned image of the eye, and one measurement having the most proper centration and focusing and the least eyelid shadow was chosen for the following analysis. The dioptric power of all measurement points was downloaded as an ASCII file.

By use of Fourier series harmonic analysis, dioptric powers on a mire ring, \( F_i(\sigma) \), can be transformed into trigonometric components of the form:20–22

\[
F_i(\sigma) = a_0 + \sum [a_n \cos(n\sigma) + b_n \sin(n\sigma)]
\]

(1)

This can be rewritten as follows:

\[
F_i(\sigma) = a_0 + c_1 \cos(\sigma - \alpha_1) + c_2 \cos(2(\sigma - \alpha_2))
\]

\[
+ c_3 \cos(3(\sigma - \alpha_3)) + \ldots + c_n \cos(n(\sigma - \alpha_n))
\]

(2)

where \( a_0 \) is the spherical equivalent of the ring, \( 2c_1 \) the decentration component, \( 2c_2 \) the regular astigmatism component, \( \alpha_2 \) the phase (or axis) of regular astigmatism, and \( c_{3..n} \) the nonregular astigmatism components in a strict sense (higher order irregular astigmatism).\(^23\) The decentration component represents asymmetry or skewness of the surface. Among these, spherical equivalent power \( (a_0) \) and regular astigmatism \( (2c_1, 2c_2) \) can be corrected by a spherocylinder lens, whereas the remaining components \( (n = 1 \text{ and } n \geq 3) \) cannot. Therefore, \( 2c_2 \) and \( c_{3..n} \) represent corneal irregular astigmatism in a broad sense.

These calculations were done on rings 2 to 9, which approximately represent the central 3-mm zone of the cornea,\(^23\) and the values were averaged for each parameter. For each parameter of each eye, the yearly rate of change was computed by use of the least squares method. Forty eyes of 20 subjects served as age-matched normal controls. For each eye, measurements were repeated at least three times, 16 eyes (19%) four times, and 16 eyes (19%) five times or more.

Refractive parameters calculated by Fourier analysis of the videokeratography data on the first examination are shown in Table 1. All the parameters, including spherical component, regular astigmatism, decentration component, and higher order irregular astigmatism, were significantly larger in the keratoconus group than in the normal controls \( (P < 0.001, \text{Student’s } t \text{ test}) \).

The yearly rate of change calculated for each parameter in the keratoconus group is shown in Table 2. The rate was significantly larger than zero for spherical component and higher order irregular astigmatism but not for regular astigmatism and decentration component.

On the color-coded maps, 24 eyes were judged to have apparent progression of keratoconus during the follow-up period, whereas 61 eyes were judged to have no progression. In eyes with apparent progression, spherical component showed significantly positive change rate per year, but other parameters did not (Table 3). In eyes without apparent progression, the yearly change rate of higher order irregular astigmatism was significantly greater than zero but not for other parameters.

### Results

Seventeen eyes (20%) underwent videokeratography examinations twice with an interval of 1 year or longer, 36 eyes (42%) three times, 16 eyes (19%) four times, and 16 eyes (19%) five times or more.

Refractive parameters calculated by Fourier analysis of the videokeratography data on the first examination are shown in Table 1. All the parameters, including spherical component, regular astigmatism, decentration component, and higher order irregular astigmatism, were significantly larger in the keratoconus group than in the normal controls \( (P < 0.001, \text{Student’s } t \text{ test}) \).

The yearly rate of change calculated for each parameter in the keratoconus group is shown in Table 2. The rate was significantly larger than zero for spherical component and higher order irregular astigmatism but not for regular astigmatism and decentration component.

### Discussion

By use of Fourier series harmonic analysis, we decomposed the topography data into four refractive components, such as spherical component, regular astigmatism, decentration component, and higher order irregularity. As shown in the results, all four components were significantly greater in the keratoconic eyes than in the normal controls (Table 1), indicating that corneas with evident keratoconus have significantly steeper curvature, larger astigmatism, more asymmetry, and severer irregularity. These findings are in agreement with previous qualitative interpretation of color-coded maps of videokeratography.\(^24–26\)

The time-course of changes in refractive components was evaluated by analyzing the serially acquired corneal topography over years. The calculated change rate per year was significantly positive for spherical component and higher order irregular astigmatism (Table 2). This result suggests that the progression of keratoconus may be represented by increases in spherical component and higher order irregular astigmatism. Maguire and Lowry\(^8\) reported that an increase of the refractive power at the cone apex seen on the corneal topography was a good indicator of progression of keratoconus. Studies using a keratometer indicated that increased central steepening over time is one of the characteristic signs of keratoconus.\(^1\) Smolek et al\(^10\) demonstrated with cinemakeratography that, in parallel with the progression of keratoconus, steepening of the cone apex and increases in corneal irregularity, such as peripheral steepening.

### Table 1. Mean Refractive Parameters Calculated by Fourier Analysis of Videokeratography Data in Keratoconus Group and Normal Controls

<table>
<thead>
<tr>
<th></th>
<th>Keratoconus* (85 Eyes)</th>
<th>Normal Controls (40 Eyes)</th>
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<tbody>
<tr>
<td>Spherical component</td>
<td>48.8 ± 4.6* (D)</td>
<td>43.5 ± 1.3 (D)</td>
</tr>
<tr>
<td>Regular astigmatism</td>
<td>2.5 ± 2.2* (D)</td>
<td>0.39 ± 0.29 (D)</td>
</tr>
<tr>
<td>Decentration component</td>
<td>3.5 ± 2.5* (D)</td>
<td>0.25 ± 0.69 (D)</td>
</tr>
<tr>
<td>Higher order irregular astigmatism</td>
<td>1.3 ± 1.2* (D)</td>
<td>0.11 ± 0.06 (D)</td>
</tr>
</tbody>
</table>

\(D = \text{Diopters.} \)

*Significantly larger than normal controls \( (P < 0.001, \text{Student’s } t \text{ test}) \).

### Table 2. Yearly Change Rate of Refractive Parameters Calculated by Fourier Analysis of Videokeratography Data

<table>
<thead>
<tr>
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<th>Rate of Change per Year</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spherical component</td>
<td>0.41 ± 1.39 (D)</td>
<td>0.008*</td>
</tr>
<tr>
<td>Regular astigmatism</td>
<td>0.022 ± 0.74 (D)</td>
<td>0.783</td>
</tr>
<tr>
<td>Decentration component</td>
<td>−0.079 ± 0.98 (D)</td>
<td>0.460</td>
</tr>
<tr>
<td>Higher order irregular astigmatism</td>
<td>0.068 ± 0.25 (D)</td>
<td>0.015*</td>
</tr>
</tbody>
</table>

\(D = \text{Diopters.} \)

*Significantly larger than zero (Student’s t test). \( N = 85 \text{ eyes.} \)
and relative cone expansion, were observed. The results of this study quantitatively confirm those previous findings.

By qualitatively comparing the color-coded maps of the first and last visits, we classified the eyes into two groups. In eyes that showed apparent progression of keratoconus on the map during the follow-up period, spherical component increased significantly (Table 3). Higher order irregular astigmatism tended to increase, but the correlation was not significant. This may be due to the noise of measurements, variability of study group, small number of eyes in this subgroup, or high level of irregular astigmatism already existing on the first examination. In eyes without apparent progression, spherical component did not increase, but the higher order irregular astigmatism increased significantly. It was suggested that corneal irregularity increases even in the absence of clinically observable progression of keratoconus, and the irregular astigmatism component calculated by Fourier analysis of the videokeratography data could be a useful index for the detection and documentation of keratoconus progression in eyes without apparent topographic changes.

One weakness of our study is the use of sagittal maps in the qualitative evaluation of keratoconus progression. It has been known that the sagittal map based on axial distance is less sensitive than the tangential map, derived from instantaneous radius of curvature algorithms, in detecting subtle corneal topographic changes in keratoconus. Moreover, the instantaneous curvature map has been reported to better represent the apical position and apex curvature in keratoconus than the axial curvature map. Because the instantaneous curvature map was not available to our topographer, the current qualitative judgments might have underestimated the actual progression of keratoconus. Further studies are needed to explain these points.

References


