Corneal and Refractive Astigmatism in a Sample of 3- to 5-Year-Old Children with a High Prevalence of Astigmatism

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ABSTRACT: Purpose: To examine the relation between corneal and refractive astigmatism in a sample of pre-school-age Native American children with a high prevalence of astigmatism. Methods: Subjects were 250 Tohono O’odham children, 3 to 5 years of age. Each child had corneal astigmatism measured with the Marco Nidek KM-500 portable autokeratometer without pupil dilation, and with the Nikon Retinomax K-Plus portable autorefractor/autokeratometer without and with pupil dilation. Refractive astigmatism was measured using the Retinomax K-Plus, with cycloplegia, confirmed by retinoscopy. Results: Corneal astigmatism exceeded refractive astigmatism, with a median vector dioptric difference of 0.88 D for the KM-500, 0.76 D for the Retinomax K-Plus without dilation, and 0.75 for the Retinomax K-Plus with dilation. The relation between corneal and refractive astigmatism was adequately described by the modification by Grosvenor et al. of Javal’s rule, but not by Javal’s rule. Conclusions: The results are in agreement with data reported previously for older Native American and non-Native American populations. The modified Javal’s rule adequately describes the relation between corneal and refractive astigmatism in a population; however, this rule does not provide accurate prediction of refractive astigmatism in individual children or adults. (Optom Vis Sci 1999;76:855–860)

Key Words: astigmatism, Native Americans, children, corneal astigmatism, refractive astigmatism, Javal’s rule

A high prevalence of astigmatism has been reported among school-age and adult members of some Native American tribes, including Navajo,1-3 Sioux,4-8 Tohono O’odham,9,10 and Zuni.2,11 Although studies have indicated that astigmatism among Native Americans is primarily corneal (rather than lenticular),5,9,11,12 only three studies have examined the relation between corneal and refractive astigmatism in a Native American population,5,5,11 and none of these have included children in the pre-school-age group.

In 1890, shortly after he invented his keratometer, Javal formulated a rule that related the cylindrical power of the cornea to the total (refractive) astigmatism of the eye.13 This rule states that:

\[ \text{total astigmatism} = p \text{ (corneal astigmatism)} + k \]

where \( p \) is 1.25 and \( k \) is 0.50 diopter (D) against-the-rule astigmatism. More recently, Grosvenor et al.14 provided a modified version of Javal’s rule, in which the value of \( p \) is 1.00. Although estimates of both \( p \) (the slope of the line) and \( k \) (residual, noncorneal astigmatism) have varied, recent researchers have concluded that the modified rule provides a satisfactory description of the relation between total and corneal astigmatism that can be applied across a range of populations.15,16 pupil diameters,17 and amounts of astigmatism.18 Data from 420 Zuni children, kindergarten through grade 12, suggest that the modified rule can also provide a good description of the relation between corneal and refractive astigmatism in Native American children; the value obtained for \( p \) was 1.05 and the value for \( k \) was 0.39.11 Similarly, in a population of 571 Sioux tribal members between 5 and 70 years of age, the value obtained for \( p \) was 1.08 and the value for \( k \) was 0.65.5 More recent data comparing corneal and refractive astigmatism in 1106 Navajo children between 6 and 20 years of age did not provide an estimate of \( p \) or \( k \), but did report an average difference between corneal and refractive astigmatism of 0.44 D.3

The purpose of the present study is to provide data relating corneal and total astigmatism in an even younger group of Native American children. These children are 3- to 5-year-old members of the Tohono O’odham Nation, a population with a documented high prevalence of astigmatism in adults10 and school-age children.9,10
METHODS
Subjects

Subjects were 250 children between 3 and 5 years of age who
were participants in the Tohono O'Odham Early Childhood Head
Start program in the fall of 1997. The group represents approxi-
mately one half of all children in this age range who live on the
Tohono O'Odham reservation. Twenty-nine additional children
were tested, but their data were excluded from analyses be-
cause they were younger than 3 years (n = 7) or were 5 years or older
(n = 2) on the first day of class (September 1, 1997), were classified
as “special needs” by the Head Start program (n = 17), had ocular
abnormalities other than ametropia (n = 1 with nystagmus), or did
not undergo cycloplegic refraction (n = 2).

Procedure

The study was approved by the Institutional Review Board of
the University of Arizona, and informed written consent was ob-
tained from parents of all children before testing. Before dilation,
each child’s corneal astigmatism was measured with the Marco
Nidek KM-500 hand-held automated keratometer and the Nikon
Retinomax K-Plus (RmaxK+) autorefractor/autokeratometer
(Nikon Corp, Tokyo, Japan). The KM-500 provides one measure-
ment of corneal astigmatism for each eye. The RmaxK+ makes up
to eight measurements of corneal astigmatism and up to eight
measurements of refractive error for each eye; it then provides one
composite measurement of corneal astigmatism and one compos-
te measurement of refractive error for each eye. Typically, eight
measurements are completed in < 15 s.

After testing with the KM-500 and the RmaxK+, each child
received one drop of proparacaine 0.5% in each eye, followed
immediately by one drop per eye of 2% cyclopentolate, followed 5
min later by one drop per eye of 1% cyclopentolate. Girls weigh-
ing < 35 pounds, boys weighing < 35 pounds, and any child with
a history of seizures were given 1% cyclopentolate in place of the
2% cyclopentolate. Forty minutes or more after instillation of the
first dilating drop, adequacy of cycloplegia was assessed using dy-
namic retinoscopy. If inadequate, refraction was delayed for at least
5 additional minutes. Corneal astigmatism and refractive error
were measured to the nearest 0.25 D with the RmaxK+. A pedi-
atrie ophthalmologist or optometrist who was masked to the
RmaxK+ results used retinoscopy, along with a phoropter or a
skiascopy rack, to measure the refractive error of each eye to the
nearest 0.25 D. If the vector dioptric distance (VDD) between
the RmaxK+ and retinoscopy results was less than 1.50 D, the
RmaxK+ results were used as the measure of cycloplegic re-
fractive error. If the difference was 1.50 D or more, a second
RmaxK+ reading was obtained. If this value differed by less than
1.50 D from the retinoscopy reading, the second RmaxK+ value
was used as the measure of cycloplegic refractive error. Otherwise,
the retinoscopist made another (unmasked) measurement and the
value obtained was used as the measure of cycloplegic refractive
error. This final step occurred in only 17 (7%) of 250 children
tested.

Data Analysis

Results are presented for the right eye of each subject, to avoid
the lack of independence of data points that occurs when both eyes
of an individual subject are entered into the analysis.

For the primary analysis, the VDD between corneal and refrac-
tive astigmatism measurements was calculated using a method de-
scribed by Long19 and modified by Harris20, 21 (see Appendix).
This method incorporates both cylinder power and cylinder axis
into calculations of differences. Because corneal astigmatism mea-
sures the astigmatic error and refraction measures spherical and
astigmatic correction, vectorial comparisons were made only on the
astigmatic component of the refractive measure of astigmatism,
after it was converted into an equivalent error. A vertex distance
correction of astigmatic power was not made, in keeping with
previous studies.

In addition, because most previous studies have reported differ-
cences between corneal and refractive astigmatism only in terms of
cylinder power, we conducted a secondary analysis of our data in
terms of cylinder power alone. To be consistent with previous
studies, we used parametric statistics (mean and SD) to character-
ize differences between corneal and refractive astigmatism, even
though the differences are typically not normally distributed.

RESULTS

Prevalence of Refractive Astigmatism

The results confirmed previous reports of a high prevalence of
refractive astigmatism among members of the Tohono O’Odham
nation.9, 10, 25 Among the 250 subjects, 109 (44%) had astigma-
mast ≥ 1 D, 54 (22%) had astigmatism ≥ 2 D, and 28 (11%) had
astigmatism ≥ 3 D. Among the 109 subjects with astigmatism
≥ 1 D, 100 (92%) had with-the-rule astigmatism with plus
cylinder axis of 90 ± 15° and 108 (99%) had plus cylinder axis of
90 ± 30°. No subjects had against-the-rule astigmatism, and one
subject had oblique astigmatism (axis 54°).

Comparison between Corneal and Refractive
Astigmatism

Fig. 1 shows the distribution of VDD19–21 between corneal and
refractive astigmatism for measurements of corneal astigmatism
obtained with the KM-500 without pupil dilation (Fig. 1A), the
RmaxK+ without pupil dilation (Fig. 1B), and the RmaxK+ with
pupil dilation (Fig. 1C). For the 250 subjects, the median VDD
between corneal and refractive astigmatism was 0.88 D for the
KM-500, 0.76 D for the RmaxK+ without pupil dilation, and
0.75 D for the RmaxK+ with pupil dilation.

When results for cylinder power alone were examined, the mean
difference between corneal and refractive astigmatism was 0.85 D
(SD = 0.72) for the KM-500, 0.61 D (SD = 0.46) for the
RmaxK+ without dilation [excluding subject 216, who had a
value of 0.25 D for refractive astigmatism and a clearly aberrant
(> 7 SD from the mean) estimate for corneal astigmatism of 11.38
D], and 0.66 D (SD = 0.69) for the RmaxK+ with dilation
[excluding subject 214, who had a value of 2.75 D for refractive
astigmatism and an aberrant (> 7 SD from the mean) value of
10.50 D for corneal astigmatism].

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Javal's Rule and the Modified Rule as Descriptors of the Relation between Corneal and Refractive Astigmatism

Both Javal's rule\textsuperscript{13} and the modified Javal's rule\textsuperscript{14} were formulated to describe the relation between corneal and refractive astigmatism in cases in which the astigmatic axis is horizontal or vertical (with-the-rule or against-the-rule astigmatism). Neither rule is applicable in cases of oblique-axis astigmatism. Fig. 2 shows data from subjects in the present study in whom the axes of both corneal and refractive astigmatism were within ±15° of 90° or 180°, along with lines representing the relations described by Javal's rule\textsuperscript{13} and by the modified rule.\textsuperscript{14} The aberrant data points omitted from Fig. 1, B and C, are also omitted from Fig. 2, B and C, respectively. In all three graphs, the data are predicted better by the modified rule than by Javal's original rule. The regression equation for data obtained with the KM-500 (Fig. 2A) is: $T = 0.86C - 0.52ATR$ ($r = 0.82$), where $T$ represents total (refractive) astigmatism, $C$ repre-
sents corneal astigmatism, and ATR indicates against-the-rule astigmatism. The regression equation for data obtained with the RmaxK+ without dilation (Fig. 2B) is: \( T = 1.10C - 0.79 \) ATR \( (r = 0.93) \). The regression equation for data obtained with the RmaxK+ with dilation (Fig. 2C) is: \( T = 1.05C - 0.74 \) ATR \( (r = 0.91) \).

**DISCUSSION**

This study is the first to examine the relation between corneal and refractive astigmatism in a sample of pre-school-age Native American children in which there is a high prevalence of astigmatism. The results indicate that in this population of Native American pre-school-age children, corneal astigmatism generally exceeds refractive astigmatism (Fig. 1), and the relation between corneal and refractive astigmatism is better described by the Grosvenor et al.\(^{14}\) modification of Javal's\(^{15}\) rule than by Javal's rule itself (Fig. 2).

In contrast to previous studies, in which one method of measuring corneal astigmatism was used, the present study employed three techniques. These techniques were the Marco Nidek KM-500 portable keratometer without pupil dilation, the Nikon RmaxK+ autokeratometer without pupil dilation, and the Nikon RmaxK+ autokeratometer with pupil dilation. As shown in Fig. 1, more subjects showed vector dioptic differences of 1.50 or greater with the KM-500 than with the RmaxK+. This may be because the value provided by the KM-500 is based on one measurement from each person, whereas the value provided by the RmaxK+ is based on up to eight measurements per person. It may also be because the comparison of KM-500 estimates of corneal astigmatism with the RmaxK+ estimates of refractive astigmatism involves a between-instrument comparison, but the comparison of RmaxK+ estimates of corneal astigmatism with RmaxK+ estimates of refractive astigmatism does not.

Another unique aspect of the present study is the measurement of corneal astigmatism with the same instrument under undilated and nondilated conditions. Although corneal astigmatism itself would not be expected to be affected by pupil dilation, it is possible that the accuracy with which an instrument measures corneal astigmatism could be affected differently by the distribution of background light across the iris and pupil in the presence versus the absence of pupil dilation. The results indicated that RmaxK+ measurements of corneal astigmatism obtained before instillation of cycloplegic/dilating drops were similar to those obtained more than 40 min after the drops were instilled (Fig. 1, B and C, and Fig. 2, B and C). This suggests that measurements of corneal astigmatism are affected little, if at all, by changes in the distribution of background light across the iris and pupil.

In previous studies, residual (noncorneal) astigmatism has been estimated as the difference in cylinder power between corneal and refractive astigmatism. To compare the results of the present study with results of previous studies, we calculated the mean and SD of the differences in cylinder power between corneal and refractive astigmatism for each testing condition. The results are shown in Table 1, along with mean values for residual astigmatism found in several studies of older non-Native American subjects. Despite the younger age of our subjects, and the large amounts of astigmatism shown by many of them, the average magnitude of their noncorneal astigmatism is similar to that reported for other populations. Also in accordance with results from older Native American\(^{5,11}\) and non-Native American populations\(^{15-18}\) is the finding that the relation between corneal and refractive astigmatism in pre-school-age Native American children is described better by the modified Javal's\(^{14}\) original formulation of the rule. A strength of the present study is the inclusion of a substantial number of subjects with astigmatism >2.00 D. Shortly after Grosvenor et al.\(^{14}\) formulated their modification of Javal's rule, Grosvenor and Ratnakaram\(^{18}\) expressed concern that there were many more subjects with large amounts (>2.00 D) of astigmatism in the population tested by Javal than in the population used to formulate the modified rule. As a result, Grosvenor and Ratnakaram\(^{18}\) were concerned that the modified rule might be applicable only to eyes with smaller amounts of astigmatism. To test this hypothesis, Grosvenor and Ratnakaram\(^{18}\) compared corneal and refractive astigmatism in an additional 93 patients with astigmatism between 2.25 D and 6.50 D. When data from these patients were combined with data from the 200 patients tested previously,\(^{14}\) and both linear and nonlinear fits were applied to the data, Grosvenor and Ratnakaram\(^{18}\) found that the relation between corneal and refractive

**TABLE 1.**

Average Residual (Noncorneal) Astigmatism

<table>
<thead>
<tr>
<th>Study</th>
<th>Age (years)</th>
<th>N Pts</th>
<th>N Eyes</th>
<th>Residual Astigmatism (D) Mean (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dobson et al.</td>
<td>3–5</td>
<td>250</td>
<td>250</td>
<td>0.85 (0.72)</td>
</tr>
<tr>
<td>Nidek KM-500</td>
<td>3–5</td>
<td>249</td>
<td>249</td>
<td>0.66 (0.69)</td>
</tr>
<tr>
<td>RmaxK+ without dilation</td>
<td>3–5</td>
<td>249</td>
<td>249</td>
<td>0.61 (0.46)</td>
</tr>
<tr>
<td>RmaxK+ with dilation</td>
<td>3–5</td>
<td>44</td>
<td>44</td>
<td>0.57 (——)</td>
</tr>
<tr>
<td>Loper(^{25})</td>
<td>20–41</td>
<td>—</td>
<td>—</td>
<td>0.60 (0.41)</td>
</tr>
<tr>
<td>Carter(^{26})</td>
<td>17–50</td>
<td>—</td>
<td>—</td>
<td>0.71 (——)</td>
</tr>
<tr>
<td>Kapoor(^{27})</td>
<td>&lt;10</td>
<td>204</td>
<td>408</td>
<td>0.51 (0.45)</td>
</tr>
<tr>
<td>Sarver(^{28})</td>
<td>16–30</td>
<td>15</td>
<td>15</td>
<td>0.70 (——)</td>
</tr>
<tr>
<td>Anstic(^{29})</td>
<td>5–9</td>
<td>—</td>
<td>34</td>
<td>0.62 (——)</td>
</tr>
<tr>
<td>Baldwin and Mills(^{30})</td>
<td>51 (mean)</td>
<td>198</td>
<td>198</td>
<td>0.30 (0.53)</td>
</tr>
<tr>
<td>McKendrick and Brennan(^{31})</td>
<td>18–35</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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astigmatism was adequately characterized by the straight-line function of the modified rule. The present study is the first since that of Grosvener and Ratnakaram\textsuperscript{18} to include a substantial number of subjects with astigmatism $> 2.00$ D. As shown in Fig. 2, the results from the present study support Grosvener and Ratnakaram’s\textsuperscript{18} conclusion that the modified rule adequately describes the relation between corneal and refractive astigmatism across the range from low to high astigmatism.

To this point, the discussion has centered on Javal’s rule and the modified rule as descriptors of the relation between corneal and refractive astigmatism in a population of eyes. In vision screening settings and in clinical settings, however, the emphasis is on the individual patient. That is, one would like to know whether a measurement of corneal astigmatism in an individual patient can be used as an accurate predictor of refractive astigmatism for that patient. Mote and Fry\textsuperscript{24} considered this issue with reference to Javal’s rule, and concluded that Javal’s rule cannot be applied in individual cases, because errors as large as 1.50 D in the prediction of refractive astigmatism can occur. More recently, Elliott et al.\textsuperscript{16} also concluded that the modified rule\textsuperscript{14} has little clinical value. Their data showed that the difference between refractive astigmatism predicted from corneal astigmatism and actual measurements of refractive astigmatism was $> 0.50$ D in 34% of cases,\textsuperscript{16} a result similar to the value of 30% reported in a previous study.\textsuperscript{15} Similar conclusions concerning the clinical value of Javal’s rule and the modified rule can be drawn in the present study. Application of the modified rule to keratometric readings from preschool children showed a difference of $> 0.50$ D between astigmatism predicted by the modified rule and measured astigmatism in 25% of measurements made with the KM-500 without dilation, 25% of measurements made with the RmaxK+ without dilation, and 22% of measurements made with the RmaxK+ with dilation.

CONCLUSIONS

In conclusion, the results of the present study demonstrate that there is a high prevalence of astigmatism among pre-school-age members of the Tohono O’Odham nation. The results also confirm that the astigmatism is primarily corneal in origin, and that corneal astigmatism exceeds refractive astigmatism by an amount similar to that reported in samples of older Native American and non-Native American persons with astigmatism. As has been demonstrated in older populations, the relation between corneal and refractive astigmatism in pre-school-age Native American children can be characterized by the Grosvener et al.\textsuperscript{14} modification of Javal’s\textsuperscript{13} rule, which states that, on average, corneal astigmatism exceeds refractive astigmatism by 0.50 D. However, as in other populations, the modified rule has limited utility for the prediction of an individual Native American child’s refractive astigmatism because of the considerable variability across individual children in the degree to which corneal astigmatism exceeds refractive astigmatism.

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APPENDIX

VDD between corneal and refractive astigmatism was calculated as follows:

First, corneal and refractive astigmatism were each converted to vectorial representation $(f_{i1}, f_{i2}, f_{i3})$ according to the following formulæ\textsuperscript{19, 20}:

- $f_{i1} = F \cdot F_c \cdot (\sin \alpha)^2$
- $f_{i2} = -F \cdot F_c \cdot (\sin \alpha \cdot \cos \alpha)
- $f_{i3} = F \cdot F_c \cdot (\cos \alpha)^2$

where $F$ = spherical power, $F_c = cylinder power$, and $\alpha = axis$ (in radians).

Then, VDD was calculated according to the following formula:

$VDD = \sqrt{(f_{c11} - f_{r11})^2 + (f_{c21} - f_{r21})^2 + (f_{c32} - f_{r32})^2}$

where $f_c$ = vectorial value for corneal astigmatism and $f_r$ = vectorial value for refractive astigmatism.

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