Using Corneal Oxygen Demand to Optimize Rigid Contact Lens Design

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ABSTRACT

To evaluate the effects of base curve radius, overall diameter, and axial edge lift on rigid contact lens tear pump efficiency, corneal oxygen uptake rates were measured on six eyes under three conditions: normal open eye, after 5 min of static (without blinking) wear, and after 5 min of dynamic (with blinking once every 5 s) wear. The three parameters were varied one at a time from a standard lens design. Differences in corneal oxygen demands between the static and dynamic rates provided quantitative measures of the tear pump efficiency for each lens design. Tear exchange was found to be most sensitively related to changes in base curve radius, followed by overall diameter changes (55.9% as effective) and axial edge lift changes (64.6% as effective). Design equivalencies (to produce identical tear exchange to a 0.05-mm flattening of base curve toward alignment) were 0.07-mm steepening of the base curve toward alignment, 0.35-mm decrease in overall diameter, or 0.037-mm increase in axial edge lift.

Key Words: contact lens, tear pump efficiency, overall diameter, axial edge lift, base curve radius

Normal corneal metabolism and physiological function are maintained only with an adequate supply of oxygen.1,3 While wearing a rigid contact lens, there are two ways in which oxygen can be delivered to the cornea: transmission through the lens material itself or through the pumping of tears beneath the contact lens during blinking.4,5 Contact lens designs of appropriate corneal/contact lens base curve relations, overall and optic zone diameters, and peripheral curve width and radius should enhance the pumping action that takes place during blinking.6,11

However, questions remain: (1) How much reduction in the corneal oxygen uptake associated with the static wear of a non-gas permeable rigid contact lens can be brought about by blinking? (2) Which cornea/contact lens base curve fitting relations, overall and optic zone diameters, and axial edge lifts are associated with the best tear pump efficiencies? (3) How much effect on tear pump efficiency do the following rigid contact lens parameter changes (representing the minimal clinically relevant change in each parameter) have: 0.05-mm flattening of base curve radius toward the "on K" fit, 0.05-mm steepening of base curve radius toward the on K fit, 0.2-mm reduction in overall and optic zone diameter, and 0.02-mm increase in axial edge lift? (4) Which parameter change is most efficient in enhancing the tear pump?

METHODS

Subjects

Six subjects (4 males and 2 females) ranged in age from 23 to 28 years (mean 24.5 years). The keratometry value of the flattest (horizontal) corneal meridians ranged from 41.37 to 43.37 D (mean 42.29 D), whereas corneal toricity (all with-the-rule) ranged from 0.37 to 1.00 D (mean 0.75 D). The mean palpebral aperture height was 10.5 mm, with a range from 8.5 to 12.0 mm. All subjects had good ocular health, and none had worn contact lenses.

Contact Lenses

All contact lenses were made of polymethyl methacrylate (PMMA), which has negligible oxygen transmissivity, so that changes in oxygen uptake rate would reflect effects of contact lens design on tear pump efficiency. The reference design lens had an overall diameter of 8.8 mm, an optic zone diameter of 7.4 mm, a base curve radius fitted on K (i.e., parallel to the flattest corneal meridian), a back vertex power of −3.00 D, and a center thickness of 0.14 mm.

When base curve radius was the study variable, it was fitted 0.10 mm steeper-than-K, 0.05 mm steeper-than-K, on K, 0.05 mm flatter-than-K, and...
Table 1. Differences, in Hypoxic Stress Units (HSU’s), between the static condition data and dynamic condition data for each of 6 subjects and 15 lens designs (5 with base curve radius varying from 0.10 mm flatter-than-K to 0.10 mm steeper-than-K in 0.05-mm steps, 5 with overall diameter varying from 8.2 to 9.4 mm in 0.3-mm steps, and 5 with axial edge lift varying from 0.06 to 0.13 mm in 0.02-mm steps; each value is the difference between 8 measurements obtained under static conditions and 8 measurements obtained under dynamic conditions.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Subject 1</th>
<th>Subject 2</th>
<th>Subject 3</th>
<th>Subject 4</th>
<th>Subject 5</th>
<th>Subject 6</th>
<th>Population</th>
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<tbody>
<tr>
<td>BCRA</td>
<td>15.629</td>
<td>2.284</td>
<td>2.132</td>
<td>3.873</td>
<td>3.075</td>
<td>3.821</td>
<td>6.779</td>
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<td>8.2</td>
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<td>30.013</td>
<td>23.399</td>
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<td>20.424</td>
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<td>27.164</td>
<td>5.735</td>
<td>19.951</td>
<td>3.729</td>
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<td>OAD</td>
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<td>36.483</td>
<td>12.612</td>
<td>1.489</td>
<td>6.208</td>
<td>10.149</td>
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<tr>
<td>AEL</td>
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<td>19.077</td>
<td>18.745</td>
<td>11.739</td>
<td>6.412</td>
<td>4.196</td>
<td>11.590</td>
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<td>AEL</td>
<td>0.07</td>
<td>23.421</td>
<td>18.283</td>
<td>16.537</td>
<td>9.133</td>
<td>10.733</td>
<td>20.483</td>
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<tr>
<td>AEL</td>
<td>0.09</td>
<td>20.759</td>
<td>18.368</td>
<td>19.283</td>
<td>10.447</td>
<td>5.869</td>
<td>26.746</td>
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<td>27.684</td>
<td>22.723</td>
<td>25.363</td>
<td>4.938</td>
<td>11.734</td>
<td>35.811</td>
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<tr>
<td>AEL</td>
<td>0.13</td>
<td>31.570</td>
<td>21.469</td>
<td>34.350</td>
<td>16.802</td>
<td>4.029</td>
<td>39.028</td>
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</tbody>
</table>

Abbreviations: BCRA, base curve radius; OAD, overall diameter; AEL, axial edge lift; STK, steeper-than-K; FTK, flatter-than-K; on K, base curve radius equal to that of the flattest corneal meridian as measured with the keratometer.

0.10 mm flatter-than-K. When overall diameter was the study variable, lenses of 8.2, 8.5, 8.8, 9.1, and 9.4 mm diameter were used, with the optic zone diameter being 1.4 mm smaller than the overall diameter in all cases. When axial edge lift was the study variable, values of 0.05, 0.07, 0.09, 0.11, and 0.13 mm were used.

Procedure

A series of three studies was performed with the same six subjects. In each study only one contact lens parameter (i.e., base curve radius, overall diameter, or axial edge lift) varied; the others remained constant. Oxygen uptake rates were measured on the right eye of 6 subjects using a Clark-type polarographic electrode (25 μm cathode, 12 μm thick polycarbonate membrane). Calibration was performed by alternately placing the electrode in saline baths bubbled with air (150 mm Hg) and nitrogen (0 mm Hg) and maintained at 36°C. Measurements were made under three conditions: (1) normal, open eye; (2) after 5 min of static (non-blinking) wear of each of the five contact lenses (variable overall diameter, variable base curve radius, or variable axial edge lift); and (3) after 5 min of dynamic (with blinking once every 5 s) wear of each of the five contact lenses. In each study, lenses were used in random order. All measurements were repeated eight times.

The Hypoxic Stress Unit (HSU) scale was used, in which oxygen uptake rates after 5 min of static wear of the PMMA reference lens are associated with the 100 HSU value and those of the normal open eye are associated with the 0 HSU value.1 The following equation can be used to calculate the HSU values for each condition:

$$\text{HSU} = \frac{\text{TD} - \text{Air}}{\text{REF} - \text{Air}} \times 100$$

where TD is the oxygen uptake rate associated with the test design, Air is the oxygen uptake rate of the normal open eye, and REF is the oxygen uptake rate associated with the static wear of the PMMA reference lens.

RESULTS

HSU values were determined for the means of the 8 measurements made under each of the 2 conditions (static and dynamic) for each of the 6 subjects and 15 lens designs. The differences between the static and dynamic condition data were calculated for all subject/lens design combinations and then adjusted to account for mean difference in the reference lens design results among the three studies.

Table 1 shows the adjusted difference values in HSU’s for each subject and lens design [i.e., between the static and dynamic condition data for: (1) each base curve radius flatter than and steeper than the on K fit; (2) the five overall diameters; and (3) the five axial edge lifts]. The equations for the four regression lines were determined relating, for the population, the differences between static and dynamic condition data in HSU’s to the parameter changes. They are: (1) for the 3 contact lens base curve radius to cornea fitting relations 0.10 mm steeper-than-K, 0.05 mm steeper-than-K, and on K: difference value = 113.0 (ftn) + 17.5; (2) for

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the 3 contact lens base curve radius to cornea fitting relations 0.10 mm flatter-than-K, 0.05 mm flatter-than-K, and on K; difference value = -77.5 (fit) + 17.1, (3) for the 5 contact lens overall diameters: -15.9 (diameter) + 15.7, and (4) for the 5 axial edge lift: 154.0 (axial edge lift) + 4.7.

Table 2 shows the results of the analysis of variance and Tukey analysis, a multiple-range test designed to compare all possible pairs of means in any group. The population data (six corneas, each observed eight times under both static and dynamic conditions) for each of the three studies (base curve radius, overall diameter, and axial edge lift) were used in these analyses.

**DISCUSSION**

Blinking plays an important role in tear exchange for the rigid contact lens wearer. It results in vertical motion and rocking of the lens while pumping oxygenated tears across the corneal surface and removing metabolic wastes and debris from beneath the lens. A contact lens design which enhances this pumping action should result in the measurement of significantly lower oxygen uptake rates after the contact lens has been worn dynamically than after it has been worn statically.

In order to determine how well the cornea is securing oxygen with lenses of various designs, a Clark-type polarographic oxygen electrode can be used to assess any increase in the epithelial oxygen uptake rate after disruption of the anterior oxygen supply. This increased oxygen uptake rate is greater when a rigid contact lens that is impermeable to oxygen is worn statically (that is, without blinking) than when the patient is allowed to blink. Using this technique, the effect of various contact lens designs on the oxygen uptake rate of the cornea can be determined under both static and dynamic conditions. The differences between the static and dynamic condition data reveal the tear pump efficiencies. The relative influence of each parameter on hypoxic stress of the cornea and its relief, as well as the determination of prescription equivalencies resulting in similar tear pump efficiencies, has been investigated in this study.

Past studies have shown that the best tear pump efficiency is associated with contact lens base curves fitted close to on K, with steeper fits resulting in less tear exchange than flatter fits. Reduction in overall diameter, reduction in optic zone diameter, and increase in axial edge lift are also associated with enhancement of tear bulk-flow. The presence of prism ballasting can inhibit tear exchange with the blink and moderate to high powered plus lenses can be associated with significantly lower tear exchange than minus lenses of moderate power.

Almost every lens design parameter contributes to the fluid forces acting on the contact lens, affecting the positioning, movement, and tear flow. However, it is often impractical to change many of these parameters when fitting a rigid contact lens to a particular patient. For example, reduction in lens overall diameter might not be prudent for patients with lower upper lids or for patients being fitted with bifocal contact lenses that require larger lenses. Increase in axial edge lift might result in problems with 9:00 and 9:00 o'clock staining or discomfort to the patient. In these cases, a physiologically equivalent change in another contact lens parameter is needed.

Previous studies have shown that, for a population of normal individuals, a 0.3 mm decrease in overall and optic zone diameters (about the smallest change in diameter one might consider clinically) is approximately equivalent to a 0.03 mm increase in axial edge lift as a means of enhancing tear pump efficiency. In order to compare several studies and parameters, a means of relativizing the data must be established. The HSU scale can be used to relate contact lens design to a physiological response of the cornea/contact lens uptake. It is based on a relative scale of 0 to 100 HSU's, in which 0 repre-

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**Table 2.** Tests of statistical difference among population (6 corneas, each observed 6 times) in the relief of corneal stress (reduction in oxygen uptake rate between static and dynamic conditions, measured in HSU's) associated with variations in 3 lens parameters (cornea/base curve radius fitting relation, overall and optic zone diameters, and axial edge lift).

<table>
<thead>
<tr>
<th>Analysis of Variance:</th>
<th>F-Ratio</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lens Parameter</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BCR*</td>
<td>F&lt;sub&gt;.025&lt;/sub&gt; = 3.547</td>
<td>p = 0.020</td>
</tr>
<tr>
<td>OAD</td>
<td>F&lt;sub&gt;.025&lt;/sub&gt; = 4.522</td>
<td>p = 0.007</td>
</tr>
<tr>
<td>AEL</td>
<td>F&lt;sub&gt;.025&lt;/sub&gt; = 1.649</td>
<td>p = 0.193</td>
</tr>
</tbody>
</table>

* BCR, base curve radius; OAD, overall diameter; AEL, axial edge lift; STK, steeper-than-K; FTK, flatter-than-K; on K: Base curve radius equal to flattest corneal meridian as measured with the keratometer. Those lenses overlapped by the same column of asterisks had responses not significantly different from one another (p < 0.05).

**Table 3.** Enhancement of tear pump efficiency, in HSU's, brought about by the following parameter changes: 0.05 mm flattening of the base curve radius from steeper-than-K to on K, 0.50 mm steepening of the base curve radius from flatter-than-K to on K, 0.20 mm reduction in overall diameter from 8.8 to 6.6 mm, and 0.02 mm increase in axial edge lift from 0.09 to 0.11 mm.

<table>
<thead>
<tr>
<th>Parameter Change</th>
<th>Change in HSU's</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05 mm STK to on K</td>
<td>5.65</td>
</tr>
<tr>
<td>0.05 mm FTK to on K</td>
<td>3.68</td>
</tr>
<tr>
<td>8.8 mm OAD to 8.6 mm OAD</td>
<td>3.19</td>
</tr>
<tr>
<td>0.09 mm AEL to 0.11 mm AEL</td>
<td>3.08</td>
</tr>
</tbody>
</table>

* Abbreviations: BCR, base curve radius; OAD, overall diameter; AEL, axial edge lift; STK, steeper-than-K; FTK, flatter-than-K; on K, base curve radius equal to flattest corneal meridian as measured with the keratometer; HSU, Hypoxic Stress Unit.
sents the oxygen uptake rate of the normal open eye and 100 represents the oxygen uptake rate associated with severe hypoxic stress (i.e., after an impermeable, unswelling PMMA contact lens has been worn until maximum corneal oxygen uptake rates are reached). Because a given lens tends to evoke very similar HSU responses even from different eyes, this relative scale becomes a convenient tool to compare the oxygen performance of various lens designs on the cornea.12

From Table 1 it can be seen that blinking results in a reduction in corneal stress of between 6.07 (for the 9.4 mm overall diameter lens) and 28.74 (for the 8.2 mm overall diameter lens) HSU's, depending on the lens design. An even greater range in corneal stress reduction is seen among the data from the individual subjects. From the population data, the best tear pump efficiencies were associated with the following cornea/contact lens base curve fitting relation, overall and optic zone diameters, and axial edge lift: on K fit, small overall and optic zone diameters (8.2 and 6.8 mm, respectively), and large axial edge lift (0.13 mm). Individual variations in lens designs associated with best tear pump efficiencies are apparent from Table 1.

Table 3 lists, for the population, the enhancement in tear pump efficiency, in HSU's, brought about by the following parameter changes: 0.05 mm flattening of the base curve radius from steeper-than-K to on K, 0.05 mm steepening of the base curve radius from flatter-than-K to on K, 0.2 mm reduction in overall diameter from 8.8 to 8.6 mm, and 0.02 mm increase in axial edge lift from 0.09 to 0.11 mm. These improvements in tear exchange were determined using the equations relating the difference value to the parameter. They are 0.65 HSU's, 3.88 HSU's, 3.19 HSU's, and 3.08 HSU's, respectively. In order to provide for a reduction in corneal stress of 5.65 HSU's, the following parameter changes can be made: 0.05 mm flattening of the base curve radius toward alignment, 0.07 mm steepening of the base curve radius toward alignment, 0.35 mm decrease in overall diameter, or 0.037 mm increase in axial edge lift. Therefore, of the parameters studied, flattening of a steep base curve radius toward the on K fit is the most efficient way to enhance the tear pump. The average of the improvements in tear exchange brought about by changes in base curve radius (i.e., either flattening or steepening by 0.05 mm) is 4.77 HSU's. Overall diameter changes are 0.65% as effective as this and axial edge lift changes are 64.6% as effective as this in enhancing tear exchange.

REFERENCES


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