Oxygen tension under a contact lens

Kenneth A. Poise and Marianne Decker

Corneal thickness changes were measured on human subjects who wore gel lenses that varied in center thickness. Using these measurements and the results of an earlier study in which changes in corneal thickness were monitored on human corneas exposed to oxygen tensions below that in air, we showed that the oxygen tension under most contact lenses varies from 0 to 25 mm Hg, which produces a corresponding oxygen flux into the cornea of 0 to 6 μl cm⁻² hr⁻¹. A critical oxygen tension and flux under the lens was found to be 10 mm Hg and 2 μl cm⁻² hr⁻¹, respectively, below which corneal swelling occurs. To maintain these critical levels of tension and flux, the minimum oxygen transmissibility of a stationary lens on the cornea was determined to be 5 × 10⁻⁹ and 15 × 10⁻⁹ (cm × ml O₂)/(sec × ml × mm Hg) for the open and closed eye conditions, respectively.

Key words: oxygen flux, oxygen transmissibility, corneal swelling, contact lens thickness, oxygen permeability

The oxygen tension at the anterior corneal surface must remain above a critical level, or epithelial metabolism will be altered and corneal swelling will result.¹ A contact lens may reduce the oxygen tension below this critical level. If this occurs, corneal edema, formation of vertical striae, and epithelial cell loss may result.²⁻⁵ Clinicians have therefore presumed that it is essential to maintain the oxygen tension under the contact lens above the critical level so that normal corneal physiology is not interrupted.

When a hard lens is worn, oxygen reaches the cornea by mixing with the tears during blinking. There is, however, little or no mixing with gel lenses, so oxygen must reach the cornea by diffusion through the lens material. According to Fick's law of diffusion, an increase in the oxygen permeability (Dk) or decrease in lens thickness (L) would increase the level of oxygen under a soft lens. This would result in an increase of oxygen flux into the cornea.⁶⁻⁸ Although the oxygen tension under a contact lens and oxygen flux into the cornea can be regulated by varying the oxygen permeability and the thickness of the lens, there have been no measurements on humans of oxygen tension or oxygen flux under a gel lens. There is no information to indicate the minimum oxygen transmissibility of a lens required to maintain normal corneal metabolism. An understanding of the effects of different lens materials on the oxygen tension and flux levels under a contact lens may provide information useful in designing lenses that will not disturb corneal function.

In this study, the swelling of human corneas resulting from wearing hydrogel lenses of various center thicknesses while other lens parameters remained unchanged was measured. Using these data and the results of an earlier study in which changes in corneal thickness were monitored on human corneas exposed to oxygen tension below that
in air, it was possible to infer the oxygen tension under the lens and calculate the oxygen flux into the cornea. The results can be used to predict the oxygen tension at the contact lens–cornea interface and the oxygen flux into the cornea for any contact lens system when the oxygen permeability and thickness of the lens are known. From these data the minimum oxygen transmissibility of a contact lens necessary to maintain normal corneal metabolism was determined.

Materials and methods

**Apparatus.** Corneal thickness was monitored using a modified Mentor slit-lamp with a Haag-Streit pachometer attachment, which has been described elsewhere. The oxygen transmissibility (Dk/L) is the oxygen permeability (Dk) of the material divided by the center thickness of the lens (L). Oxygen transmissibility of each contact lens was measured directly with a polarographic measuring procedure originally described by Fatt and St. Helen which has been further modified to improve the reliability and accuracy of the measurements. Fatt and Morris have shown that readings by a single operator using this technique will vary less than 2%. Oxygen permeability (Dk) can then be calculated from the Dk/L measurements by an independent determination of the center lens thickness (L).

Center thickness of the lenses was measured optically using a radioscope by focusing first on the plane of the microscope and second on the concave surface of the lens, the difference representing the actual lens thickness. These thicknesses were remeasured by means of an electrical micro meter, which has been shown to provide accurate and repeatable measurements. For three measurements taken on each lens using both the optical and electrical methods, the mean difference between the methods was 0.001 mm, which was not statistically significant (Walsch Test, p = 0.01).

**Materials.** Five Durasoft lenses, which were composed of 70% poly(2-hydroxyethylmethacrylate) and 30% water, were used. Each lens was designed so that the posterior apical radius, peripheral curves, and diameter were identical. The anterior radius was altered in order to vary the thickness of the lens. These lenses, when fully hydrated, varied in center thickness from 0.05 to 0.43 mm. Oxygen transmissibility (Dk/L) was measured directly using the polarographic measuring technique. Oxygen permeability (Dk) was calculated by independently measuring lens center thickness and dividing this value into the oxygen transmissibility value of the lens. The parameters of the lenses are listed in Table I.

**Subjects.** Four subjects (one female and three males; mean age, 25 years) participated in the study. All subjects were free of active or inactive corneal disease. Each subject had been adapted to lens wear before any test measurements were made.

**Methods.** On each test day, prior to lens wear, baseline corneal thickness measurements were made. Lenses were placed in coded vials so that neither the observer nor the subject knew which lens was to be worn on any given test day (double masking). After baseline corneal thickness readings were taken, the lens was inserted on the right eye, while the left eye served as a control. At 3, 5, and 8 hr of wear, the lens was momentarily re-

### Table I. Specifications of the lenses worn by four subjects

<table>
<thead>
<tr>
<th>Lens</th>
<th>Power (D)</th>
<th>Base curve (mm)</th>
<th>Diameter (mm)</th>
<th>Center thickness (mm)</th>
<th>Dk* (x 10^-11)</th>
<th>Dk/L† (x 10^-9)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>-3.50</td>
<td>8.1</td>
<td>12.8</td>
<td>0.05</td>
<td>2.25</td>
<td>4.5</td>
</tr>
<tr>
<td>B</td>
<td>-2.00</td>
<td>8.2</td>
<td>12.8</td>
<td>0.17</td>
<td>2.55</td>
<td>1.5</td>
</tr>
<tr>
<td>C</td>
<td>-1.00</td>
<td>8.2</td>
<td>12.8</td>
<td>0.20</td>
<td>1.80</td>
<td>0.9</td>
</tr>
<tr>
<td>D</td>
<td>+0.50</td>
<td>8.2</td>
<td>12.8</td>
<td>0.32</td>
<td>2.58</td>
<td>0.9</td>
</tr>
<tr>
<td>E</td>
<td>+2.00</td>
<td>8.2</td>
<td>12.8</td>
<td>0.43</td>
<td>2.38</td>
<td>0.6</td>
</tr>
</tbody>
</table>

* Lens oxygen permeability; Units are (cm² × ml O₂) / (sec × ml × mm Hg).
† Lens oxygen permeability divided by lens thickness (L) in centimeters.

### Table II. Mean percent corneal swelling

<table>
<thead>
<tr>
<th>Lens</th>
<th>Lens center thickness (mm)</th>
<th>3hr</th>
<th>5hr</th>
<th>8hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.05</td>
<td>2.9 ± 1.1</td>
<td>3.1 ± 1.6</td>
<td>3.4 ± 1.4</td>
</tr>
<tr>
<td>B</td>
<td>0.17</td>
<td>5.4 ± 3.2</td>
<td>5.0 ± 2.5</td>
<td>6.2 ± 2.2</td>
</tr>
<tr>
<td>C</td>
<td>0.20</td>
<td>7.8 ± 2.6</td>
<td>7.5 ± 2.8</td>
<td>8.1 ± 2.1</td>
</tr>
<tr>
<td>D</td>
<td>0.32</td>
<td>7.5 ± 1.6</td>
<td>7.0 ± 2.0</td>
<td>7.9 ± 2.6</td>
</tr>
<tr>
<td>E</td>
<td>0.43</td>
<td>8.3 ± 3.4</td>
<td>9.2 ± 3.4</td>
<td>9.6 ± 3.6</td>
</tr>
</tbody>
</table>
moved (1 to 3 min) and corneal thickness was measured. This test procedure was repeated three times for each lens in four subjects, resulting in a total of 12 measurements for each lens.

Results

Table II shows the mean change in central corneal thickness for the group after 3, 5, and 8 hr of lens wear for different center thicknesses. The amount of corneal swelling that developed was related to lens thickness; e.g., for the group, the mean change in central corneal thickness after 8 hr of wear for lens A was 3.4% ± 1.4%, and for lens E it was 9.6% ± 3.6%. The control eye for both the individual and group data developed less than 1% of edema over the 8 hr wearing period. For all lenses, most of the corneal swelling occurred during the first 3 hr of wear, and after that time there was approximately a 1% unit additional swelling.

Fig. 1 shows the change in corneal thickness after 8 hr of lens wear as a function of lens center thickness. As subjects wore lenses of increasing center thickness, more corneal swelling resulted. A large change in corneal thickness occurred when lens thickness was increased from 0.05 to 0.20 mm. The rate of corneal swelling tended to level off as lens thickness was increased beyond 0.20 mm.

Using the corneal swelling and lens thickness data from Fig. 1, the change in corneal thickness as a function of lens oxygen transmissibility (Dk/L) after 8 hr of wear was plotted and is shown in Fig. 2. The Dk/L for three Bausch & Lomb Soflenses (water content 38%) and three Hydrocurve lenses (water content 45%) with center thicknesses of 0.52, 0.25, 0.06, 0.32, 0.22, and 0.11 mm, respectively, were also measured, and their effects on corneal swelling were determined. The oxygen permeability (Dk) for the Bausch & Lomb and Hydrocurve lenses was calculated to be $8 \times 10^{-11}$ and $16 \times 10^{-11}$ (cm$^2$ ml O$_2$/sec x ml x mm Hg), respectively. The solid circles and triangles in Fig. 2 represent the change in corneal thickness as a function of Dk/L for the Bausch & Lomb and Hydrocurve lenses, respectively. Fig. 2 shows that there was an inverse relationship between the oxygen transmissibility of the lens and the degree of corneal swelling.

Change in corneal thickness resulting from exposing the anterior cornea to different oxygen tensions has been previously studied. Using those data and the results shown in Fig. 2, the oxygen tension at the lens-cornea interface in the open eye condition can be determined (assuming insignificant tear interchange from lens movement) for any contact lens when the oxygen permeability and lens center thickness are known. This is done by determining the percent corneal swelling that corresponds to a specific Dk/L (Fig. 2) and then obtaining the oxygen tension at the tear-cornea interface (no lens) which causes that amount of swelling. From this information, curve A of Fig. 3 was plotted to show the oxygen tension under the lens as a function of Dk/L. The oxygen tension at the cornea–contact lens interface as a function of Dk/L for the closed eye condition (curve B) is
calculated as follows: Fick's law of diffusion gives a flux across the lens for the open eye as the following (all terms are defined in Table III):

\[ j = \frac{1}{A} \left( \frac{Dk}{L} \right) (P_a - P_t) \]  

(1)

The flux for closed eye can be written as:

\[ j = \left( \frac{Dk}{L} \right) (P_{sc} - P_t) \]  

(2)

The flux into the cornea at steady state is exactly equal to the flux across the contact lens, and this flux into the cornea is dependent only on \( P_t \). Equations 1 and 2 can be equated to give:

\[ \frac{Dk}{L} = \frac{Dk}{L} \frac{P_{sc} - P_t}{P_a - P_t} \]  

(3)

Substituting \( P_a \), the oxygen tension in air, with 155 mm Hg, and \( P_{sc} \), the oxygen tension on the palpebral conjunctive, with 55 mm Hg:

\[ \left( \frac{Dk}{L} \right) = \left( \frac{Dk}{L} \right) \frac{155 - P_t}{55 - P_t} \]  

(4)

For any value of \( \left( \frac{Dk}{L} \right) \) and \( P_t \) in Fig. 3, the \( \left( \frac{Dk}{L} \right) \) can be calculated that will give the same \( P_t \) when the eye is closed. In this way curve B was determined. Fig. 3 shows that the partial pressure of oxygen under a contact lens whose \( Dk/L \) ranges from \( 1 \times 10^{-9} \) to \( 30 \times 10^{-9} \) (cm x ml O\(_2\)/(sec x ml x mm Hg)), can vary from 0 to approximately 25 mm Hg. Using this range of oxygen tensions, the oxygen flux through the cornea can be calculated from equation 1 as a function of the PO\(_2\) at the tear-lens interface. Equation 1 shows that the higher the PO\(_2\), the greater the oxygen flux into the cornea. When the PO\(_2\) is between 0 and 10 mm Hg, the flux into the cornea is less than \( 2 \mu l \) cm\(^{-2}\) hr.

Oxygen flux can also be related to the \( Dk/L \) of the lens. As \( Dk/L \) gets larger, the oxygen tension at the anterior corneal surface increases, which results in increased oxygen flux into the cornea. Fig. 4 shows the relationship between oxygen flux and \( Dk/L \) in the open and closed eye condition. This
Fig. 4. Oxygen flux into the cornea as a function of oxygen transmissibility (Dk/L) in the closed and open eye conditions.

Table III. Definition of terms

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dk</td>
<td>Lens oxygen permeability (D is the oxygen diffusion coefficient in the lens, and k is the oxygen solubility)</td>
<td>( \text{cm}^2 \text{ ml O}_2 / (\text{sec} \times \text{ml} \times \text{mm Hg}) )</td>
</tr>
<tr>
<td>Dk/L</td>
<td>Lens oxygen transmissibility</td>
<td>( \text{cm} \times \text{ml} \text{ O}_2 / (\text{sec} \times \text{ml} \times \text{mm Hg}) )</td>
</tr>
<tr>
<td>L</td>
<td>Lens thickness</td>
<td>mm</td>
</tr>
<tr>
<td>j</td>
<td>Oxygen flux into cornea</td>
<td>( \mu \text{L cm}^{-2} \text{ hr}^{-1} )</td>
</tr>
<tr>
<td>P_a</td>
<td>Oxygen tension in air</td>
<td>mm Hg</td>
</tr>
<tr>
<td>P_t</td>
<td>Oxygen tension at anterior corneal surface</td>
<td>mm Hg</td>
</tr>
<tr>
<td>P_c</td>
<td>Oxygen tension at palpebral conjunctival surface</td>
<td>mm Hg</td>
</tr>
<tr>
<td>J</td>
<td>Total oxygen movement into the lens</td>
<td>( \mu \text{L/hr} )</td>
</tr>
<tr>
<td>A</td>
<td>Area of contact lens</td>
<td>( \text{cm}^2 )</td>
</tr>
</tbody>
</table>

Graph was plotted by determining from Fig. 3 the partial pressure of oxygen under the gel lens with a certain Dk/L, calculating the oxygen flux corresponding to this oxygen tension, and then plotting the oxygen flux as a function of Dk/L.

Using 10 mm Hg as a previously established minimum level of oxygen necessary to prevent corneal swelling, the maximum allowable thickness for any lens permeability (Dk) can be determined from Fig. 5. Material having an oxygen permeability of \( 10 \times 10^{-11} \) (\( \text{cm}^2 \times \text{ml} \text{ O}_2 / (\text{sec} \times \text{ml} \times \text{mm Hg}) \)) will require a center thickness of 0.20 mm or less to provide an oxygen tension of 10 mm Hg under the lens in the open eye condition. To maintain a partial pressure of oxygen of 10 mm Hg under the same lens in the closed eye condition, the thickness must be reduced to 0.07 mm.

Discussion

The results show a direct relationship between the thickness and oxygen permeability of the lens material and the amount of corneal swelling which develops during lens wear: the thicker the lens or the lower the oxygen permeability, the greater the degree of corneal swelling. This relationship holds until the lens is of sufficient thickness that the oxygen tension under the lens is at or near zero. The corneal swelling would be expected to be similar for any lens in which the oxygen tension at the tear-lens interface is near or at zero. Most currently worn gel lenses must be relatively thin (approximately 0.20 mm or less) if corneal edema is to be prevented. Lenses having oxygen transmissibilities ranging from 0 to \( 30 \times 10^{-9} \) (\( \text{cm} \times \text{ml} \text{ O}_2 / (\text{sec} \times \text{ml} \times \text{mm Hg}) \)) will have oxygen tensions at the tear-lens interface ranging from 0
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Fig. 5. Maximum allowable lens center thickness required to provide a minimum oxygen tension of 10 mm Hg under the lens for the open and closed eye as a function of lens oxygen permeability.

...to 25 mm Hg, which corresponds to an oxygen flux into the cornea of 0 to 6µl cm² hr. We predict that an oxygen flux of 2µl cm² hr represents a critical level, since a flux below this amount would correspond to a partial pressure of oxygen under the lens of 10 mm Hg or less. It has been previously shown that oxygen tensions of 10 mm Hg or less will result in 4% or greater corneal swelling. Corneal swelling of greater than 4% may exceed clinically acceptable levels.

To obtain a flux of 2µl cm² hr, the minimum oxygen transmissibility of a lens must be $5 \times 10^{-9} \text{ cm} \times \text{ml O}_2/(\text{sec} \times \text{ml} \times \text{mm Hg})$ for the open and closed eyes, respectively. As the $D_k/L$ falls below this level, the $P_O_2$ under the lens will decrease and corneal swelling will occur.

Some lenses now being used for extended wear have oxygen permeabilities of $30 \times 10^{-11}$ to $40 \times 10^{-11} \text{ cm}^2 \times \text{ml O}_2/(\text{sec} \times \text{ml O}_2 \times \text{mm Hg})$. If the center thickness of these lenses is below 0.20 mm, there should be an adequate oxygen flux present to maintain normal corneal metabolism both during open and closed eye conditions. As lens thickness increases beyond 0.20 mm (as in high plus lenses) the oxygen tension and flux will drop below the critical level and corneal edema will occur. Extended wear with high plus lenses (as used in aphakia) will require materials having very high oxygen permeabilities of $70 \times 10^{-11} \text{ cm}^2 \times \text{ml O}_2/(\text{sec} \times \text{ml} \times \text{mm Hg})$ or greater if corneal edema is to be prevented during sleep.

REFERENCES