Permeability of hydrophilic contact lenses

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Oxygen permeability and water diffusion characteristics were determined for several types of hydroxyethyl-methacrylate hydrophilic contact lenses and a silicone contact lens material. A two- to fourfold difference in the diffusion rates for capillary flow of water was found among the different hydrophilic lenses. Oxygen permeability studies demonstrate that the hydrophilic lenses are capable of transmitting many times more than the calculated amount of dissolved oxygen in the capillary water flow if an oxygen partial pressure gradient exists across the lens. The silicone contact lens will transmit oxygen more than four times faster than will the most permeable hydrophilic lens; however, the silicone lens is almost totally impermeable to water and ostensibly impermeable to tears.

Key words: hydroxyethyl-methacrylate, hydrophilic contact lenses, silicone contact lenses, oxygen permeability, water diffusion

Hydrophilic soft contact lenses made from different hydrogels of hydroxyethyl-methacrylate have been the subject of many recent investigations. Several clinical testing programs are being conducted to evaluate the utility of these lenses for both therapeutic and cosmetic use. Different manufacturers have varied the amount of polymer cross-linking, the polymer curing procedures, and techniques of fabrication of the finished contact lens. The resulting lenses have separate and distinct physical properties such as mechanical strength, thermal degradation, absorption and elution of aqueous solution, and degree of hydration.

An earlier study indicated that the hydrogel lenses fabricated in Czechoslovakia were as impermeable to oxygen as the methyl-methacrylate contact lenses. The state of the art of hydrophilic contact lens fabrication has changed so rapidly, however, that the various lenses available today are quite different from those examined previously. The water and oxygen permeability of some of the hydroxyethyl-methacrylate hydrogel materials have recently been studied; however, the permeability characteristics of the currently available hydrophilic contact lenses have not been determined.

It is the purpose of this report to describe the water and oxygen permeability of some of these hydrogel contact lenses.

Materials and methods

The capillary diffusion of water through hydrophilic contact lenses was determined by measuring the diffusion of tritiated water from one
Lucite perfusion chamber to another with the lens clamped in a leak-free holder between the chambers. The Lucite chambers previously described had a fluid circulation network and a special clamp constructed to hold a lens with an approximate curvature radius of 8 mm. The lumen diameter of the clamp was 1 cm., allowing an exposed lens surface area of 89.2 mm.² An airlift siphon provided adequate fluid circulation within the two chambers. Dyes were completely mixed throughout the chambers within ten seconds after their addition to the reservoir. Initially 5.0 ml. of 0.9 per cent saline was added to each chamber on either side of the clamped lens. To one chamber tritiated water (specific activity of 8.1 cpm per 0.1 ml.) was added. Serial samples of 0.1 ml. were removed from each chamber reservoir at ten to 30 minute intervals, added to a scintillation solution, and counted with less than one per cent error in a liquid scintillation counter (Nuclear Chicago, Unilux II). All samples were corrected for quenching and calculated to disintegrations per minute. A minimal circulating volume of 4.0 ml. was maintained throughout the experiments, and the circulation rate averaged 4 ml. per ten seconds. The entire system was kept at 23°C in a constant-temperature room.

Oxygen permeability rates were determined with the use of a specially constructed two-chamber diffusion system as diagramed in Fig. 1. The area in which the lenses were clamped was machined to seal a lens with a curvature radius of 8.0 to 8.4 mm. without disturbing the effective surface-diffusion area of the lens. The lumen of the connecting passage to the chambers was 1 cm. in diameter. After the lens was positioned and clamped, the junction of the clamp portion of the apparatus was coated with a thick layer of silicone grease to retard leakage of oxygen in or out of the system. To the chamber on one side of the lens a measured quantity of saline, previously saturated with oxygen to a partial pressure of greater than 500 mm. Hg, was added (Chamber 2, Fig. 1). A gas mixture of 95 per cent oxygen and 5 per cent carbon dioxide was bubbled into the chamber throughout the experiment. The other chamber was filled with normal saline, previously purged with nitrogen to attain a P0₂ of about 110 mm. Hg (Chamber 1, Fig. 1). This partial pressure gradient of approximately 400 mm. Hg was selected to determine if the oxygen permeability of the lenses had some upper limit when the pressure gradient was several times greater than normal. A layer of oil was added on top of the saline to retard the exchange of dissolved oxygen with the atmosphere. The chamber was sealed with a layer of paraffin and a rubber stopper. Sequential samples were taken from each chamber at various times after the chamber was sealed. Samples were withdrawn by disposable syringe and needle and then sealed with a hard rubber stopper as is done for blood gas samples. The P0₂ in the samples was measured with a Radiometer Gas Analyser.

Although silicone materials are nominally permeable, oxygen diffusion in or out of the system was minimal. The oxygen leak rate was determined with 0.22 mm. impermeable Teflon membranes and thick rubber stoppers in place of the hydrophilic lens. All oxygen transfer rates through the lenses were corrected for the small oxygen leak rate between the chambers.

Permeability constants (Kp) were calculated from the classic equation (Equation 1) where

\[ Kp = \ln \left( \frac{C_0 - 2C_t}{C_0} \right) \cdot \frac{V}{2A} t \]  

\( C_0 = C_a + C_t \)  
\( V = \) total volume of the system,  
\( A = \) effective surface area, and \( t = \) elapsed time for the permeation of oxygen into chamber 2 to reach the value of \( C_t \). The permeability constant
Table I. Mean diffusion constants and calculated flow rates for typical lenses

<table>
<thead>
<tr>
<th>Type lens</th>
<th>No.</th>
<th>Mean diffusion constant (cm.³/cm.²-hr.)</th>
<th>Standard deviation of Df</th>
<th>Typical lens thickness (cm.)</th>
<th>Water flow rate (μl/cm.²/hr.)</th>
<th>Calc. dissolved O₂ flow rate (μl/cm.²/hr.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Griffin</td>
<td>3</td>
<td>1.95 × 10⁻²</td>
<td>0.25 × 10⁻²</td>
<td>0.04</td>
<td>487</td>
<td>2.92</td>
</tr>
<tr>
<td>Seiderman</td>
<td>4</td>
<td>1.16 × 10⁻²</td>
<td>0.14 × 10⁻²</td>
<td>0.04</td>
<td>290</td>
<td>1.74</td>
</tr>
<tr>
<td>Bausch and Lomb</td>
<td>3</td>
<td>0.61 × 10⁻²</td>
<td>0.04 × 10⁻²</td>
<td>0.035</td>
<td>175</td>
<td>1.03</td>
</tr>
<tr>
<td>Silicone</td>
<td>3</td>
<td>0.0005 × 10⁻²</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

(Kp) is expressed in units of cm.³/cm.²-hr. or cm./hr.

The diffusion constants were calculated by multiplying the permeability constants (Kp) by the thickness (centimeters) of the particular lens that was used to determine the permeability constant. The diffusion constant (Df) is expressed in units of cm.³/cm.²-hr. or cm.²/hr.

The flow rate of water or oxygen passing through a particular lens (Equation 2) is calculated by dividing the appropriate diffusion constant (Df) for that particular type of lens by the thickness (centimeters) and multiplying by the surface area of the lens in question.

\[
\text{O₂ volume flow rate} = \frac{\text{Df (cm.³/cm.²-hr.) \times area (cm.²)}}{\text{Thickness (cm.)}} = \text{cm.³/hr.}
\]

(Lens material) Three different types of hydroxyethyl-methacrylate (HEMA) copolymer lenses were used in this study. Copolymer lenses, fabricated with a constant thickness across the diffusion area, were supplied by Griffin Laboratories of Buffalo, New York. Similar lenses of PHP-1A (cross-linked poly-HEMA) hydrogel were supplied by Dr. M. Seiderman of Physiological Polymers in Hollywood, California. Another type lens, fabricated with -3.0 to -5.0 diopters, were obtained from the Bausch and Lomb Company. The silicone lens material was supplied by the Milton Roy Company of Saint Petersburg, Florida. The thickness of each lens was verified by pachometer measurements before and after each experiment. All of the lenses used had a diameter of at least 12.5 mm. The effective surface areas for diffusion were calculated from the radius of curvature of the lens and the measured diameter. At least three lenses of each type were tested for both water and oxygen diffusion.

Results

A marked difference in the water permeability of the different types of hydrophilic contact lenses was apparent. Each type of lens reached a constant water diffusion rate within the first twenty to thirty minutes of the experiments. The mean diffusion constant for each type of lens is shown in Table I. The Griffin lenses have a diffusion rate of almost four times that of the Bausch and Lomb lenses and almost twice that of the Seiderman (PHP) lenses. Using a typical thickness value for the different types of lenses currently fabricated, we find that the Griffin lens will have a water flow rate of almost 500 μl per hour per unit area. A typical Seiderman lens will have a water flow rate of about 290 μl per hour per unit area, and a typical Bausch and Lomb lens will have a permeability rate of approximately 175 μl per hour per unit area.

The amount of atmospheric oxygen dissolved in the water that diffuses across the lenses was calculated, and the permeability rate of dissolved oxygen at (STP) is tabulated in Table I. The water permeability rate for the lenses tested is apparently not sufficient to supply dissolved oxygen at a rate equal to the corneal consumption estimates of 8 to 10 μl per hour. The volume of oxygen that is supplied to the cornea in the tears that are pumped under these lenses during blinking was not evaluated.

The measured diffusion rate constants for oxygen permeability of the hydrophilic- and silicone-type soft contact lenses are compared in Table II. The order and magnitude of the measured differences in the oxygen diffusion rates for the hydrogel lenses were proportional to the differences...
**Table II.** Water to water oxygen diffusion constants measured under a $P_{O_2}$ gradient

<table>
<thead>
<tr>
<th>Type lens</th>
<th>No.</th>
<th>Ratio of partial pressure gradient across the lens</th>
<th>Mean diffusion constant (Df) $\text{cm}^2$/cm.$^2$-hr</th>
<th>Standard deviation of Df $\text{cm}^2$/cm.$^2$-hr</th>
<th>Typical lens thickness (cm.)</th>
<th>Oxygen flow rate ($\mu l$/cm.$^2$-hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Griffin</td>
<td>3</td>
<td>568:140 (4:1)</td>
<td>$7.94 \times 10^{-3}$</td>
<td>$0.98 \times 10^{-3}$</td>
<td>0.04</td>
<td>198</td>
</tr>
<tr>
<td>Seideman</td>
<td>3</td>
<td>585:139 (4.2:1)</td>
<td>$3.51 \times 10^{-3}$</td>
<td>$1.51 \times 10^{-3}$</td>
<td>0.04</td>
<td>87.8</td>
</tr>
<tr>
<td>Bausch and Lomb</td>
<td>3</td>
<td>535:139 (3.8:1)</td>
<td>$2.35 \times 10^{-3}$</td>
<td>$0.57 \times 10^{-3}$</td>
<td>0.03</td>
<td>78.3</td>
</tr>
<tr>
<td>Silicone</td>
<td>2</td>
<td>577:185 (3.1)</td>
<td>$39.95 \times 10^{-3}$</td>
<td>$0.97 \times 10^{-3}$</td>
<td>0.05</td>
<td>800</td>
</tr>
</tbody>
</table>

in water permeability noted above. The oxygen diffusion rate for the silicone lens, however, was more than four times that of the most permeable hydrogel lens (Griffin). Fig. 2 demonstrates that substantially more oxygen is transmitted through the lenses per hour (under a partial-pressure gradient) than would be consumed hourly by the entire cornea.

**Discussion**

The water and oxygen diffusion rates determined in these experiments indicate that the currently available hydroxyethyl-methacrylate hydrogel contact lenses are capable of transmitting more oxygen than are the hydrogel lenses and methyl-methacrylate lenses previously studied.\(^3\) Oxygen uptake by the rabbit corneal epithelium had been determined to be 8.4 $\mu l$ per square centimeter per hour,\(^7\) and for the human cornea, in vitro, it is approximately 10 $\mu l$ per square centimeter per hour.\(^8\) The oxygen permeability of these lenses was several times greater than the reported corneal utilization rate.

An accurate measurement of dissolved oxygen in the tears would allow calculation...
of the volume flow rate of atmospheric oxygen dissolved in the tears that permeate the lenses; however, the oxygen content of tears has not been accurately reported. The closest estimate of the dissolved oxygen that may permeate the lens within the water flow has been calculated from the oxygen tension in normal saline equilibrated with room air. These values alone approximate the estimated oxygen utilization of the cornea (Table I) but do not account for the total oxygen supply available to the cornea.

The oxygen permeability studies showed some interesting correlations to the water diffusion experiments mentioned above. It was decided that the maximum oxygen diffusion rates should be determined for each type of lens within the constraints of the differences in \( \text{PO}_2 \) that might exist across the lens in the normal physiologic situation. Ostensibly, the diffusion of oxygen through the lens would be dependant on the partial pressure gradient that existed across the lens at any particular time. Should the corneal utilization of oxygen be somewhat greater than the volume of oxygen that passed through the lens, then the oxygen content of the small tear volume between the lens and the corneal epithelium would begin to decrease. Disregarding the possibility of tear exchange around the lens, we would expect the oxygen deficit in this tear volume to provide a partial pressure gradient that would increase the diffusion rate of oxygen through the lens. If the maximum diffusion rate was not sufficient to offset the corneal utilization, then eventually the cornea would begin to encounter a physiologic deficit of metabolic oxygen available at the anterior corneal surface. Polse and Mandell have recently shown that between 11 and 19 mm. Hg of \( \text{PO}_2 \) is required by the human cornea to maintain normal hydration and presumably normal metabolism. If the \( \text{PO}_2 \) of the tear volume under a hydrophilic contact lens should ever decrease to this minimal value, the partial pressure ratio across the lens would be approximately 7:1 with the eyelids open and approximately 3:1 with the eyelids closed. These experimental determinations of the oxygen diffusion constants for the hydrophilic contact lenses were determined at a partial pressure gradient of approximately 4:1.

The oxygen diffusion rates at this pressure gradient were many times greater than the estimated corneal consumption, even for the least permeable lens. The diffusion constants for the silicone material were the same as the values Seiderman and associates reported for Silastic. The diffusion constant reported for the Seiderman material was about 20 per cent less than the diffusion constant our studies determined for the fabricated Seiderman contact lens. The increase in diffusion rates as a function of the degree of hydration of the hydroxyethyl-methacrylate hydrogels has similarly been noted by Seiderman. The comparison of the diffusion constants for the three different types of hydrophilic contact lenses also corresponds to the differences in water content of the hydrated lenses.

The oxygen diffusion characteristics of the three hydrogel lenses indicate that oxygen deprivation of the corneas should not arise from prolonged wearing and that the oxygen starvation syndrome observed with the methyl-methacrylate lenses should not occur with the use of these hydrophilic lenses.

Richard Lindemark of Physicians Contact Lens Prosthetic Service, Inc., of Milwaukee, Wisconsin, fabricated the PHP-IA lenses used in this study.

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