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Aqueous salt transport through soft contact lenses: An osmotic-withdrawal mechanism for prevention of adherence

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ABSTRACT

In addition to improving oxygen permeability, modern silicone-hydrogel (SiHy) soft contact lenses (SCLs) exceed a limiting diffusive ion permeability to aqueous sodium chloride. Below the ion-permeability threshold, siloxane-based SCLs are prone to bind against the corneal epithelium. Salt permeability is argued to reflect indirectly water hydraulic permeability. However, no quantitative explanation is available to date for a threshold salt permeability. We hypothesize that molecular salt diffusion through a SCL supports the postlens tear film (PoLTF) by enhancing water flow into the PoLTF from the cornea. Higher salt concentrations in the PoLTF raise the osmotic pressure there relative to that in the cornea increasing osmotic water withdrawal from the cornea. The proposed osmotic-withdrawal mechanism successfully predicts a self-consistent threshold lens salt permeability when thin-film attractive binding forces are introduced. For the first time, we present a quantitative picture for the possible origin of a threshold salt permeability in SCL manufacture.

1. Introduction

Incorporation of siloxane moieties into hydrogels to achieve oxygen permeability exceeding about 100 Barrer has revolutionized soft-contact-lens manufacture. High oxygen permeability minimizes corneal hypoxia and permits extended lens wear [1–3]. Concomitantly, an aqueous sodium-chloride diffusive permeability in excess of about 2×10^{-7} cm^2/s appears necessary to prevent lens adhesion to the epithelium and permit lens movement during blinking [1]. Extensive reviews of SiHy contact-lens synthesis and behavior emphasize the importance of a critical salt permeability [2,3]. Fig. 1 from the recent work of Guan et al. [4] demonstrates that all current commercial soft contact lenses (SCLs), both siloxane-based and HEMA-based, exceed the threshold NaCl permeability (see also Table III in [4]). This observation has not been generally recognized, although the importance of a threshold salt permeability to prevent lens binding was documented experimentally over a decade ago [1–5]. Unfortunately, no satisfactory physical explanation is currently available.

Nicolson et al. [1] argue that salt permeability indirectly gauges water transport rate through a SCL. Specifically, these authors hypothesize that water is compressed out of a lens during a blink and replenished during an interblink. The squeezed-out water maintains a thick enough postlens tear film (PoLTF) to avoid lens adhesion. Thus, a threshold water hydraulic permeability is necessary to maintain lens movement. According to the review chapters of Tighe [2,3], a simple calculation (not presented) confirms that above a critical hydraulic permeability, water flow in a SCL is sufficient to maintain an adequate PoLTF boundary-layer thickness. Monticelli et al. [6], however, disagree pointing out that neither a squeeze-out nor a squeeze-through mechanism can sustain the PoLTF because hydraulic permeabilities of SCLs are miniscule.

Upon neglect of gel-relaxation kinetics under lid-blink compression, the flow rate of tear expelled from a SCL obeys Darcy's law [6,7]

$$J_L = \frac{k_{\mathrm{H}}}{\mu}\left(\frac{\Delta p}{L}\right) \quad (1)$$

where J_L is the volumetric flux of water through the hydrogel, k_{H} is the hydraulic permeability, μ is the Newtonian viscosity of tear, L is the harmonic mean thickness of the lens, and Δp is the applied lid force per unit area. Typical values of the parameters are: $k_H = 10^{-8}$ μm^2 [6], μ = 1 mPa s, L = 100 μm, and $\Delta p \sim 2$ kPa [8–10]. With these values, the water volumetric flux is 10^{-4} μm/s. For a 0.1-s blink, the amount of tear exuded from the lens per blink, expressed as an increase in PoLTF thickness, is about 10^{-5} μm. This estimate is conservative because the applied lid force corresponds to that at the lid margin where the lid force is largest. Further, and consistent

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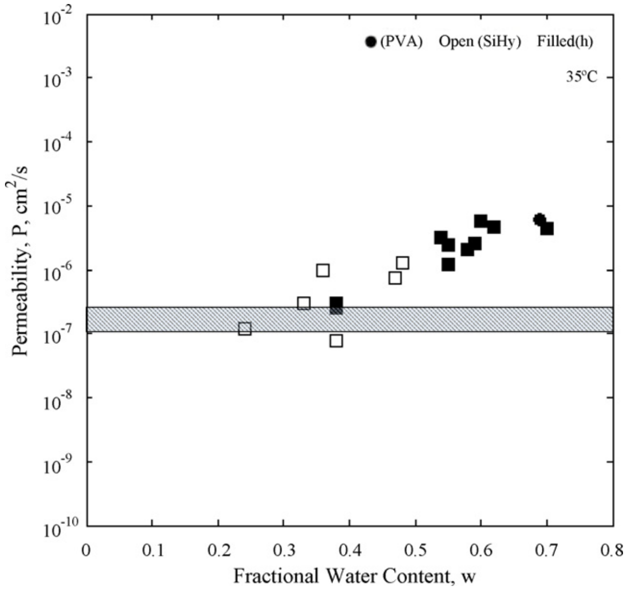

Fig. 1. Permeability, P, of aqueous NaCl in commercial SCLs as a function of equilibrium water content at 35 °C. The filled circle (≏) corresponds to a PVA-based lens (PVA). Remaining filled symbols correspond to HEMA-based materials (H) while open symbols correspond to silicone-based materials (SiHy). The cross-hatched region demarks the threshold permeability for lens movement.
After Guan et al. [4] with permission.

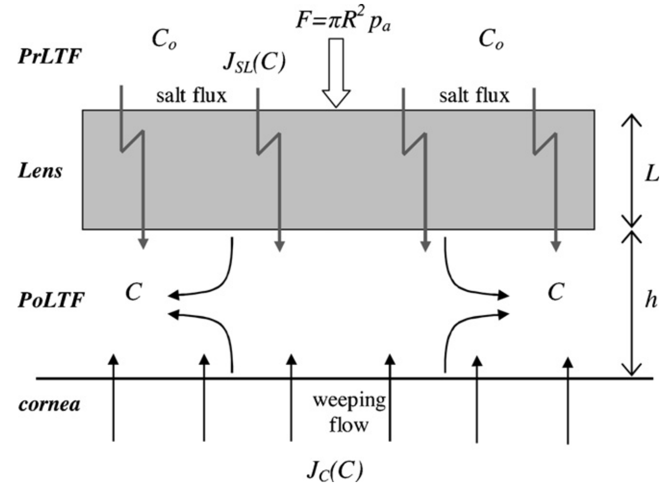

Fig. 2. Schematic of the osmotic-withdrawal mechanism for maintaining the PoLTF thickness. Salt diffuses through the SCL with flux J_{SL} increasing the PoLTF concentration, C. Water is drawn through the cornea into the PoLTF by osmotic forces at a volumetric flux J_C. Drawing is not to scale.

with the squeeze-out mechanism, an equal amount of tear is drawn back into the lens during an interblink when the applied lid force is removed. Also because SCL hydraulic permeabilities are small, osmotic-pressure-driven lens water flow is negligible. We concur with Monticelli et al. [6] that direct water hydraulic flow through a soft contact lens cannot sustain the PoLTF.

An alternate explanation for a critical salt permeability of a SCL was offered by Domschke et al. [5] and later by Nicolson and Vogt [11]. These authors suggested that continuous water paths disconnect below a critical water content in a silicone hydrogel. The threshold salt permeability for lens movement corresponds to the water percolation threshold. Recent measurements of salt permeability of low-water-content SiHy materials, however, demonstrate a continuous decline with decreasing water content down to 10^{-9} cm^2/s at 0.2 wt% water [4,12], salt permeabilities well below the cited threshold necessary for on-eye movement. The question of a definitive percolation threshold for water flow and/or salt diffusion in SCL-hydrogel materials has not been carefully addressed. Neither water hydraulic permeability [6] nor water chemical-potential-gradient-driven diffusive permeability [13–17] correlates directly against salt permeability. Likewise, pervaporation does not explain the role of lens salt permeability in preventing lens adherence [16].

We hypothesize that aqueous-salt diffusive permeability plays a direct role in maintaining the PoLTF under a SCL and is not simply an indirect assessment of water hydraulic permeability. In our picture, higher salt diffusion rates through a SCL increase the salt concentration in the PoLTF, thereby drawing water through the cornea by osmotic suction. Once the SCL salt permeability falls below a threshold value, the thickness of the PoLTF is so diminished that direct interaction with the anterior corneal surface allows local binding of the lens. Water hydraulic permeability of the lens plays no direct role in the proposed osmotic-withdrawal mechanism.

2. Osmotic-withdrawal mechanism

Upon SCL insertion on eye, the lens is deformed and some of the initially thick tear between the lens and cornea is displaced radially outward by the lid blink force (also a squeeze flow [18]). During the interblink when lid force is released, the lens rebounds away from the cornea due to elastic recoil drawing water radially into the PoLTF from tear at the lens margin. However, the lens does not return to either its original shape or to its original tear-film thickness [9] because net energy is lost through viscous dissipation during each blink. Although the process is complex, continued settling is predicted over long time periods [9]. Adherence is imminent once any portion of the lens settles to within a distance characteristic of the glycocalix protruding from epithelial microplicae (approximately 0.1 μm). An additional restoring flow of water into the PoLTF appears necessary to stabilize the lens against continued blink-induced settling.

We hypothesize that when the lens approaches close to the cornea, water withdrawn through the cornea and into the PoLTF over the blink cycle closely balances that squeezed out by the applied lid force. This is a conservative criterion for maintaining the PoLTF thickness as it neglects stabilizing flow from lens elastic recoil. Note, however, that if the lens touches the cornea during a blink and adheres, recoil is unlikely.

Fig. 2 is a schematic of the proposed osmotic-withdrawal mechanism for sustaining a finite PoLTF thickness, h. As shown by the jagged lines, tear salts (taken here as aqueous NaCl) diffuse from the prelens tear film (PrLTF) at concentration, C_0 through the SCL of thickness, L to the PoLTF at a lower concentration, C. The concentration of saline in the PrLTF, C_0, is higher than that of physiologic saline due to tear evaporation [19–21].

During a blink, the eye lid applies an anterior-inward force to the lens, specified as $\pi R^2 p_a$ where R is the lens radius and the applied pressure, p_a, is relative to that in the PoLTF. The lid force squeezes tear radially outward also convecting salt away from the PoLTF as indicated by the curved flow lines in the figure. Although the concentration of salt in the PoLTF is lower than C_0, it nevertheless lies above that of physiologic saline. Thus, the osmotic pressure in the PoLTF is higher than that at the stroma/epithelium interface. Thus, as shown by the vertical arrows in Fig. 2, water is drawn through the epithelium into the PoLTF at a volumetric flux J_C diluting the salt concentration there to a concentration below C_0. Accordingly, osmotic-driven flow of water from the cornea into the PoLTF, labeled as weeping flow in Fig. 2, presses the lens outwards away from the cornea. Over the period of a blink cycle, the upwelling osmotic-driven flow balances that squeezed out of the PoLTF during the blink by the applied lid force. Thus, a time-average