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Journal
Current Eye Research, 43(11)

ISSN
0271-3683

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et al.

Publication Date
2018-11-02

DOI
10.1080/02713683.2018.1500610

Peer reviewed

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Current Eye Research

ISSN: 0271-3683 (Print) 1460-2202 (Online) Journal homepage: http://www.tandfonline.com/loi/icey20

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To cite this article: Young Hyun Kim, Bo Tan, Meng C. Lin & Clayton J. Radke (2018): Central Corneal Edema with Scleral-Lens Wear, Current Eye Research, DOI: 10.1080/02713683.2018.1500610

To link to this article: https://doi.org/10.1080/02713683.2018.1500610

Accepted author version posted online: 17 Jul 2018.
Published online: 06 Aug 2018.

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CURRENT EYE RESEARCH
https://doi.org/10.1080/02713683.2018.1500610

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Central Corneal Edema with Scleral-Lens Wear

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ABSTRACT

Purpose: To evaluate the safety of scleral-lens designs, we model and clinically assess central corneal edema induced by scleral-lens wear for healthy subjects.

Materials and Methods: Central corneal swelling during scleral-lens wear is measured using optical coherence tomography (OCT). Transport resistances are modeled for oxygen diffusion through the scleral lens and post-lens tear-film (PoLTF), and into the cornea. Oxygen deficiency in the cornea activates anaerobic metabolic reactions that induce corneal edema. Oxygen permeability, carbon-dioxide permeability, settled-lens PoLTF thickness, and scleral-lens thickness are varied in the calculations to mimic different lens fits.

Results: Transport modeling predicts that for open eyes, increasing PoLTF thickness from 50 to 400 μm increases central corneal swelling by approximately 1–1.5% when oxygen transmissibility (*Dk/L*) is greater than 10 hBarrer/cm (i.e., hectoBarrer/cm). Although swelling is larger for oxygen *Dk/L* < 10 hBarrer/cm, PoLTF thickness has minimal impact in this range. For open eye, oxygen transmissibility of the lens plays a significant role in corneal edema, but is negligible when oxygen *Dk/L* is > 40 hBarrer/cm. For closed eye, central corneal swelling is greater than 5% for an oxygen *Dk/L* range of 0–100 hBarrer/cm with typical lens-fitting parameters. For carbon-dioxide transmissibilities increasing from 50 to 250 hBarrer/cm and with a fixed oxygen *Dk/L* of 25 hBarrer/cm, calculated swelling diminishes by an additional 0.5%. Comparison of model calculations to clinical-swelling data is within the error range of the clinical measurements.

Conclusions: Oxygen/metabolite transport calculations for open-eye scleral-lens wear show that typical PoLTF thicknesses fitted by clinicians (i.e., PoLTF thicknesses < 400 μm) with modern scleral lenses (i.e., oxygen *Dk/L* > 25 hBarrer/cm) produce corneal swelling of less than 2% in agreement with experiment. Therefore, scleral lenses prescribed today evoke less than physiological hypoxic swelling (i.e., less than 4%) for healthy corneas during openeye. Closed-eye wear, however, appears clinically unsafe.

ARTICLE HISTORY
Received 21 March 2018
Revised 31 May 2018
Accepted 22 June 2018

KEYWORDS
Scleral lens; corneal edema; hypoxia; corneal metabolism; computational modeling; contact lens; oxygen

Introduction

Human corneal health relies on avascular oxygen supply through direct exposure to the environment for open eyes or to the palpebral conjunctiva for closed eyes.[1–3] Compared to soft-contact lenses, the considerably larger lens and post-lens tear-film (PoLTF) thicknesses of rigid-gas-permeable scleral lenses (SLs) raise concern over sufficient oxygen transport from the atmosphere/palpebral conjunctiva to the cornea.[4] Previous studies with soft-contact lenses establish that oxygen deprivation of the cornea can result in adverse corneal events, such as keratitis, microcysts, acidosis, and corneal edema.[5–7]

Two main approaches are available to assess corneal hypoxia with SL wear. First, corneal edema is measured clinically with imaging instruments, such as Scheimpflug camera, ultrasound pachymeter, or optical coherence tomography (OCT).[8–12] The amount of corneal edema is reported as a gauge of corneal hypoxia. Although Scheimpflug camera, ultrasound pachymetry, and OCT used in previous studies[8-11] have similar accuracy limitations of about 3 μm,[13] 5 μm,[14] and 3 μm,[15] respectively, OCT is known to have better repeatability in measuring central corneal thickness than the former methods.[16,17] A major limitation of existing clinical studies[8–12] is lack of SL thickness measurements. Despite having known oxygen permeabilities, lens oxygen transmissibilities (*Dk/L)* may differ significantly. We find that oxygen transmissibility of SLs varies as much as ± 10 hBarrer/cm (i.e., hectoBarrer/cm) due to lens-thickness variance.

In a second approach following considerable effort on soft-contact lenses,[1–3] mathematical models calculate oxygen-tension profiles through the lens and cornea, and especially at the anterior surface of the cornea.[11,18,19] However, these models only predict oxygen profiles and cannot directly predict corneal swelling associated with hypoxia. Unlike studies done with soft-contact lenses,[1–3,20,21] oxygen-tension models and clinical-study results on SL wear yield conflicting conclusions on safe-fitting parameters.[8-12,18,19] Based on oxygen-tension calculations, Compañ et al.[11] suggested that the PoLTF thickness should be smaller than 150 μm to avoid hypoxia. Conversely, Giasson et al.[18] performed an *in-vivo* goggle study to estimate oxygen tension at the surface of the cornea

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and suggested avoidance of settled-PoLTF clearances greater than 200 μm and lens thicknesses greater than 250 μm. Arlt[8] found with OCT, however, that 350 μm thick SLs fit to 200–600 μm PoLTF thickness exhibited less than 4% swelling. Arlt concluded that SLs are safe during open-eye wear.

To overcome these inconsistencies, we extend the edema calculations of Leung et al.[3] to SLs, and we validate our modeling effort with clinical measurements. By considering how oxygen tension controls corneal metabolism, we directly calculate the amounts of corneal edema expected under hypoxic conditions and compare those to measured edema with SL wear. This approach validates prediction of conditions of safe-wear parameters unavailable with only oxygen-tension estimates of previous studies.

Methods

Model

Ample description of the metabolic-edema model is available.[2,3] We provide only a brief nonmathematical summary here. Pioneering studies of corneal edema suggest that corneal swelling is due to aqueous imbibition from the anterior chamber (AC) caused by the proclivity of stroma (St) to uptake water.[22–26] Maurice suggested that swelling is regulated by an active ion pump that lowers the osmolality at the basolateral endothelium (En), relative to that of the aqueous humor, and osmotically drives fluid from the St into the AC.[22] Hodson and Miller later determined that the ion pump actively transports bicarbonate.[27]

Leung et al.[3] built upon these prior works and those of Klyce and Russel,[23] and Li and Tighe[28] by utilizing the Kedem-Katchalsky membrane-transport formalism[29] for the ion pump. Despite extensive studies into the pump-leak mechanism and correlation between corneal swelling and anaerobic glycolysis,[30,31] direct mathematical connection to hypoxia-induced corneal swelling was not made until Leung et al.[3] The key was inclusion of aerobic and anaerobic glucose metabolic-consumption reactions.[2]

When local oxygen tension diminishes, glucose metabolism shifts towards the anaerobic pathway producing lactate ions and lowering pH. Buffering reactions then decrease bicarbonate-ion concentrations. Changes in lactate and bicarbonate-ion concentrations at the En alter corneal water uptake through membrane osmotic transport and the active ion pump. Leung et al.[3] successfully related hypoxia to corneal edema and demonstrated that lactate and bicarbonate-ion concentrations at the En play key roles in corneal swelling.

We extend the 1D hypoxia-edema transport model of Leung et al.[3] to include a SL and a thick PoLTF, as drawn in Figure 1. The lens/cornea comprises the AC, En, St, epithelium (Ep), PoLTF, SL, and pre-lens tear film (PrLTF). A SL is significantly thicker (250–500 μm) at the center than a standard soft-contact lens (80 μm).[1] Diffusion resistances in the PoLTF can no longer be ignored, due to the increased thickness (100–400 μm thickness vs. approximately 3-μm thickness under a soft-contact lens).[3] We calculate the steady concentration profiles of oxygen, carbon dioxide, glucose, lactate ion, hydrogen ion, bicarbonate ion, sodium ion, and chloride ion to determine corneal swelling for different SL transmissibilities and fitting parameters, specifically the PoLTF thickness. Electroneutrality and zero current throughout the cornea are imposed, fluxes of the various species obey the Nernst–Planck relation,[32] and oxygen consumption rate of aerobic and anaerobic reactions follow nonlinear Monod-based kinetics.[2,3] All transport equations and metabolic reactions are given in Appendix A of Leung et al.[3] Parameters necessary for the present calculations are listed in Tables A1–A4.[2,3,23,28,33–42] If not specified, central-lens thickness is 400 μm. Since carbon-dioxide permeability in SLs is not currently available, *Dk* for carbon dioxide was set at 600 Barrer based on Fatt et al.'s[34] analysis of carbon-dioxide permeability in rigid-gas-permeable contact lenses.

Two variations are made to the analysis of Leung et al.[3] First, water-hydration profiles across the cornea determined by Leung

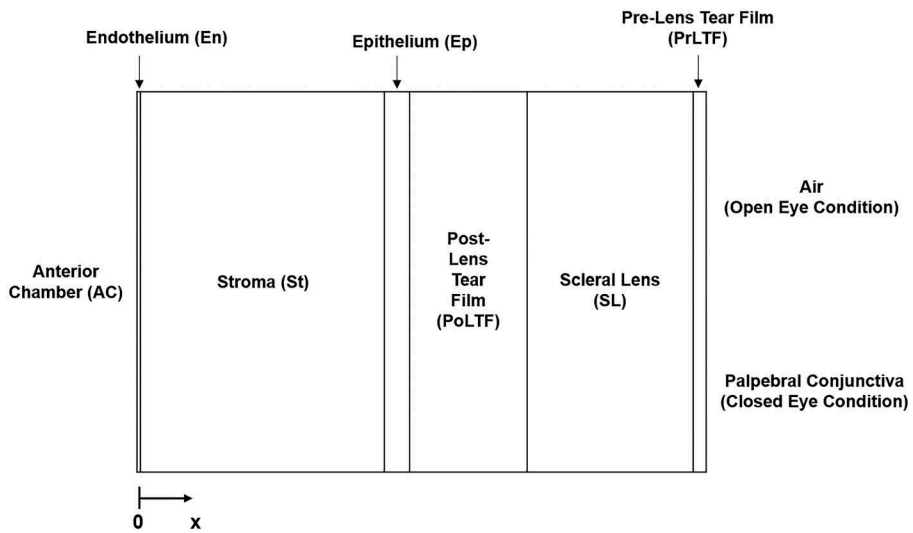

Figure 1. Schematic of the cornea-scleral lens geometry including cornea, thick post-lens tear film, thick scleral lens, and pre-lens tear film.

et al.[3] exhibit very small changes. Total water content varies with oxygenation, but is essentially a constant across the cornea. It follows that steady water flow across the cornea is minimal.[3,28] Thus, following Li and Tighe,[28] we invoke zero water flux. Under this approximation, metabolite fluxes and hydraulic pressure differences across the En and Ep are given by the following Kedem-Katchalsky expressions, respectively.

$$J_i = -\omega_i(RT\Delta C_i + z_i\langle C_i\rangle F\Delta\psi) + J_{ai} \quad (1)$$

$$\Delta P = \sum_i \sigma_i(RT\Delta C_i + z_i\langle C_i\rangle F\Delta\psi) \quad (2)$$

Here, J_i is the molar flux of solute species i, ω_i is the membrane permeability of solute i, J_{ai} is the active flux of solute species i, σ_i is the reflection coefficient of solute i, R is the ideal gas constant, T is the absolute temperature, ΔC_i is the i solute fluid concentration difference across the membrane, z_i is the valence of solute i, $\langle C_i\rangle$ is the mean of the solute fluid concentration difference across the membrane, F is the Faraday constant, and $\Delta\psi$ is the electrostatic-potential difference across the membrane. Once Eq. (2) is satisfied, swelling of the cornea follows from the swelling-pressure measurements of Hedbys and Mishima[26]

$$\Delta P = P - IOP = -\gamma e^{-H_w} \quad (3)$$

where IOP is the intraocular pressure, P is the pressure in the St, γ is an empirical fitting constant, and H_w is water hydration. Corneal thickness, and hence, swelling follows from mass balance. The first term in the summation on the right of Eqs. (1) and (2) are pivotal to predict the role of oxygen in corneal swelling. Because of the metabolic reactions, lactate and bicarbonate-ion concentrations at the En/St interface change significantly with local oxygen tension. These changes induce swelling-pressure variations at the En, which, in turn, swell or deswell the cornea.

The second model alteration from that of Leung et al.[3] arises from the larger PoLTF thickness under SLs. Because a temperature difference exists across the relatively thick PoLTF, natural convection is possible there, similar to that occurring in the AC.[43] Appendix B presents a quantitative argument establishing that even in a 400-μm thick PoLTF, natural convection is minimal. Hence, we adopt diffusion as the dominant transport mode in the PoLTF.

In addition, aqueous species that transport across the Ep but are not soluble in a rigid SL must accumulate in or deplete from the near-stagnant PoLTF.[9] For these particular species, steady transport is not possible. To overcome this limitation, we investigated the swelling effects of hydrogen, hydroxide, sodium, and chloride ions in the PoLTF. Varying the PoLTF concentrations of these species over a large range resulted in imperceptible swelling changes. Therefore, the PoLTF concentrations of these four species were set to those in standard ophthalmic saline solutions (0.9 wt% NaCl, pH = 7.6). Glucose and lactate concentrations in the PoLTF were taken as zero because of the high resistance to transport of these two species across the epithelial layer and because of their trace amounts found in human tear.[2,3] Finally, using the transport model, we estimated the flux of bicarbonate into the PoLTF caused by transport of carbon dioxide across the corneal Ep.[36] Resulting bicarbonate concentration in the PoLTF rose from 0 to 4 mM over 8 h. Corneal-swelling change induced by a 4-mM PoLTF bicarbonate concentration was negligible. Therefore, bicarbonate concentration in the PoLTF was also set to zero and buffering equilibrium of bicarbonate in the post-lens tear was not considered.

The resulting set of highly nonlinear, algebraic, coupled ordinary differential equations was solved numerically by centered finite differences and Newton iteration to obtain concentration profiles of the chemical species and the hydraulic pressure difference at the AC-En boundary. Details are available in Appendix A of Leung et al.[3] Calculations were performed in MATLAB R2016b (Mathworks, Natick, MA). To ensure that the model produces accurate estimates, we compared model predictions to the commonly accepted physiological swelling of 4% for no-lens closed eye[3,21] and to previous swelling calculations of Leung et al.[3] for soft-contact lenses. Parameter values in Table A2 reflect this comparison.

Figure 2 confirms the importance of lactate and bicarbonate ions in hypoxic edema.[3,22] Figure 2A graphs the predicted fall in oxygen tension at the endothelium with declining SL oxygen Dk/L for open eye and a PoLTF thickness of 200 μm. Figure 2B displays the effect of the oxygen-tension decline on endothelial lactate-ion (solid line) and bicarbonate-ion (dashed line) concentrations. The reason for these changes is that as oxygen tension diminishes, metabolism shifts toward the anaerobic consumption of glucose producing lactate or

$$C_6H_{12}O_6 \rightarrow 2C_3H_5O_3^- + 2H^+ \quad (4)$$

The concomitant increase in acidity is buffered by a decline in bicarbonate concentration via the reaction

$$HCO_3^- + H^+ \leftrightarrow CO_2 + H_2O \quad (5)$$

Changing lactate and bicarbonate-ion concentrations alter the hydration of the cornea through membrane transport described in Eqs. (1) and (2), and through swelling pressure in Eq. (3). Figure 2B highlights that lactate-ion concentration is more sensitive to changes in oxygen partial pressure than is bicarbonate ion.

Clinical edema

To validate the proposed cornea-edema model, we analyze the recent swelling data of Tan et al.[9] plus new swelling measurements for eight subjects wearing three different commercial lenses of somewhat larger oxygen Dk/L values. Five females and three males (Mean ± SD age = 22.0 ± 2.1 years) with no prior contact-lens wear for at least one year prior to enrollment and were free of ocular disease were recruited from the University of California, Berkeley campus and from the surrounding community. Subject demographics consisted of 50% Asian, 25% Caucasian, 12.5% Indian, and 12.5% Hispanic. Informed consent was obtained from all participants after full description of the goals, potential risks, benefits, and study procedures. This study adhered to the tenants of the Declaration of Helsinki and was approved by the Committee for Protection of Human Subjects, University of California, Berkeley.

Similar to the protocol of Tan et al.,[9] each of the eight subjects participated in four visits with at least 24-h washout between

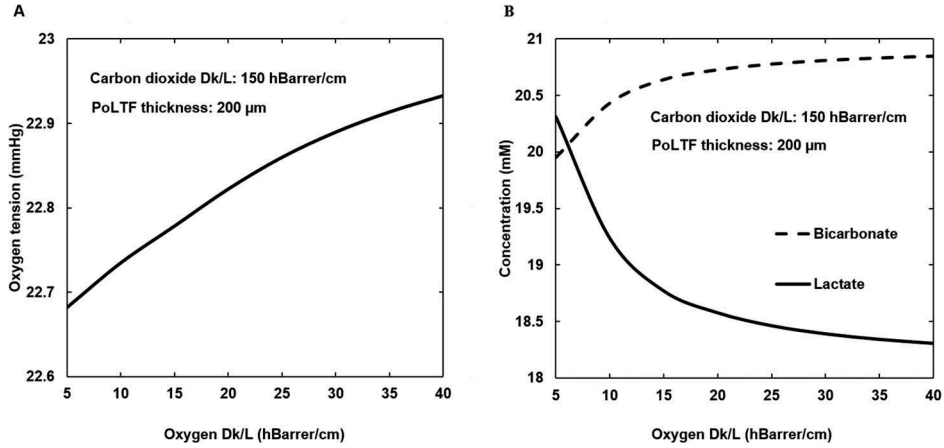

Figure 2. Model-calculated endothelial/stromal boundary concentrations as a function of oxygen transmissibility. (A) Oxygen partial pressure; (B) bicarbonate and lactate-ion concentrations.

visits. The first visit consisted of ocular-health assessment and lens fitting. Three different commercial SLs with refractive correction were ordered for each subject: Optimum Extra (*Dk* = 100 Barrer; Contamac, Ltd. Saffron Walden, UK), Boston XO2 (*Dk* = 141 Barrer; Bausch & Lomb, Rochester, NY), and Menicon Z (*Dk* = 163 Barrer; Menicon Co., Ltd., Nagoya, Japan). All ordered lenses were 15.6 mm in diameter and had standard spherical curves. The settled-central PoLTF thickness after 5 h of lens wear was measured by OCT (ENVISU 2300, Bioptigen Inc, Durham, NC). Subjects wore the lens on either the right or the left eye; choice of the specific eye, as well as the order of lens type for visits 2–4 were determined randomly.

For visits 2–4, subjects awoke at least 2 h before each visit to ensure that the cornea had deswollen from overnight edema.[21] Subjects discontinued prior usage of topical creams, allergy medications, and eye drops for at least one full day. Immediately after lens insertion, baseline central corneal thickness was measured using OCT . Central lens and PoLTF thicknesses were measured 10 times with OCT throughout the 5-h lens-wear duration. Repeated measurements of the PoLTF thickness throughout the 5-h wear period ensured that the lens had mostly settled within 2 h. Repeated central-lens thicknesses measurements were averaged to determine the central oxygen transmissibility of each lens used in the study. Immediately prior to lens removal, central corneal thickness was measured with OCT. Central corneal swelling for each subject and visit was determined from corneal thickness (after 5 h of wear) minus that at baseline and expressed as a percentage of the baseline value. Lens oxygen transmissibility followed from the manufacture-reported permeability divided by the OCT-measured lens central thickness. Lens thickness varied from about 300–500 µm, resulting in a range of lens oxygen transmissibility from about 20 to 45 hBarrer/cm.

Results

Model results

Figure 3 reports open-eye swelling of the cornea during SL wear as a function of oxygen *Dk/L* for five settled PoLTF thicknesses. For the typical settled-PoLTF-thickness range of 100–250 µm, oxygen transmissibility of 25 hBarrer/cm or greater results in corneal edema of less than 1.5%. However, for a settled-PoLTF thickness of 400 µm, oxygen transmissibility must be about 40 hBarrer/cm or greater to maintain corneal edema below 1.5%. Transport modeling predicts that for open eyes, increasing PoLTF thickness from 50 to 400 µm increases central corneal swelling by approximately 1–1.5% when oxygen *Dk/L* is greater than 10 hBarrer/cm. For settled-PoLTF thickness less than 400 µm, oxygen *Dk/L* of about 10 hBarrer/cm or less results in swelling greater than that of normal overnight no-lens swelling.

Figure 4, however, reveals that closed-eye SL wear results in corneal edema above physiologic. Even at large values of oxygen transmissibility, corneal swelling lies considerably above the overnight 4% value. Also with closed-eye wear, the PoLTF thickness has more significant impact on edema than for open-eye wear. There is up to a 2.5% increase in swelling for PoLTF thickness between 50 µm and 400 µm, whereas open-eye lens wear induces only up to 1.7% corneal swelling.

Figure 5 illustrates the role of lens carbon-dioxide transmissibility on corneal swelling during open-eye lens wear for a 400-µm PoLTF thickness and an oxygen *Dk/L* of 25 hBarrer/cm. Percentage swelling in Figure 5 includes edema originating from oxygen. Similarly, Figures 3 and 4 include the effects of carbon dioxide on edema. Rigorous separation of the two effects is not possible due to linked dependence of carbon dioxide and oxygen in corneal metabolism. A closed diamond in Figure 5 marks the carbon-dioxide transmissibility utilized in Figures 3 and 4. Over a large range of carbon-dioxide transmissibilities, there is a 1% change in swelling. Precise estimates of carbon-dioxide *Dk/L* for SLs are not available. However, for the carbon-dioxide permeability range predicted by Fatt et al.[34] for rigid-gas-permeable lenses (i.e., 50–250 hBarrer/cm), there is up to a 0.5% change in corneal swelling.

Clinical results

Figure 6 shows central swelling for 82 separate OCT measurements as a function of lens oxygen transmissibility. Not all points can be highlighted because they overlap on the scale of the figure. Open circles correspond to the results from Tan

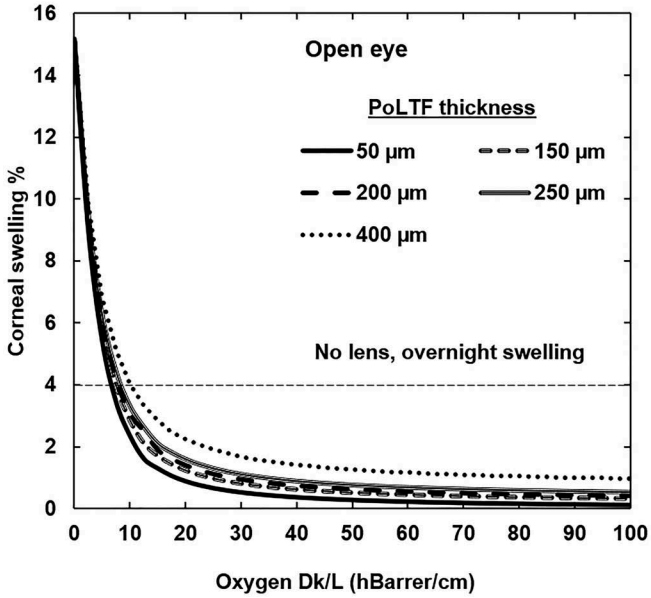

Figure 3. Predicted central corneal swelling as a function of lens oxygen transmissibility for open eye. A dashed horizontal line represents the typical amount of swelling for no-lens overnight closed eye. Five curves correspond to settled-PoLTF thicknesses of 50 µm, 150 µm, 200 µm, 250 µm, and 400 µm.

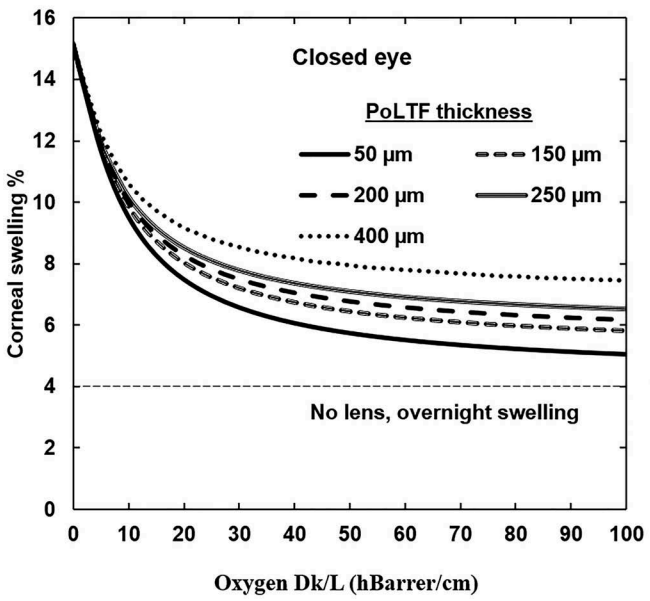

Figure 4. Predicted central corneal swelling as a function of lens oxygen transmissibility for closed eye. A dashed horizontal line represents the typical amount of swelling for no-lens overnight closed eye. Five curves correspond to settled-PoLTF thicknesses of 50 µm, 150 µm, 200 µm, 250 µm, and 400 µm.

et al.[9] while open triangles report current measurements. OCT-thickness precision is about ± 0.5% (i.e., ~3 µm).[15] Settled-PoLTF thickness cannot be controlled clinically. For each lens fit on each subject, final settled-PoLTF thickness varied, sometimes substantially. Thus, it is not possible to investigate preset settled-PoLTF thicknesses. For this reason, data in Figure 6 scatter revealing no discernable relationship to PoLTF thickness.

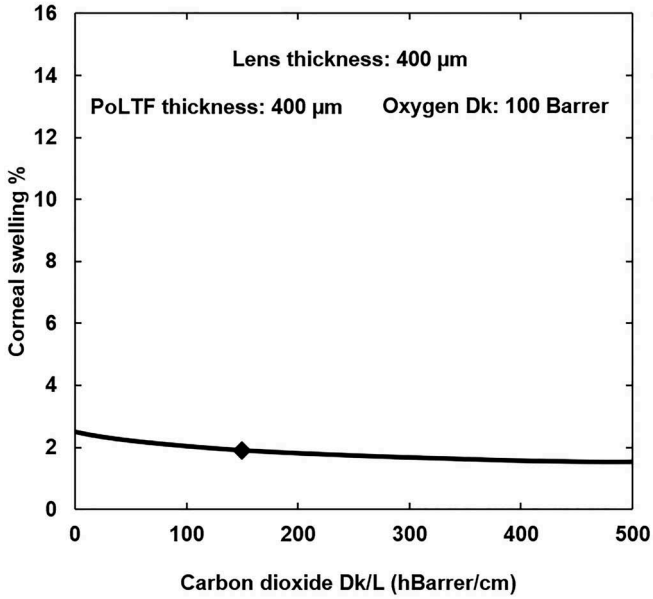

Figure 5. Predicted central corneal swelling as a function of carbon-dioxide transmissibility for open eye. Post-lens tear-film and lens thicknesses are both 400 µm; oxygen *Dk* is 100 Barrer. A closed diamond marks the carbon-dioxide transmissibility utilized in Figures 3 and 4.

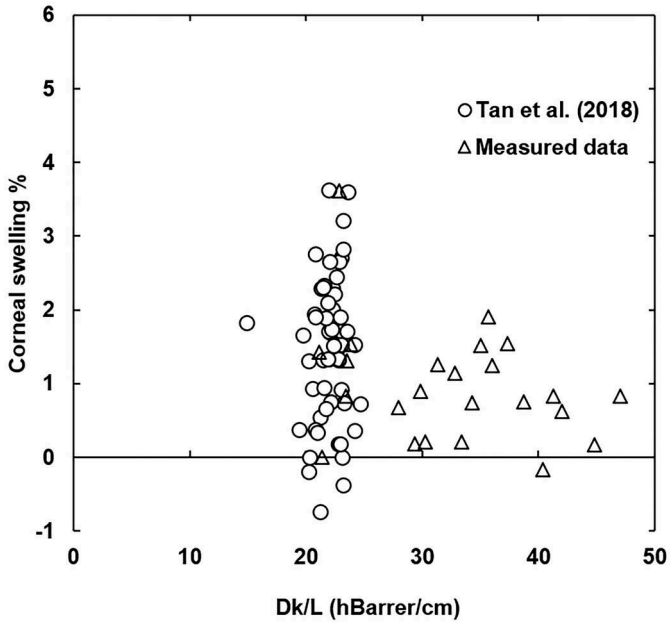

Figure 6. OCT-measured central corneal swelling in percent for 82 measurements as a function of scleral-lens oxygen transmissibility in hBarrer/cm. Open circles are from Tan et al.[9]; open triangles are from this study. Four measurements showed deswelling after lens wear. OCT-swelling precision is approximately ± 0.5%.[15] Data scatter is amplified due to differing settled-PoLTF thicknesses.

To overcome this deficiency, we parceled the measured swelling data into eight discrete increments of settled-PoLTF thickness, each with a 50-µm width. Over this increment thickness range, the data of Tan et al.[9] and theory establish that a 50-µm PoLTF thickness range has an insignificant influence on corneal swelling.

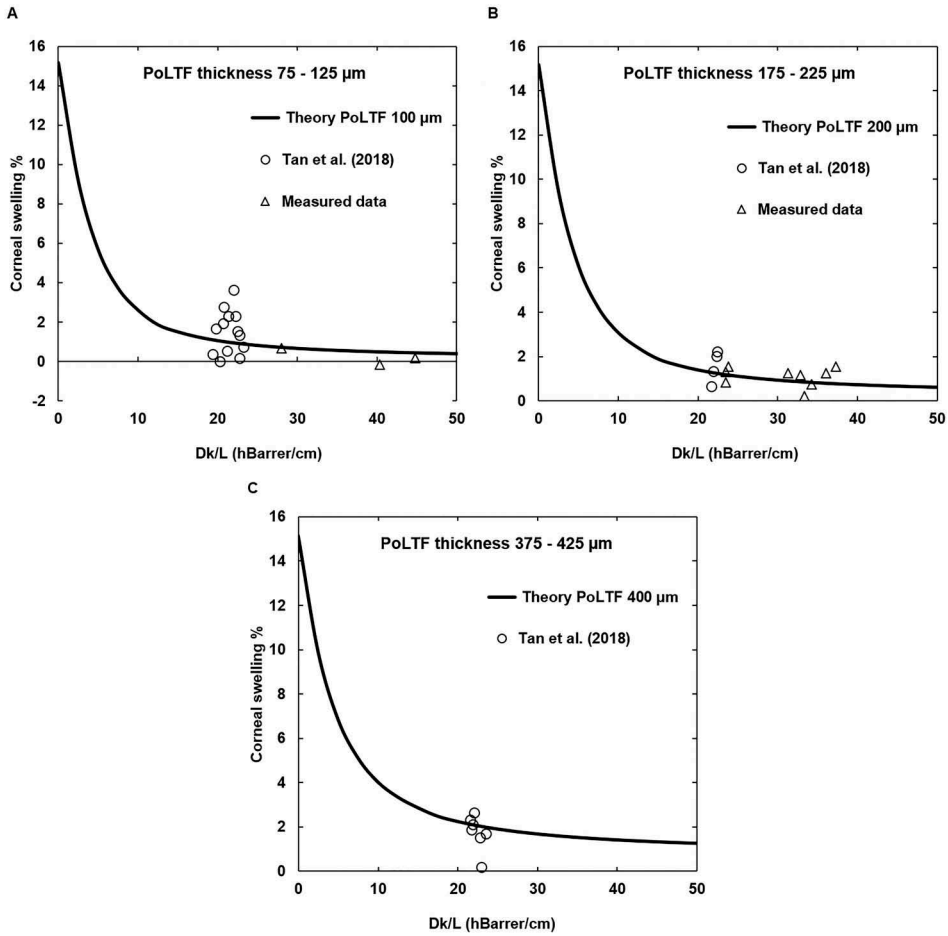

Figure 7. Comparison of theory (solid line) to OCT-measured central corneal swelling as a function of scleral-lens oxygen transmissibility for parceled settled-PoLTF thicknesses. (A) 75 −125 µm, (B) 175–225 µm, and (C) 375–425 µm, respectively. Open circles are from Tan et al.[9]; open triangles are from this study. OCT-swelling precision is approximately ± 0.5%. Theory is for median PoLTF thickness of each parcel using no adjustable parameters.

Figure 7 replots the raw swelling results as function of oxygen *Dk/L* but parceled into PoLTF thickness intervals of 75–125 µm, 175–225 µm, and 375–425 µm, respectively. These ranges were chosen to represent shallow, medium, and steep fits for PoLTF thickness. Results for the remaining PoLTF thickness intervals can be found in Appendix C. Solid lines in Figure 7 and those in Figure C1 give theory prediction using no adjustable parameters. For each plot, PoLTF thickness in the corneal-edema model was set as the median over that specific range. For those plots with sufficient data, i.e., for Figures 7A–C, and Figure C1B, C and E, theory compares well with experiment. For the PoLTF thickness increments of 25–75 µm and 275–325 µm, data are insufficient in numbers to allow comparison. Nevertheless, even for these cases, agreement with theory is acceptable.

Discussion

Predicted corneal swelling for open-eye wear of SLs shows that typical settled-PoLTF thicknesses in the range 100–250 µm, and commercially available oxygen transmissibilities provoke less than 2% swelling. Emphasis for preventing hypoxia should focus on oxygen *Dk/L* rather than on the thickness of the PoLTF. This recommendation is especially true for oxygen *Dk/L* less than 10 hBarrer/cm, as Figure 3 shows minimal impact of PoLTF thickness on corneal swelling within that region. When oxygen *Dk/L* is greater than 25 hBarrer/cm, corneal edema is minimal (i.e., less than 2% swelling) during open eye for settled-PoLTF thicknesses up to 400 µm. Figure 3 also shows that swelling plateaus above oxygen transmissibilities of about 40 hBarrer/cm. Oxygen transmissibility greater than 40 hBarrer/cm provides little additional benefit in reducing edema for daily-lens wear. In this range of *Dk/L* values, the influence of PoLTF thickness on central corneal edema also is minimal for values below about 250 µm. However, the safety of chronic swelling of the cornea during SL wear (i.e., less than 2% swelling during day lens wear followed by physiological corneal swelling during no-lens-wear overnight sleep) requires further investigation.

Corneal-swelling predictions for closed eye demonstrate that a settled-PoLTF thickness range of 50–400 µm and an oxygen *Dk/L* less than 100 hBarrer/cm cause significant corneal edema. Thus, SL wear during sleep is not recommended, even for healthy corneas. When the cornea is hypoxic, oxygen *Dk/L* and PoLTF thickness both contribute more to corneal edema than when the cornea is not deprived of oxygen.

Because of high water permeability and thin PoLTF and lens thicknesses, the influence of carbon dioxide on corneal edema is minimal for soft-contact-lens wear. However, with SL wear and larger PoLTF and lens thicknesses, the effect of carbon dioxide on corneal edema needs to be revisited. Upon comparing carbon-dioxide transmissibilities of 0 and 500 hBarrer/cm in Figure 5, we note a decline of 1% in corneal swelling. The reason for this decrease is that with higher lens carbon-dioxide transmissibility, more carbon dioxide exits the cornea. This exit shifts the chemical equilibrium in Eq. (5) toward carbon-dioxide production and reduces the concentration of bicarbonate ion in the cornea. Lower bicarbonate-ion concentration at the endothelial layer decreases the swelling pressure in Eq. (3) and, hence, reduces swelling. In this study, the contributions of lactate and bicarbonate ions to the endothelial pump and, subsequently, to edema are consistent with the *in-vivo* findings of Nguyen and Bonnano.[44]

Within the current precision of OCT-measured corneal swelling, our cornea-edema model for SLs agrees with available swelling data. However, clinical data with controlled settled-PoLTF thickness and lens transmissibility are limited. Further well-controlled studies are warranted. The proposed theory uses no adjustable physical constants. It, therefore, provides a useful tool for evaluating possible hypoxia with SL wear. We find that open-eye wear of SLs by healthy subjects induces clinically acceptable central corneal edema, whereas closed-eye wear for healthy corneas does not. Long term effects of SL wear are not addressed in this study.

Declaration of interest

The authors report no conflicts of interest.

Funding

Financial support from Clinical Research Center Unrestricted Fund (MCL) and Lagado Corporation (MCL) is acknowledged.

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Appendix A. Parameters

Tables A1–A4 report parameter values used in the calculations.

Table A1. Physical Parameters at the Anterior Chamber and the Tear Films.

	Anterior Chamber	PoLTF	PrLTF (open/closed)
P_O (mmHg)	24[†]	(Solved for)	155[†]/61.5[†]
P_C (mmHg)	38[‡]	(Solved for)	0.5[§]/38[‡]
C_{Na} (mM)	146.55[‖]	150*	150[‖]
C_{Cl} (mM)	102.85[‖]	150*	137.9[‖]
C_B (mM)	36[‖]	0*	12.1[¶]
pH	7.6[#]	7.6*	7.6[◊]
C_L (mM)	7.7[□]	0[└]	0[└]
C_G (mM)	6.9[§]	0[§]	0[§]
P (Pa)	2670[┘]	0	0

*Determined by using the model. Explained in Methods.
[†]Obtained from Brennan.[35]
[‡]Obtained from Bonanno et al.[36]
[§]Obtained from Fatt et al.[33]
[‖]Obtained from Leung et al.[3]
[¶#]Obtained from Rismondo et al.[37]
Obtained from Giasson et al.[38]
[◊]Obtained from Fischer et al.[39]
[□]Obtained from Imre.[40]
[└]Obtained from Klyce.[41]
[┘]Obtained from Klyce et al.[23]

Table A2. Membrane Coefficients for the Endothelium and Epithelium Boundary Layers.

Coefficient	Endothelium	Epithelium
σ_{Na}	0.45[‡,§]	0.79[‡,§]
σ_{Cl}	0.45[‡,§]	0.79[‡,§]
σ_B	0.48*	0.79[‡,§]
σ_H	0.45[‡,§]	0.79[‡,§]
σ_L	0.54*	1[‡]
σ_G	0.45[‡,§]	1[‡]
σ_O	0.45[‡,§]	0.79[‡,§]
σ_C	0.45[‡,§]	0.79[‡,§]
$\omega_{Na}RT \times 10^5$ (cm/s)	8[‡,§]	0.019[‡,§]
$\omega_{Cl}RT \times 10^5$ (cm/s)	8[‡,§]	0.019[‡,§]
$\omega_BRT \times 10^5$ (cm/s)	8[‡,§]	0.019[‡,§]
$\omega_HRT \times 10^5$ (cm/s)	8[‡,§]	0.019[‡,§]
$\omega_LRT \times 10^5$ (cm/s)	3[‡,§]	0[‡,§]
$\omega_GRT \times 10^5$ (cm/s)	8[‡,§]	0[‡,§]
$\omega_O k_O RT$ (mol O_2 cm/(s mm Hg cm^3))	15.8 × 10^{-12}[‡]	$\frac{D_o k_o}{\Delta x}$ [†]
$\omega_C k_C RT$ (mol O_2 cm/(s mm Hg cm^3))	316 × 10^{-12}[‡]	$\frac{D_C k_C}{\Delta x}$ [†]
$J_{ai} \times 10^{10}$ (mol/cm^2 s)	−9.4[‡] (bicarbonate)	0.16[‡] (chloride)

*Adjusted from Leung et al.[3], and Klyce and Russel.[23]
[†]Calculated following Leung et al.[3] ωkRT is set as Dk divided by the mesh size.
[‡]Obtained from Leung et al.[3]
[§]Obtained from Klyce and Russel.[23]

Table A3. Diffusion and Reaction Parameters of the Corneal-Lens System*.

	Endothelium	Dry stroma	Epithelium	PoLTF	SL	PrLTF
Corneal Thickness (μm)	1.5	78	50	Variable	Variable	3
$D_{Na}\times10^6$ (cm^2/s)	-	9	9	-	-	-
$D_{Cl}\times10^6$ (cm^2/s)	-	9	9	-	-	-
$D_B\times10^6$ (cm^2/s)	-	1.5	0.22	-	-	-
$D_H\times10^5$ (cm^2/s)	-	1.18	0.19	-	-	-
$D_L\times10^6$ (cm^2/s)	-	4.4	4.4	-	-	-
$D_G\times10^6$ (cm^2/s)	-	3	3	-	-	-
D_Ok_O (Barrer)	5.3	29.5	18.8	90	Variable	90
D_Ck_C (Barrer)	106	590	376	900	Variable[†]	900
$Q_o^{max}\times10^9$ (mol/(cm^3 s))	-	6.28	11.6	-	-	-
$Q_L^{min}\times10^9$ (mol/(cm^3 s))	-	24.7	4.83	-	-	-

*Obtained from Leung et al.[3]
[†]When not varying carbon dioxide Dk/L, 150 hBarrer/cm is used.[34]

Table A4. Physical Constants.

Parameter	Value
IOP (Pa)	2670*
γ (Pa)	$2.41 * 10^{5}$[†]
ρ_d (g/cm^3)	1.49[‡]
ρ_w (g/cm^3)	1.00[‡]
K_O^O (mm Hg)	2.2[§]
K_O^L (mm Hg)	2.2[§]
K_G^O (mM)	0.4[§]
K_G^L (mM)	0.4[§]
K_{pH}	0.1[§]
pK_B	6.04[§]
s_C (mM/mm Hg)	0.0258[§]
T (K)	310.5
R (J/(mol K)	8.314
F (C/mol)	9.648×10^4

*Obtained from Leung et al.[3]
[†]Obtained from Fatt et al.[42]
[‡]Obtained from Li et al.[28]
[§]Obtained from Chhabra et al.[2]

Appendix B. Diffusion versus Natural Convection in the PoLTF Behind a Scleral Lens

To establish whether species diffusion versus natural convection dominates transport through the PoLTF behind a scleral lens, we estimate Péclet number[45]

$$Pe \equiv \frac{u\delta}{D} \tag{B1}$$

where δ is the characteristic thickness of the PoLTF, u is the characteristic velocity due to natural convection, and D is the diffusivity of the aqueous species. $Pe \leq 1$ indicates that diffusion dominates solute transport and vice versa.[45]

Diffusivities of metabolic species in water are near 2×10^{-5} cm^2/s.[45] The PoLTF thickness (central) was ranged from 100 to 400 μm. To establish the characteristic velocity in the PoLTF, we adopted the simple analysis in Bird et al.[45] of natural convection between two vertical parallel plates with a set temperature difference between them. Thus, we assumed that the cornea and the lens are locally flat with a fixed thickness corresponding to that of the central PoLTF. Bird et al.[45] give the following result for the characteristic (i.e., average) velocity for natural convection between two parallel vertical plates as

$$u = \frac{\rho\beta g\delta^2\Delta T}{192\mu} \tag{B2}$$

where ρ is mass density of the tear, β is the coefficient of volume expansion of tear (0.00030 1/°C), g is gravitational acceleration, μ is the viscosity, and ΔT is the temperature difference between the epithelial-PoLTF interface and the scleral lens-PrLTF interface. To estimate ΔT in Eq. B2, we adopt Dursch

et al.'s[46] early-time corneal temperature-profile calculations with incorporation of PoLTF and scleral-lens thermal resistances. Specific heat and thermal conductivity of PoLTF were set as 3997 J/(kg K) and 0.58 W/(m K), respectively. Lens thickness and density were set as 400 μm and 1185 kg/m^3[3,47] respectively. Reasonable ranges of the thermal properties of fluorosilicone-acrylate scleral lenses were tested: 1000–3000 J/(kg K) for specific heat and 0.1–0.4 W/(m K) for thermal conductivity, respectively, as they are not readily available in the literature. We calculate ΔT to be less than 1 °C for PoLTF thicknesses of up to 400 μm. Accordingly, we adopt a 1 °C temperature difference for our estimates of *Pe*. Results for several PoLTF thicknesses are given in Table B1.

Within the typical PoLTF settled-thickness range seen in the clinic, i.e., 100–400 μm, the Péclet number is less than about 0.5. Eq. B2 overestimates the characteristic velocity in the PoLTF because of gap narrowing near the lens periphery. Likewise, our temperature-difference estimate is likely high. Consequently, the assumption appears valid that the PoLTF behind a scleral lens is stagnant.

Table B1. Calculated Natural-Convection Péclet Numbers.

PoLTF thickness (μm)	Velocity (mm/h)	Péclet number
100	0.70	0.010
150	1.57	0.033
200	2.79	0.077
250	4.35	0.151
300	6.27	0.261
400	11.14	0.619

Appendix C: Comparison Plots for Parceled-PoLTF Clinical Data to the Model

Comparison of theory (solid lines) to OCT-measured central corneal swelling as a function of scleral-lens oxygen transmissibility for parceled settled-PoLTF thicknesses is shown in Figure C1.

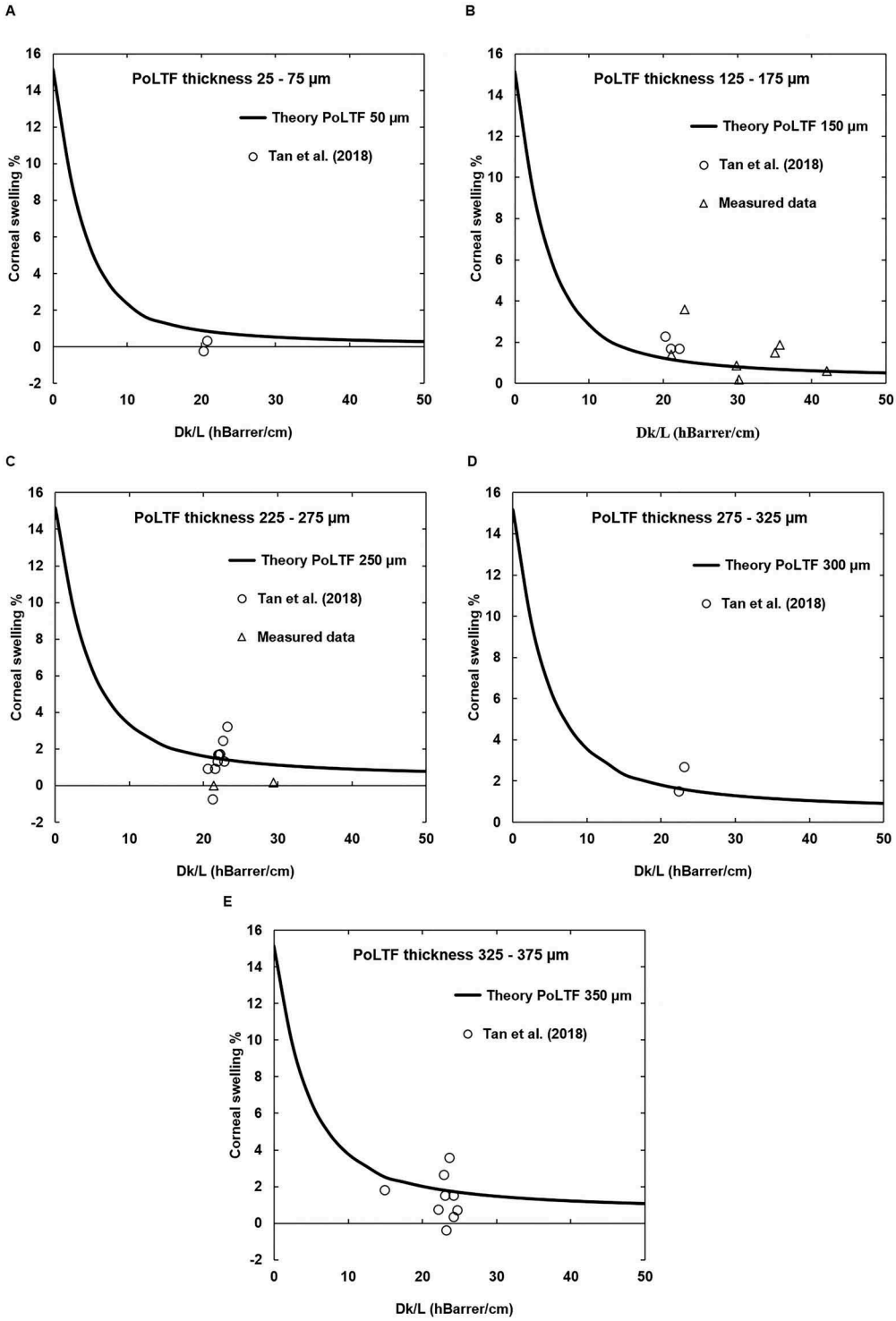

Figure C1. Comparison of theory (solid line) to OCT-measured central corneal swelling as a function of scleral-lens oxygen transmissibility for parceled settled-PoLTF thicknesses. (A) 25–75 µm, (B) 125–175 µm, (C) 225–275 µm, (D) 275–325 µm, and (E) 325–375 µm, respectively. Open circles are from Tan et al.[9]; open triangles are from this study. OCT-swelling precision is approximately ± 0.5%. Theory is for median PoLTF thickness of each parcel using no adjustable parameters.