Precorneal and Pre- and Postlens Tear Film Thickness Measured Indirectly with Optical Coherence Tomography

Jianhua Wang, Desmond Fonn, Trefford L. Simpson, and Lyndon Jones

PURPOSE. To demonstrate the feasibility of indirectly measuring the precorneal tear film thickness and pre- and postlens tear film (PLTF) thickness using optical coherence tomography (OCT).

METHODS. Central corneal thickness (C₁) which includes the tear film (T) of both eyes of 40 non-contact lens wearers was measured using OCT after calibration. The mean age of the 40 subjects was 31.2 ± 9.3 years with a mean horizontal K-reading of 7.87 mm. Rigid contact lenses with base curves 0.3- to 0.5-mm steeper than the flattest K of the eye were fitted to measure real corneal thickness (C₂), independently of the postlens tear film. T was calculated by T = C₂ - C₁. To measure pre- and postlens tear film thickness, Focus Night & Day and Acuvue lenses (Vistakon, Johnson & Johnson Vision Care, Jacksonville, FL) were fitted on both eyes. Central soft lenses thickness (L₁), which includes the prelens tear film (PLTF), was measured by OCT in situ and in saline in a wet cell (L₂). P was calculated by P = L₁ - L₂. Thickness of the central cornea plus the postlens tear film (C₃) was measured during lens wearing. Postlens tear film (PLTF) thickness was calculated by PLTF = C₃ - C₂.

RESULTS. The mean ± SD precorneal tear film thickness was 3.3 ± 1.5 μm (range, 0–6.9) before lens insertion and 4.7 ± 2.3 μm (range, 0.7–11.0) after lens fitting, which was significantly thicker (paired t-test: P < 0.01). The prelens tear film thickness was 3.9 ± 2.6 and 3.6 ± 2.1 μm (mean ± SD; paired t-test: P = 0.52) and the postlens tear film thickness was 4.5 ± 2.3 and 4.7 ± 3.1 μm (paired t-test: P = 0.08) on and under Focus Night & Day and Acuvue lenses, respectively. Post hoc tests showed that precorneal (baseline) and postlens tear films were equivalent, and each was different (thinner; Tukey honestly significant difference P < 0.05) from the postlens tear film.

CONCLUSIONS. OCT can noninvasively measure the thickness of the precorneal and prelens tear film as well as the postlens tear film. The thickness of the normal precorneal tear film is approximately 3 μm and becomes thicker after lens fitting. The postlens tear film is thicker than the precorneal and prelens tear films with soft contact lenses. The thickness of both pre- and postlens tear films appears to be independent of the investigated lens types. (Invest Ophtalmol Vis Sci. 2003;44: 2524–2528) DOI:10.1167/iovs.02-0731

Human precorneal tear film thickness still interests researchers and clinicians, because it may be related to dry eye and corneal integrity, as well as symptoms of dryness and discomfort with contact lens wear. However, the true thickness of the tear film remains controversial, with widely differing published results.1–3 For example, Prydal and Campbell1 and Prydal et al.2 reported that the mean thickness of the tear film was 34 to 45 μm, using confocal microscopy, and King-Smith et al.3 demonstrated that it is only approximately 3 μm using reflection spectra. The reason for these controversial results is mainly due to the difficulty of the measurement of tear film thickness.

Dryness and discomfort with contact lens wear have been reported by as many as 50% of contact lens wearers and are two major reasons associated with premature contact lens discontinuation.4,5 However, the etiology of these complications is unknown.4 Pre- and postlens tear layers may play an important role in these contact lens wearers. Unfortunately, there are no consistent results of pre- and postlens tear film thickness in the literature. Using optical pachometry, Lin et al.6 reported postlens tear film thickness measurements of 11 to 12 μm, whereas Nichols and King-Smith (ARVO Abstract 3198, 2001) reported results of approximately 2.5 μm with the same type of lenses.

Based on an interferometric technique, optical coherence tomography (OCT) allows quick measurements of corneal thickness in multiple adjacent locations almost simultaneously, to yield precise results with good repeatability from approximate 1 μm7 to 3 μm.8 OCT has been used to measure corneal and epithelial thickness in a variety of studies, including those investigating diurnal variations and changes after contact lens wear, both centrally and topographically.8–11 Knowing that all OCT measurements of corneal thickness would include the precorneal tear film,12 a new method has been developed by our group to measure indirectly the thickness of the tear film.

The purpose of this study was to demonstrate the feasibility of indirectly measuring the precorneal tear film thickness and pre- and postlens tear film thickness using OCT. This study used the technique to compare pre- and postlens tear film thickness in wearers of traditional hydrogel and silicone-hydrogel contact lenses.

METHODS

OCT and Calibration

An OCT system (Carl Zeiss Meditec, Dublin, CA) was used in this study to measure corneal thickness as described previously (Fonn D, Wang JH, Simpson T, ARVO Abstract 3591, 2000).8,10,13,14 The thickness was measured as the distance between a pair of peaks in individual sagittal scans, as described in other studies8,10,13 and as shown in Figure 1. OCT measurements were taken in subjects’ eyes, with and without contact lenses, to calculate the thickness of the tear film, as reflected in Figure 1.
Tear Film Measurements

Central corneal thickness \( (C_1) \) which includes the tear film \( (T) \) was measured using OCT after calibration. Rigid contact lenses with base curves 0.5 to 0.5 mm steeper than the flattest \( K \) of the eye were fitted in order to measure real corneal thickness \( (C_2) \), independently of the postlens tear film, \( T \) was calculated by using \( T = C_1 - C_2 \). To measure pre- and postlens tear film thickness, Focus Night & Day and Acuvue lenses were fitted on eyes. Central soft lens thickness \( (L_1) \) which includes the prelens tear film \( (P) \) was measured in situ and in saline in a wet cell \( (L_2) \) using OCT. \( P \) was calculated by using \( P = L_1 - L_2 \). Thickness of the central cornea plus the postlens tear film \( (L_2) \) was measured during lens wearing. PLTF was calculated by using PLTF \( = C_3 - C_2 \). OCT displays of these measurements are in Figure 1 and their expiartions are in legend to Figure 1.

Experimental Procedure

Forty subjects (16 men and 24 women, age 31.2 ± 9.3 years) with no history of contact lens wear or any current ocular or systematic diseases were recruited for this study. Informed consent was obtained from each subject after ethics approval was obtained from the Office of Research Ethics, University of Waterloo. All subjects were treated in accordance with the tenets of the Declaration of Helsinki.

Acuvue lenses (back vertex power \( [BVP] \) −0.25 to −0.50 D, base curve \( [BC] \) 8.8 mm, diameter 14.0 mm; Vistakon, Johnson & Johnson Vision Care, Jacksonville, FL) and Focus Night & Day lenses \( (BVP \sim 0.25 \text{ to } -0.50 \text{ D}, \text{ BC } 8.6 \text{ mm, diameter } 13.8 \text{ mm}; \text{ Ciba Vision, Duluth, GA}) \) were used in this study. Also PMMA lenses \( (BC: 7.03 \text{–} 8.55 \text{ mm, diameter: } 9.2 \text{–} 9.8 \text{ mm}; \text{ BVP: plano}) \) were used.

In a prospective experimental study, a screening visit was scheduled after 10 AM to ensure that corneal edema induced by sleeping the previous night had dissipated. At this visit, participants were screened. The study procedure was explained to all participants. If they were eligible for the study, they were asked to sign an informed consent.

All subjects were instructed to fixate on a central target in the OCT and a television monitor was used to ensure the position of perpendicular light over the entrance pupil by monitoring the specular reflection from the apex of the cornea. A single line scan (length of 1.13 mm) in the horizontal meridian was used to measure the corneal thickness. The central 21 of 100 A-scans in each OCT measurement were analyzed,7 which provides a lateral sampling interval of 11.3 μm. Peaks were identified from each of the 21 A-scans and these thickness measurements were averaged.

To obtain OCT thickness of contact lenses in vitro, a device with a 45° mirror and lens holder (Con-Ta-Chek; Plastic Contact Lens Co., Chicago, IL) was mounted on the OCT to hold and measure the contact lenses vertically in dry and wet (immersed in saline) conditions.

OCT was calibrated using a set of polymethylmethacrylate (PMMA) lenses with different base curves and known central thicknesses obtained with an electronic thickness gauge \( (ET-1; \text{ Rehder Development Co., Castro Valley, CA}) \). Two lenses were placed together, and saline was used to fill the gap between them. This combination was measured with OCT and the thickness gauge centrally. Therefore, central OCT thickness and true thickness of the saline layer can be indirectly calculated as shown in Figure 2. Linear regression yielded the equation shown in the figure, where \( y \) is the true central thickness of the saline layer between two lenses and \( x \) is OCT thickness converted by the difference of refractive indices between OCT setting and saline (conversion factor, 1.37/1.335). This equation indicates that the converted OCT thickness is approximately equal to the physical thickness of the saline layer, as shown in Figure 2.
letter. A biomicroscopic examination, automated refraction and keratometry and measurements with OCT were conducted.

At the study visit, baseline corneal thickness (including the precorneal tear film) was measured with OCT. Steep PMMA lenses were inserted in both eyes (steeper than the flattest corneal curvature, 0.3–0.5 mm) and the fit was checked to ensure no postlens debris or air bubbles were present. OCT measurements were repeated, and the corneal thickness (excluding the tear film) of the contact lens–wearing eye was then calculated, as explained in the legend to Figure 1. After the PMMA lenses were removed, a pair of soft lenses (one Acuvue lens and one Focus Day & Night lens) was randomly fitted to the eyes, and OCT measurements were repeated. The pair of lenses was then switched between eyes, and OCT measurements were taken again. Immediately after soft lens removal, corneal thickness (including tear film) was measured again. Each data point represents the mean of three measurements.

Data Analysis

The central 21 scan points from OCT raw data were analyzed using custom software. Two-tailed paired t tests were used (Statistica; StatSoft, Inc., Tulsa, OK) to compare the thickness of different tear layers, and post hoc paired t tests were used to determine whether there were pair-wise differences ($P < 0.05$).

RESULTS

Precorneal Tear Film

In 80 eyes of 40 non–contact lens wearers, the mean ± SD precorneal tear film thickness was $3.3 ± 1.5$ μm (range, 0.8–8.2). After removal of the lens, the mean precorneal tear film thickness was $4.7 ± 2.3$ μm (range, 0.7–11.0) and was significantly thicker than baseline (paired $t$ test: $P < 0.01$). Precorneal tear film thickness is shown in Table 1 and Figures 3 (before contact lens wear) and 4 (after contact lens removal) comparing right and left eyes. There was no significant difference between eyes (paired $t$ test: $P > 0.05$).

Prelens Tear Film

The prelens tear film thickness in the right and left eyes for hard and soft lenses is shown in Table 1. There was no significant difference between right and left eyes and between the first and second soft lens fits (mean of both eyes) with both soft lenses (paired $t$ test: $P > 0.05$). The mean prelens tear film thickness of both eyes with hard lenses ($9.8 ± 7.3$ μm; SD) was significantly thicker than with soft lenses ($3.9 ± 2.6$ μm for first fit and $3.6 ± 2.1$ μm for second fit, post hoc Tukey honestly significant difference [HSD]; $P < 0.05$; Fig. 5). There were no significant differences between the first and second soft lens fits (paired $t$ test: $P > 0.05$) for either Acuvue lenses or Focus Night & Day lenses (Table 2).

Postlens Tear Film

With the steeply fitted PMMA lenses, a thick postlens tear film ($8.3 ± 24.1$ μm) was created by design. There was no significant difference between the thickness of postlens tear film under Focus Night & Day ($4.5 ± 2.3$ μm) and Acuvue soft lenses ($4.7 ± 3.1$ μm; paired $t$ test: $P > 0.05$; Fig. 6).

Post hoc tests showed that precorneal (before contact lens wear) and prelens tear films were equivalent and that each was

### Table 1. The Thickness of Precorneal and Pre- and Postlens Tear Film between Right and Left Eyes

<table>
<thead>
<tr>
<th></th>
<th>Right Eye</th>
<th>Left Eye</th>
<th>$P$</th>
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<tbody>
<tr>
<td>Precorneal tear film</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Before lens insertion</td>
<td>$3.2 ± 1.2$</td>
<td>$3.5 ± 1.8$</td>
<td>0.38</td>
</tr>
<tr>
<td>After lens removal</td>
<td>$4.6 ± 2.2$</td>
<td>$4.9 ± 2.4$</td>
<td>0.44</td>
</tr>
<tr>
<td>Prelens tear film</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PMMA fit</td>
<td>$9.4 ± 8.3$</td>
<td>$10.1 ± 6.3$</td>
<td>0.62</td>
</tr>
<tr>
<td>First SCL fit</td>
<td>$3.8 ± 2.4$</td>
<td>$4.0 ± 2.7$</td>
<td>0.80</td>
</tr>
<tr>
<td>Second SCL fit</td>
<td>$4.0 ± 2.1$</td>
<td>$3.2 ± 2.1$</td>
<td>0.05</td>
</tr>
<tr>
<td>Postlens tear film</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PMMA fit†</td>
<td>$82.4 ± 26.1$</td>
<td>$83.7 ± 22.0$</td>
<td>0.74</td>
</tr>
<tr>
<td>First SCL fit†</td>
<td>$4.6 ± 2.9$</td>
<td>$4.7 ± 2.5$</td>
<td>0.85</td>
</tr>
<tr>
<td>Second SCL fit†</td>
<td>$4.5 ± 2.6$</td>
<td>$4.4 ± 2.9$</td>
<td>0.57</td>
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</tbody>
</table>

Data are expressed as mean micrometers ± SD. $n = 40$.* Polymethylmethacrylate.
† Soft contact lens.

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**Figure 3.** Precorneal tear film thickness (in micrometers) before contact lens wear, comparing right and left eyes in 40 subjects, showed no significant difference. The mean thickness of all measurements was $3.3 ± 1.5$ μm.

**Figure 4.** Precorneal tear film thickness (in micrometers) after contact lens wear comparing right and left eyes in 40 subjects showed no significant difference. The mean thickness of all measurements was $4.7 ± 2.3$ μm.
significantly different (thinner; Tukey HSD: $P < 0.05$) from the postlens tear film.

**DISCUSSION**

In this study, we demonstrated that OCT can be used to indirectly measure human precorneal tear film thickness, which was approximately 3 $\mu$m, in agreement with the work of King-Smith et al. Using confocal microscopy, Prydal et al. found the thickness of the human precorneal tear film was 41 to 46 $\mu$m. The results in King-Smith et al. are based on interferometry, and OCT uses a Michelson interferometer.

When we compared the tear film after contact lens wear, we found that it thickened significantly compared with before lens insertion, which suggests that the thickness of the precorneal tear film could be altered by reflex tearing and also suggests that the method we have reported in this study effectively detected differences in tear film thickness under different conditions.

The postlens tear film thickness under an Acuvue lens was less than Lin et al. measured (11–12 $\mu$m). The potential sources of the difference are that Lin et al. appears to have used the physical thickness of soft lenses measured with an electronic thickness gauge to calculate the postlens tear film thickness. Apparent thickness of lenses (optical pachymetry measurements) is greater than real thickness, and had Lin et al. used these data, it would have reduced the tear film thickness to be closer to our data. Another difference is that optical pachymetry measurements may include the mucin layer whereas OCT probably does not.

In Nichols and King-Smith (ARVO Abstract 3198, 2001) the postlens tear film thickness of 2.5 $\mu$m was slightly lower than our result. One possible explanation for our higher result is that reflex tearing in our study may have increased the postlens tear thickness, because all our participants were fitted with PMMA lenses before wearing soft lenses and had never worn lenses before. The difference may also have been due to different sample sizes—nine in Nichols et al., compared with 40 in ours—and the lens parameters may have been different.

This study also showed that there were no differences in the thicknesses of the pre- and postlens tear film between Acuvue (a conventional hydrogel lens) and Focus Night & Day (a silicone hydrogel) contact lenses. Similar results have been reported by Nichols and King-Smith who compared Acuvue with Purevision (a silicone hydrogel; Bausch & Lomb, Tampa, FL) lenses and found there was no significant difference in pre- and postlens tear film thickness. These two studies suggest that the postlens tear film thickness is independent of lens material and water content.

In our study we also examined the thickness of the prelens tear film of rigid contact lenses, which, to the best of our knowledge, has never been reported before. The results showed that the thickness of the prelens tear film on the PMMA lenses was thicker than the thickness of the precorneal tear film and prelens tear film on soft lenses. Guillon et al. found the pre-rigid-lens tear film was more unstable than the precorneal tear film and pre-soft-lens tear film, which could account for the thickness difference and can be verified by comparing the prelens tear film thickness of adapted and nonadapted rigid lens wearers. Another possible explanation is that the reflex tearing induced during PMMA lens wear resulted in a temporary increase in the thickness of the prelens tear film. Using OCT to measure the thickness of pre- and postlens

**TABLE 2.** The Thickness of the Pre- and Postlens Tear Film with Soft Lenses

<table>
<thead>
<tr>
<th></th>
<th>Focus Night &amp; Day*</th>
<th>Acuvue*</th>
<th>$P$</th>
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<tbody>
<tr>
<td><strong>Prelens tear film</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>First fit</td>
<td>4.2 ± 2.9</td>
<td>3.7 ± 2.1</td>
<td>0.35</td>
</tr>
<tr>
<td>Second fit</td>
<td>3.7 ± 2.2</td>
<td>3.5 ± 2.1</td>
<td>0.57</td>
</tr>
<tr>
<td><strong>Postlens tear film</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>First fit</td>
<td>4.5 ± 2.2</td>
<td>4.9 ± 3.1</td>
<td>0.36</td>
</tr>
<tr>
<td>Second fit</td>
<td>4.5 ± 2.4</td>
<td>4.5 ± 3.1</td>
<td>0.91</td>
</tr>
</tbody>
</table>

Data are expressed as mean micrometers ± SD. $n = 40$.

* Vistakon, Johnson-Johnson Vision Care.
tear film may help in understanding the dryness and discomfort of contact lens wear.

There are several factors that may contribute to the measurement error in this study. Measurements of central corneal thickness before and after PMMA lens wear may not be in the same central location, which is an issue for all techniques using indirect measurements of tear film thickness (Nichols and King-Smith, ARVO Abstract 3198, 2001). The second source of measurement error could be reflex tearing, which may alter pre- and postlens tear thickness caused by wearing PMMA lenses. In this study, we examined only non-lens wearers, and therefore reflex tearing was most likely to occur when wearing PMMA lens. It seems feasible that this method could be used for studying thickness changes of the precorneal and prelens tear film under various conditions with various lenses, such as tear thickness changes overnight and in dry air conditions.

In conclusion, in this study OCT allowed rapid and noninvasive (indirect) measurement of the thicknesses of the precorneal, prelens, and postlens tear films. The thickness of the normal precorneal tear film is approximately 3 μm and becomes thicker after lens fitting. There was no difference between Acuvue and Focus Night & Day lenses in both pre- and postlens tear film thickness, although the postlens tear film was thicker than the precorneal and prelens tear films.

References