Cornea

Corneal Thickness Changes in Hyperopic Orthokeratology Measured by Optical Pachometry

Paul Gifford, Ahmed Alharbi, and Helen A. Swarbrick

Purpose. To investigate the time course of corneal thickness changes in overnight hyperopic orthokeratology (OK) lens wear for a 4-day lens-wearing period.

Methods. Fourteen subjects (age range, 20–37 years) were fitted with hyperopic OK lenses in one eye only. The fellow eye acted as a non-lens wearing control. Lenses were worn overnight only for 4 nights, and changes from baseline in subjective refraction, corneal topography, and corneal thickness (Holden-Payor optical pachometer) at central and para-central locations were measured on days 1 and 4 after overnight lens wear, at lens removal (AM), and 8 hours after lens removal (PM).

Results. There was a significant refractive and corneal topographic effect at all visits. The central total cornea thickened significantly at AM visits only because of significant stromal thickening consistent with the overnight lens wearing edema response, and returned to baseline at PM visits once edema resolved. The para-central epithelium significantly thinned at all AM and PM visits. This counteracted para-central stromal thickening at AM and resulted in significant thinning of the total para-central cornea at PM visits when stromal thickness had returned to baseline.

Conclusions. Para-central corneal epithelial thinning explains corneal anterior surface steepening in hyperopic OK and is sufficient to account for the lens-induced refractive response. Whereas corneal thickening is an additional factor reported in myopic OK, this was not the case in hyperopic OK. Constraint of corneal surface change mechanisms to para-central corneal epithelial thinning alone in hyperopic OK may explain the reduced refractive effect compared with myopic OK. (*Invest Ophthalmol Vis Sci.* 2011;52:3648–3653) DOI:10.1167/iovs.10-6323

Orthokeratology (OK) is a procedure by which rigid contact lenses temporarily alter corneal curvature with the intention to correct ametropia after lens removal. A number of studies have shown that myopic OK lenses flatten corneal curvature during wear and provide reliable refractive correction for up to −4.50D of myopia on lens removal.[1–4] More recently, it has been shown that hyperopic OK lenses steepen corneal curvature during lens wear.[5–9] However, the refractive effect with hyperopic OK lenses is less consistent beyond +1.50D of targeted refractive change.[7] Previous studies have shown that changes to corneal thickness (assuming no change in curvature of the posterior corneal surface) can account for the refractive change induced by myopic OK lenses.[1,4] Swarbrick et al.[1] suggested that OK-induced corneal curvature change represents an anterior corneal phenomenon rather than an overall bending of the cornea. Hyperopic OK lenses are designed on principles similar to those of myopic OK lenses, so it is reasonable to hypothesize that changes in corneal curvature from hyperopic OK lenses could be equally limited to the anterior corneal surface.

In a previous study conducted by our group,[7] we reported that the time course of refractive and corneal topographic change in hyperopic OK is analogous to that of myopic OK, at least in the first 7 nights of lens wear. We also reported no increase in central corneal thickness using ultrasonic pachometry once corneal edema from overnight wear had resolved during the day without lens wear, despite significant retention of refractive effect at the end of the day. This led to the suggestion that, in the absence of central corneal thickening, the para-central cornea might have thinned in hyperopic OK to allow for the corneal steepening. Two previous publications have reported on the profile of corneal thickness change after hyperopic OK; both used optical coherence tomography (OCT) to measure changes to total, stromal, and epithelial thickness induced by the Paragon corneal refractive therapy lens for hyperopia (CRT; Paragon Vision Sciences, Mesa, AZ). Lu et al.[10] measured the short-term response over up to 60 minutes of lens wear and found no significant change from baseline in central epithelial thickness but did find significant para-central epithelial thinning after 30 minutes of lens wear. However, when CRT lens wear was extended to 1 night in the closed eye, Haque et al.[8] found that rather than becoming thinner, the para-central corneal epithelium thickened, with greater thickening occurring in the central epithelium. To the best of our knowledge, no studies have been published of corneal thickness changes in hyperopic OK beyond 1 night of lens wear.

The purpose of the present study was to gain understanding of the change in the corneal thickness profile during hyperopic OK lens wear over a longer wearing period of 4 nights. In a previously published study,[5] we showed that 4 nights of lens wear was a sufficient period during which to induce refractive and corneal topographic effect in hyperopic OK for low refractive targets. To provide an alternative perspective to OCT, changes to corneal total and stromal thickness were measured with the Holden-Payor optical pachometer, and epithelial thickness was calculated by subtraction. Optical pachometry has been used previously to assess corneal thickness changes in myopic OK[1,4,11,12] and has been shown to provide good intrasession repeatability for total corneal thickness of ±2.0

From the School of Optometry and Vision Science, University of New South Wales, Sydney, New South Wales, Australia.

Supported by the Australian Research Council Linkage Project Scheme, with support from industry partners Polymer Technology Corporation (a Bausch & Lomb Company), BE Enterprises, and Capricornia Contact Lens.

Submitted for publication August 1, 2010; revised December 5, 2010, and January 9, 2011; accepted February 3, 2011.

Disclosure: **P. Gifford**, Bausch & Lomb (F), BE Enterprises (F), Capricornia Contact Lens Pty Ltd (F); **A. Alharbi**, Bausch & Lomb (F), BE Enterprises (F), Capricornia Contact Lens Pty Ltd (F); **H.A. Swarbrick**, Bausch & Lomb (F), BE Enterprises (F), Capricornia Contact Lens Pty Ltd (F)

Corresponding author: Paul Gifford, School of Optometry and Vision Science, University of New South Wales, Sydney, NSW 2052, Australia; p.gifford@unsw.edu.au.

μm and $\pm$4.3 μm at the central and para-central regions, respectively, and good repeatability across consecutive days to within 3.2 $\pm$ 2.2 μm.[4]

Materials and Methods

Study Design

Lenses were worn overnight only for 4 nights in the nondominant eye; the fellow eye acted as a non–lens wearing control. Measurements were taken at baseline, day 1, and day 4, in the morning (AM) and again 8 hours after lens removal (PM). Baseline measurements were taken in the early afternoon at least 2 hours after waking to allow full resolution of any overnight edema. On measurement days, the lenses were removed at our clinical laboratory within 1 hour of waking, and AM measurements were taken within 5 minutes of lens removal once the tear film had stabilized.

Subjects

Fourteen subjects were enrolled from the University of New South Wales student community (mean age, 23.6 $\pm$ 4.7 years; range, 20–37 years; 4 men, 10 women; 1 hyperopic, 6 emmetropic, 7 myopic). Approval from the institutional human research ethics committee was obtained before the study began. All subjects gave informed written consent, were screened before enrolment, and were found to be in good general health and free of ocular disease. None had been previous wearers of rigid gas-permeable lenses. Corneal topography (E300 videokeratoscope; data analyzed with Medmont Studio 4 software version 4.9.0.5; both Medmont Pty Ltd, Melbourne, VIC, Australia) was measured at baseline to confirm that corneal astigmatism was $\leq$1.50D with-the-rule (Table 1). All subjects were treated in accordance with the tenets of the Declaration of Helsinki.

Lenses

Study lenses were based on the BE hyperopic OK biaspheric design (BE Enterprises, Brisbane, QLD, Australia), manufactured by Capricornia Contact Lens Pty Ltd (Slacks Creek, QLD, Australia), in high Dk material (Boston XO; Dk 100 ISO/Fatt; Bausch & Lomb, Rochester, NY). The lenses measured 10.5 mm in overall diameter and had a nominal center thickness of 0.28 mm, giving a nominal Dk/t of 35.7 ISO/Fatt units.

Lens-Fitting Protocol

Lens specifications were calculated empirically from corneal topography data to target +2.50D target correction and the same post-lens tear film profiles across all subjects. Three lenses were ordered for each subject, one just touching at the edge of the back optic zone (BOZ), one with 5 μm greater clearance at the BOZ edge, and one with 5 μm less clearance at the BOZ edge. The lenses were inserted and examined on-eye at the baseline visit after the initial study measurements had been taken. The lens providing the best on-eye centration was chosen as the study lens, and the remaining lenses were discarded.

Table 1. Subject Baseline Refraction and Keratometry

	Test Eyes	Control Eyes
Subjective Refraction		
M (spherical equivalent)	−1.46 ± 1.87	−1.50 ± 1.82
J_{180}	−0.04 ± 0.19	−0.03 ± 0.19
J_{45}	0.04 ± 0.14	−0.03 ± 0.17
Keratometry (simulated K from Medmont E300 videokeratoscope)		
Flat K	43.42 ± 1.47	43.55 ± 1.40
Steep K	44.28 ± 1.62	44.38 ± 1.62
M (spherical equivalent)	43.85 ± 1.54	43.97 ± 1.50
J_{180}	0.34 ± 0.15	0.29 ± 0.18
J_{45}	0.23 ± 0.15	0.18 ± 0.25

All values are in diopters (mean ± SD).

Measurement Techniques

All refraction and corneal topography measurements were carried out by the lead investigator (PG). Optical pachometry measurements were carried out by a coauthor (AA), who is an experienced optical pachometrist. AA was masked as to which eye had been wearing the lens. At all visits, measurements were taken first for corneal thickness, then for corneal topography, and then for refraction.

Refraction

Subjective non-cycloplegic sphero-cylindrical refraction was measured at all visits using standard optometric techniques. Individual results were then converted to spherical equivalent (sphere + [0.5 × cylinder]).

Corneal Topography

A videokeratoscope (E300; Medmont Pty Ltd) was used to capture corneal topography. Four images of each eye were obtained at each visit and were analyzed with appropriate software (Medmont Studio 4; Medmont Pty Ltd). Apical curvature (R_0, D) and axial curvature along the horizontal meridian at 0.5-mm intervals over a chord of 8 mm were extracted from each topography image, and the data from the four images taken at each subject visit were averaged. The curvature data from the post-lens wear visits were subtracted from baseline curvature data to provide change in curvature from baseline. Change in axial curvature was averaged across subjects for each post-lens wear visit and was plotted with 95% confidence intervals for each data point to allow comparison between the four visits by inspection.

Corneal Thickness

Corneal thickness was measured using a Holden-Payor optical pachometer that was modified to incorporate an arc of LED fixation lights along the horizontal meridian and two optical beam alignment LEDs, as described by Chan-Ling and Pye.[13] Measurements were conducted at central (0.5 mm temporal to apex), temporal (3.5 mm temporal to apex), and nasal (2.5 mm nasal to apex) corneal locations by instructing the subjects to fixate the appropriate LED fixation lights, which were sequentially illuminated using a computer interface. These locations were chosen to compensate for the 0.5-mm temporal lens decentration evident on lens fitting and to correspond with the para-central annulus of corneal flattening identified in topography plots from previous studies,[5,7] which also showed a slight temporal decentration of corneal steepening effect. In all cases the right eye was measured first, starting with temporal through central to nasal locations in each eye. At each corneal location, total corneal thickness was measured first followed by stromal thickness, with five measurements taken of each. The highest and lowest values from each set of five measurements were discarded, and the remaining three readings were averaged. Stromal thickness was then subtracted from total corneal thickness to give the epithelial thickness at each location. Temporal and nasal thickness values were also averaged to give a combined para-central measurement for total, stromal, and epithelial thickness. Subject baseline values for corneal thickness are given in Table 2. Repeatability of the optical pachometry measurements has been reported by Alharbi and Swarbrick[4] as very good, with a maximum SD at the central cornea of $\pm$2 μm and at the midperiphery of $\pm$4.3 μm. To further validate the optical pachometer measurements in the present study, a repeatability analysis was conducted on the para-central epithelial thickness measurements from the control eyes at morning visits.

Statistical Analysis

Two-way repeated-measures ANOVA was carried out on refraction, corneal curvature, and corneal thickness data to compare test eyes

Table 2. Corneal Thickness at Baseline

	Test Eyes	Control Eyes
Central cornea		
Total	549.3 ± 22.4	546.8 ± 25.1
Stroma	496.9 ± 25.8	496.9 ± 27.5
Epithelium	52.4 ± 10.4	49.9 ± 10.6
Temporal cornea		
Total	590.4 ± 25.9	583.5 ± 23.4
Stroma	539.5 ± 25.0	535.8 ± 26.4
Epithelium	50.9 ± 10.5	47.7 ± 12.6
Nasal cornea		
Total	587.4 ± 30.6	585.4 ± 33.0
Stroma	533.8 ± 33.2	534.1 ± 27.0
Epithelium	53.6 ± 13.4	51.3 ± 17.7

All values are in micrometers (mean ± SD).

with control eyes and change over time relative to baseline. Post hoc *t*-tests with Bonferroni correction were used to compare post-lens wearing measurements to baseline and change between different lens-wearing intervals (SPSS version 16; SPSS Inc, Chicago, IL). The *P* values for post hoc tests were adjusted by the SPSS software according to the Bonferroni correction, such that a reported $P < 0.05$ denoted statistical significance. Corneal curvature analysis was carried out at the same locations as the corneal thickness measurements.

Results

Baseline Variables

There was no statistically significant difference at baseline between the experimental and the control eyes in terms of refractive error, corneal curvature, or corneal thickness (Tables 1, 2; *t*-test; $P > 0.05$).

Refraction

Spherical equivalent refractive error changed significantly over time ($F_{(4,\ 52)} = 26.20$; $P < 0.001$) in test eyes only, with a significant difference from baseline at all post-lens wearing measurements ($P \leq 0.01$). Spherical equivalent refraction changed by −0.96 ± 0.61D at the AM visit on day 1, with further change by −1.35 ± 0.68D at the AM visit on day 4 ($P < 0.05$). Refractive effect regressed throughout the day on both measurement days to −0.46 ± 0.42D at the PM visit on day 1 (mean ± SD, $P < 0.01$) and to −0.99 ± 0.48D at the PM visit on day 4 ($P < 0.05$).

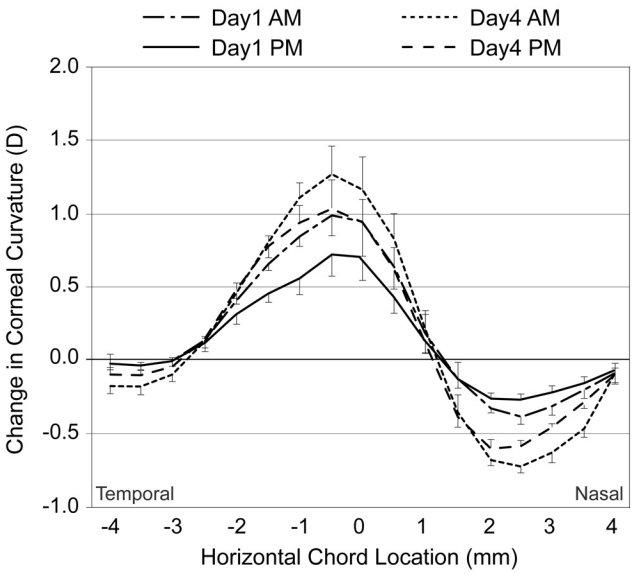

Figure 1. Change from baseline in corneal axial curvature (D) along the horizontal chord at lens removal (AM) and 8 hours after lens removal (PM) on day 1 and day 4. Error bars, 95% confidence intervals.

Table 3. Changes from Baseline in Central and para-Central Corneal Axial Curvature

	Day 1	Day 4	*P**
Central			
AM	1.02 ± 0.41	1.27 ± 0.54	NS
PM	0.74 ± 0.32	1.02 ± 0.53	NS
P†	<0.05	<0.05	
para-Central			
AM	−0.44 ± 0.21	−0.48 ± 0.22	NS
PM	−0.13 ± 0.12	−0.19 ± 0.15	<0.05
P†	<0.001	<0.001	

All values are in diopters (mean ± SD) at lens removal (AM) and 8 hours after lens removal (PM) on days 1 and 4. NS, not significant.

* Statistical significance for days 1 versus 4.

† Statistical significance for AM versus PM.

Corneal Topography

There was a change in central and para-central corneal topography over time in test eyes only ($F_{(4,\ 52)} = 23.07$ [$P < 0.001$] and $F_{(2.44,\ 29.33)} = 18.75$ [$P < 0.001$], respectively). The central cornea steepened and the para-central cornea flattened from baseline at all AM and PM visits ($P \leq 0.001$; Fig. 1). There was a regression of effect throughout the day on both measurement days centrally and para-centrally ($P < 0.05$). Extending lens wear to 4 nights did not lead to a significant increase in topographic effect at central or para-central locations on lens removal ($P > 0.05$; Table 3). However, there was significantly greater retention of para-central flattening at the PM visit on day 4 compared with the PM visit on day 1 ($P < 0.05$).

Corneal Thickness

Changes to temporal and nasal corneal thickness (Table 4) failed to reach statistical significance; however, significance was reached once the temporal and nasal thickness values were pooled to provide combined para-central corneal thickness (Figs. 2–4).

Table 4. Changes from Baseline in Central, Temporal, and Nasal Corneal Thickness at Lens Removal and 8 Hours after Lens Removal on Day 1 and Day 4

	Total	Stroma	Epithelium
Central			
Day 1 AM	11.6 ± 14.7	8.6 ± 14.2	3.0 ± 10.9
Day 1 PM	2.1 ± 11.85	2.4 ± 17.3	−0.3 ± 12.8
Day 4 AM	13.7 ± 17.1	10.0 ± 13.2	3.7 ± 13.5
Day 4 PM	−2.9 ± 6.9	−1.5 ± 13.2	−1.4 ± 15.9
Temporal			
Day 1 AM	1.1 ± 16.4	5.5 ± 15.4	−4.4 ± 12.0
Day 1 PM	−8.4 ± 14.5	0.2 ± 17.8	−8.5 ± 16.9
Day 4 AM	4.2 ± 20.4	8.2 ± 20.8	−4.0 ± 18.2
Day 4 PM	−11.8 ± 14.6	−5.1 ± 17.5	−6.7 ± 16.9
Nasal			
Day 1 AM	2.3 ± 16.6	9.4 ± 22.8	−5.8 ± 10.8
Day 1 PM	−10.0 ± 16.2	−2.2 ± 13.9	−9.6 ± 13.3
Day 4 AM	2.8 ± 14.8	9.6 ± 19.1	−8.2 ± 9.2
Day 4 PM	−11.5 ± 14.6	0.2 ± 7.9	−11.3 ± 17.6

All values are in micrometers (mean ± SD).

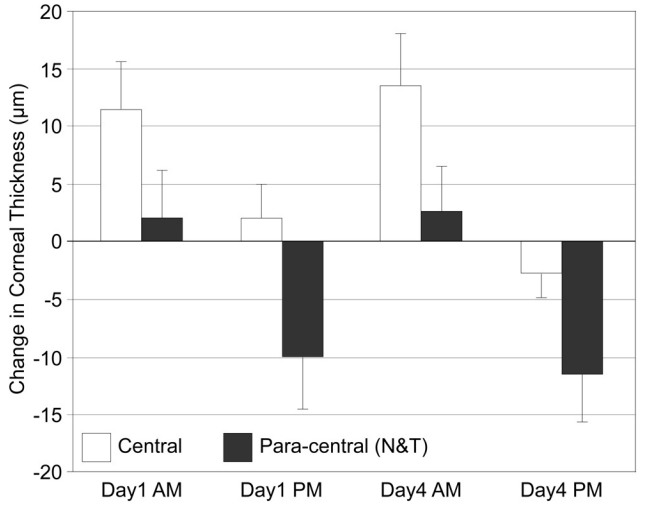

FIGURE 2. Change from baseline in total corneal thickness after 1 night and 4 nights of lens wear at lens removal (AM) and 8 hours after lens removal (PM) at central and combined nasal (N) and temporal (T) para-central locations. Error bars, standard error of the mean.

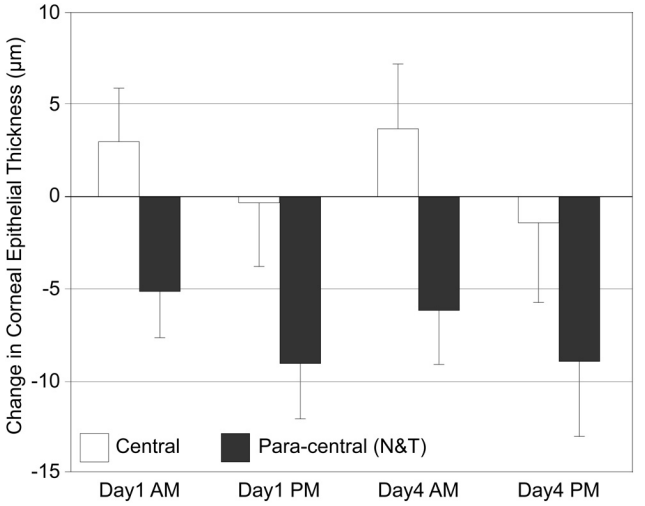

FIGURE 4. Change from baseline in corneal epithelial thickness after 1 night and 4 nights of lens wear at lens removal (AM) and 8 hours after lens removal (PM) at central and combined nasal (N) and temporal (T) *para*-central locations. Error bars, standard error of the mean.

Repeatability

The repeatability analysis performed on the para-central epithelial thickness measurements in the control eyes at the morning visits revealed a within-eye repeatability of 3.95 μm, a coefficient of repeatability of 7.74 μm, a coefficient of variation at 0.75, and an intraclass correlation of $r = 0.78$.

Total Corneal Thickness Changes

Total corneal thickness changed over time in test eyes only at both central ($F_{(4,\ 52)} = 6.97$; $P = 0.001$) and combined para-central ($F_{(2.06,\ 26.08)} = 4.99$; $P < 0.05$) locations. Central total corneal thickness increased significantly at AM visits only, by 11.6 ± 14.7 μm (2.1% ± 2.7%) on day 1 and 13.7 ± 17.1 μm (2.5% ± 3.2%) on day 4 (mean ± SD, $P < 0.05$; Fig. 2). There was no significant difference in the change in total central corneal thickness between the two AM visits and no significant difference from baseline at the PM visits on either measurement day ($P > 0.05$).

The opposite effect was seen at the para-central corneal locations, with no significant change in total corneal thickness from baseline at AM visits. However, total para-central corneal thickness reduced by −10.0 ± 16.3 μm (−1.7% ± 2.7%) and by −11.5 ± 14.6 μm (−1.9% ± 2.5%) at PM visits on days 1 and 4, respectively ($P < 0.05$). There was no significant difference in the changes in combined para-central corneal thickness between the two PM visits ($P > 0.05$).

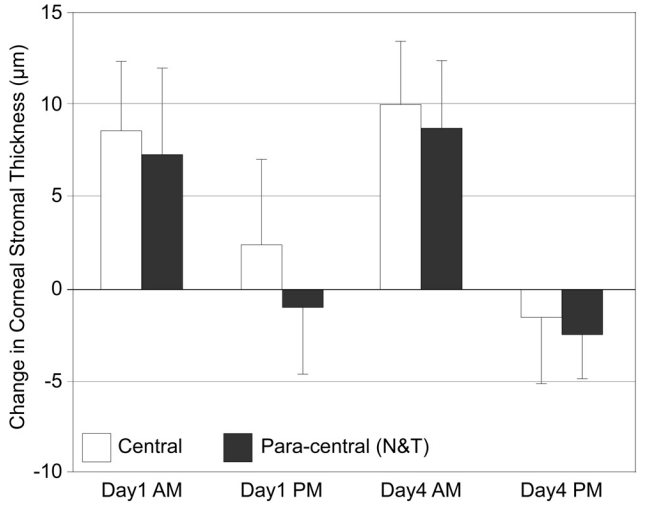

FIGURE 3. Change from baseline in corneal stromal thickness after 1 night and 4 nights of lens wear at lens removal (AM) and 8 hours after lens removal (PM) at central and combined nasal (N) and temporal (T) *para*-central locations. Error bars, standard error of the mean.

Corneal Stromal Thickness Changes

Corneal stromal thickness changed over time in test eyes only at both central ($F_{(4,\ 52)} = 2.68$; $P < 0.05$) and combined para-central ($F_{(4,\ 48)} = 3.65$; $P < 0.05$) locations. A significant increase in stromal thickness was present at the central and para-central locations at AM visits on days 1 and 4 ($P < 0.05$), but there was no difference in effect between days 1 and 4 ($P > 0.05$; Fig. 3). The central corneal stroma thickened by 8.6 ± 14.2 μm (1.8% ± 2.9%) at the AM visit on day 1 and by 10.0 ± 13.2 μm (2.1% ± 2.7%) at the AM visit on Day 4, whereas the para-central corneal stroma thickened by 7.4 ± 17.4 μm (1.5% ± 3.2%) at the AM visit on day 1 and by 8.9 ± 13.5 μm (1.7% ± 2.6%) at the AM visit on day 4 (mean ± SD, $P < 0.05$). Stromal thickness at PM visits was not significantly different from baseline measurements.

Corneal Epithelial Thickness Changes

Central corneal epithelial thickness did not change significantly in either test or control eyes or over time ($P > 0.05$). There was no significant change over time in para-central corneal epithelial thickness in control eyes ($P > 0.05$). However, combined nasal and temporal para-central corneal epithelial thickness did change over time in test eyes only ($F_{(4,\ 52)} = 3.83$; $P < 0.01$). There was a significant, though not clinically relevant, thinning of the para-central corneal epithelium at AM visits, by −5.1 ± 9.6 μm (−8.4% ± 22.0%) on day 1 and by −6.1 ± 11.3 μm (−10.2% ± 25.4%) on day 4 (mean ± SD, $P < 0.05$; Fig. 4). There was also significant thinning in para-central corneal thickness at PM visits, by −9.0 ± 11.5 μm (−15.5% ± 25.6%) on day 1 and by −9.0 ± 14.2 μm (−15.2% ± 28.8%) on day 4. There was no difference in para-central epithelial thickness

changes at the AM visits from day 1 to day 4, at PM visits from day 1 to day 4, or between AM and PM visits on either day ($P > 0.05$).

Discussion

This study has shown that overnight wear of hyperopic OK lenses causes a change in the profile of corneal thickness. Stromal thickening was present in the morning after lens removal at the central and para-central locations and returned to baseline values 8 hours later without lens wear, consistent with the normal hypoxic edema response from overnight lens wear. An interesting finding was that there was no thickening of the epithelium at the corneal apex at any visit, and changes to central corneal thickness were governed by stromal changes alone. At the morning visits, stromal thickening led to a 2.1% increase in total central corneal thickness after 1 night and to a 2.5% increase after 4 nights of lens wear. This is less than the 8% swelling Holden and Mertz[14] predicted for overnight wear of the lenses used in this study, which had a nominal Dk/t of 35.7, and is likely to be a reflection of measurements taken up to 1 hour after eye opening. As stromal thickness returned to baseline during the day without lens wear, so did the total central corneal thickness. This led to no significant difference from baseline in central corneal thickness at the afternoon measurement 8 hours after lens removal, despite significant retention of refractive and corneal topographic effect.

The para-central cornea followed a diurnal pattern different from that of the central cornea in total thickness change. Significant thinning of the para-central epithelium was present at all visits. At the morning visits epithelial thinning was sufficient to cancel out stromal thickening, resulting in no change from baseline in total para-central corneal thickness. However, once stromal thickness had returned to baseline 8 hours later, para-central epithelial thinning instead led to thinning of the para-central cornea.

The changes in central corneal thickness reported here are in agreement with a previous study, which showed an increase in total central corneal thickness at lens removal approximately 1 hour after eye opening when measured with an ultrasound pachometer.[7] In the previous study total central corneal thickness also returned to baseline after 8 hours of no lens wear, which, because of the significant retention of clinical effect, led us to speculate that the para-central cornea may be thinning. The results from the present study confirm this previous hypothesis. The results presented here on epithelial thickness change in hyperopic OK are also in agreement with a previous short-term clinical study on corneal thickness changes after up to 1 hour of hyperopic Paragon CRT lens wear.[10] The authors reported a significant refractive effect within 15 minutes of lens wear, with significant thinning of the para-central corneal epithelium after 30 minutes of lens wear but no central thickening at any measurement interval.

However, an alternative perspective is provided by Haque et al.,[8] who used OCT to measure change in corneal thickness immediately on waking after a single night of hyperopic CRT lens wear. The authors found that there was an increase in both central and para-central epithelial thickness at lens removal, by 21.5% and 13.3%, respectively. This equates to an approximate difference between the central and para-central changes in epithelial thickness of 8.2%. In the present study there was no change in central epithelial thickness at lens removal after 1 night of lens wear, whereas the para-central epithelium showed evidence of thinning by 8.4%. This would create a similar degree of differential effect between the two measurement locations compared with Haque et al.[8] However, it fails to explain why the changes to epithelial thickness reported here using optical pachometry are comparatively smaller overall than those previously reported by Haque et al.[8] using the OCT.

Muscat et al.[15] have reported that the OCT model used by Haque et al.[8] has a high degree of repeatability and reproducibility across different measurement sessions for measuring central corneal thickness. The authors did not measure peripheral corneal thickness but suggested that reliability could be reduced because of errors in maintaining a perpendicular beam alignment and a bias toward overestimation of corneal radius of curvature by the instrument. OCT has been shown to correlate closely with optical pachometry in measuring the center thickness of test contact lenses once each instrument is correctly calibrated.[16] However, when measuring human eyes, Wang et al.[17] reported overestimation of central corneal thickness with OCT compared with optical pachometry, with a greater degree of overestimation in the presence of corneal edema.

Haque et al.[8] took precautions to minimize potential errors in para-central corneal measurements by ensuring perpendicular beam alignment at all measurement locations. However, the reported tendency for OCT to overestimate corneal thickness in comparison with optical pachometry, especially in the presence of edema, must be considered and offers a possible explanation for the difference between the values reported here compared with the corneal thickness changes reported by Haque et al.[8] Differences in measurement protocol between the two studies might also have influenced any differential measurement effect between these instruments. Haque et al.[8] reported on clinical changes immediately on eye opening, which would have led to greater levels of edema than found in the present study, in which measurements were taken up to 1 hour after eye opening. The graphs published by Haque et al.[8] appear to show minimal change from baseline in central corneal and epithelial thickness and the possibility of some para-central thinning 3 hours after lens removal, by which time most of the overnight edema should have resolved.

A pilot histologic study investigating corneal thickness changes in the cat after 4 hours, 8 hours, and 14 days of continuous hyperopic CRT lens wear has also been published.[18] Epithelial thickness changes were minimal after 4 hours of lens wear, showed mild central thickening and para-central thinning after 8 hours, and marked central thickening and para-central thinning after 14 days. However, because of the pilot nature of the study, the sample size was limited to one animal for each lens-wearing interval. The authors also recognized that outcomes might have been influenced by suturing of the nictitating membranes of the cats to facilitate lens retention, which might have increased the force of the lens on the eye and exacerbated the hypoxic response from the closed eye environment.

The para-central epithelial thinning reported in the present study and previously by Lu et al.[10] is consistent with the concept that hyperopic OK lenses induce a para-central corneal epithelial compressive effect. This is analogous to the central corneal epithelial thinning that is reported in response to the apical compression induced by myopic OK lenses.[1,2,4,12,18–21] The present study reveals a similar degree of para-central epithelial thinning in hyperopic OK compared with the profile of central epithelial thickness change in myopic OK. At the end of the day after 1 night and after 4 nights of lens wear, we found that the para-central epithelium had thinned by 15%. In comparison, Alharbi and Swarbrick[4] reported 17% of central epithelial thinning at the end of the day after 1 night of myopic OK lens wear, whereas Haque et al.[20] reported 15% of central epithelial thinning 14 hours after lens removal after 4 continuous nights of myopic OK lens wear.

Swarbrick et al.[1] and Alharbi and Swarbrick[4] applied Munnerlyn's formula[22] to calculate refractive change from the change in profile of corneal thickness for myopic OK (Munnerlyn's formula is used to calculate ablation depth in refractive laser surgery to achieve a desired refractive result). They showed that the predicted refractive effect from the change in corneal thickness profile using Munnerlyn's formula was very close to the actual change in refraction that was measured, leading them to suggest that corneal flattening in myopic OK was isolated to the anterior surface. We have shown that the time course of clinical changes in hyperopic OK is analogous to that of myopic OK.[7] It is, therefore, reasonable to suggest that similar agreement between predicted change in refraction based on Munnerlyn's formula and actual refractive effect should be expected with hyperopic OK. We reported 11.5 μm of para-central corneal thinning after 4 nights of lens wear, coincident with the compressive annulus of the lens, which has a diameter of 5.50 mm. Using Munnerlyn's formula, this equates to a predicted refractive change of 1.15D, which is very close to the 0.99D change to spherical equivalent refraction reported at the same interval (day 4 PM) and suggests that corneal steepening in hyperopic OK is also limited to the anterior corneal surface.

Conclusions

The refractive effect induced by hyperopic OK lens wear can be explained in terms of anterior corneal surface steepening caused by lens-induced thinning of the para-central corneal epithelium alone. This anterior corneal surface effect is in agreement with myopic OK, for which the opposite profile of anterior corneal surface flattening has been shown to be caused by a combination of central corneal epithelial thinning and para-central corneal thickening.[1,4,18,20] Although corneal thickening was a factor reported in myopic OK, this was not the case in hyperopic OK, for which intuitively central corneal thickening might have been expected, at least in the first 4 nights of lens wear reported here. Constraint of corneal surface change mechanisms to para-central corneal epithelial thinning may explain the reduced refractive effect in hyperopic OK compared with myopic OK.

Acknowledgments

The authors thank Capricornia Contact Lens Pty Ltd for the supply of lenses used in the study and Bausch & Lomb (Australia) for the supply of contact lens solutions.

References

1. Swarbrick HA, Wong G, O'Leary DJ. Corneal response to orthokeratology. *Optom Vis Sci.* 1998;75:791–799.
2. Soni PS, Nguyen TT, Bonanno JA. Overnight orthokeratology: visual and corneal changes. *Eye Contact Lens.* 2003;29:137–145.
3. Tahhan N, Du Toit R, Papas E, Chung H, La Hood D, Holden B. Comparison of reverse-geometry lens designs for overnight orthokeratology. *Optom Vis Sci.* 2003;80:796–804.
4. Alharbi A, Swarbrick HA. The effects of overnight orthokeratology lens wear on corneal thickness. *Invest Ophthalmol Vis Sci.* 2003; 44:2518–2523.
5. Gifford P, Au V, Hon B, Siu A, Xu P, Swarbrick HA. Mechanism for corneal reshaping in hyperopic orthokeratology. *Optom Vis Sci.* 2009;86:306–311.
6. Gifford P, Swarbrick HA. The effect of treatment zone diameter in hyperopic orthokeratology. *Ophthalmic Physiol Opt.* 2009;29: 584–592.
7. Gifford P, Swarbrick HA. Time course of corneal topographic changes in the first week of overnight hyperopic orthokeratology. *Optom Vis Sci.* 2008;85:1165–1171.
8. Haque S, Fonn D, Simpson T, Jones L. Epithelial thickness changes from the induction of myopia with CRTH RGP contact lenses. *Invest Ophthalmol Vis Sci.* 2008;49:3345–3350.
9. Lu F, Sorbara L, Simpson T, Fonn D. Corneal shape and optical performance after one night of corneal refractive therapy for hyperopia. *Optom Vis Sci.* 2007;84:357–364.
10. Lu F, Simpson T, Sorbara L, Fonn D. Malleability of the ocular surface in response to mechanical stress induced by orthokeratology contact lenses. *Cornea.* 2008;27:133–141.
11. Alharbi A, La Hood D, Swarbrick HA. Overnight orthokeratology lens wear can inhibit the central stromal edema response. *Invest Ophthalmol Vis Sci.* 2005;46:2334–2340.
12. Jayakumar J, Swarbrick HA. The effect of age on short-term orthokeratology. *Optom Vis Sci.* 2005;82:505–511.
13. Chan-Ling T, Pye DC. Pachometry: clinical and scientific applications. In: *Contact Lens Practice*. Ruben M, Guillon M, eds. London: Chapman & Hall; 1994:407–435.
14. Holden BA, Mertz GW. Critical oxygen levels to avoid corneal edema for daily and extended wear contact lenses. *Invest Ophthalmol Vis Sci.* 1984;25:1161–1167.
15. Muscat S, McKay N, Parks S, Kemp E, Keating D. Repeatability and reproducibility of corneal thickness measurements by optical coherence tomography. *Invest Ophthalmol Vis Sci.* 2002;43:1791–1795.
16. Moezzi AM, Sin S, Simpson TL. Novel pachometry calibration. *Optom Vis Sci.* 2006;83:366–371.
17. Wang J, Fonn D, Simpson TL, Jones L. Relation between optical coherence tomography and optical pachymetry measurements of corneal swelling induced by hypoxia. *Am J Ophthalmol.* 2002; 134:93–98.
18. Choo JD, Caroline PJ, Harlin DD, Papas EB, Holden BA. Morphologic changes in cat epithelium following continuous wear of orthokeratology lenses: a pilot study. *Contact Lens Anterior Eye.* 2008;31:29–37.
19. Wang J, Fonn D, Simpson TL. Topographical thickness of the epithelium and total cornea after hydrogel and PMMA contact lens wear with eye closure. *Invest Ophthalmol Vis Sci.* 2003;44:1070–1074.
20. Haque S, Fonn D, Simpson T, Jones L. Corneal and epithelial thickness changes after 4 weeks of overnight corneal refractive therapy lens wear, measured with optical coherence tomography. *Eye Contact Lens.* 2004;30:189–193.
21. Matsubara M, Kamei Y, Takeda S, Mukai K, Ishii Y, Ito S. Histologic and histochemical changes in rabbit cornea produced by an orthokeratology lens. *Eye Contact Lens.* 2004;30:198–204.
22. Munnerlyn CR, Koons SJ, Marshall J. Photorefractive keratectomy: a technique for laser refractive surgery. *J Cataract Refract Surg.* 1988;14:46–52.