ORIGINAL ARTICLE

Corneal Response to Short-Term Orthokeratology Lens Wear

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ABSTRACT: *Purpose.* **This study investigated short-term corneal changes induced by reverse-geometry lenses worn for orthokeratology.** *Methods.* **Nine young adult subjects wore reverse-geometry rigid gas-permeable lenses (BE; UltraVision Contact Lenses, Brisbane, Australia) in one eye only for 10, 30, and 60 min in the open eye and 8 h in the closed eye. The fellow eye acted as a non-lens-wearing control. Corneal topographic changes were monitored using the Medmont E-300 corneal topographer and keratometry. Changes in uncorrected logarithm of the minimum angle of resolution (log MAR) visual acuity were also recorded. Data were analyzed by analysis of variance and *post hoc* t-tests.** *Results.* **Significant central corneal flattening (−0.61 ± 0.35 D; p = 0.014) and the formation of a defined "treatment zone" (diameter, 3.86 ± 0.88 mm) were found after 10 min of open-eye lens wear, which progressed with increasing periods of lens wear. Significant improvement in unaided logMAR (−0.16 ± 0.18; p = 0.005) was also apparent after 10 min and showed further improvement with longer periods of lens wear. Corneal asphericity showed a trend toward corneal sphericalization, which reached statistical significance after 8 h of lens wear. There was no significant change in corneal toricity.** *Conclusions.* **The cornea responds rapidly to the application of reverse-geometry lenses for orthokeratology, with significant central corneal flattening and improvement in visual acuity after just 10 min of lens wear. This suggests that the corneal epithelium is able to be molded or redistributed very rapidly in response to the tear film forces generated behind reverse-geometry lenses. (Optom Vis Sci 2003;80:200–206)**

Key Words: orthokeratology, corneal topography, rigid gas-permeable contact lenses, myopia, corneal asphericity

There has been a renewal of clinical and research interest in orthokeratology (OK) since the development of reverse-geometry contact lens designs by Wlodyga and Stoyan in the late 1980s.[1] To differentiate the current incarnation of OK from traditional OK, which essentially involved the use of conventionally designed, usually flat-fitting, rigid contact lenses, the term "accelerated orthokeratology" has been used. This term refers to the rapid onset of refractive and corneal topographic changes that occur with reverse-geometry lenses. Nichols et al.[2] and Swarbrick and Alharbi[3] have reported that the refractive endpoint is typically reached with these lenses after between 7 and 10 d of wear with the use of an overnight lens-wearing protocol. This compares with traditional OK, where the refractive endpoint may take weeks to months of open-eye rigid lens wear to achieve.[4–7]

As early as 1968, Mandell and St. Helen[8] reported that significant transient changes in corneal curvature could be induced by lid forces, digital pressure, and eye rubbing. Carney and Clark[9] subsequently described short-term corneal topographic changes resulting from the pressure associated with applanation tonometry. More recently, Horner et al.[10] reported significant corneal flattening after 1 h of reverse-geometry contact lens wear in the open eye.

Swarbrick et al.[11] have also documented rapid corneal curvature changes within the first few hours of wear of reverse-geometry rigid contact lenses.

In clinical practice, many OK practitioners utilize a short lens-wearing trial as a predictive test for the likely success of subsequent OK lens wear. The usefulness of such trials and the appropriate period of lens wear for reliable prediction of the eventual refractive endpoint have not been investigated. In this article, we report in detail the changes in visual acuity and corneal topography in the first hour of reverse-geometry lens wear and compare these changes with those induced by a single overnight lens-wearing session.

METHODS
Subjects

Nine subjects were recruited from the student population of the School of Optometry and Vision Science at the University of New South Wales, Sydney. After approval for this study by the institutional human research ethics committee, written informed consent was obtained from all subjects after the risks and benefits of OK lens wear and study procedures had been fully explained. Subjects

were required to be 18 to 35 years of age, free of ocular disease or any contraindications to rigid contact lens wear, and to have with-the-rule corneal toricity of <1.50 D. None of the subjects were current rigid gas-permeable or full-time soft lens wearers. Baseline ocular parameters are summarized in Table 1.

Lenses

The reverse-geometry rigid contact lenses used in this study were of a quadracurve design (BE; UltraVision, Brisbane, Queensland, Australia). The lenses were 11.00 mm in overall diameter with a 6.00-mm optic zone diameter. All lenses were made in Boston XO material (nominal Dk 145×10^{-11} [cm^2.mL O_2]/[sec.mL.mm Hg]), with a nominal center thickness of 0.22 mm.

The lens to be worn by each subject was selected using the software provided by the manufacturer, which calculates the nearest appropriate lens base curve in the trial set based on the subject's apical corneal radius as determined by the corneal topographer (see below), the corneal sagittal depth at a 9.34-mm chord, and the targeted refractive change. In this study, the targeted refractive change was +2.00 D for all subjects, irrespective of the initial refractive error, to control the pressures developed behind the lenses across the study group.

Reverse-geometry lenses give a "bull's eye" fluorescein fitting pattern with a central zone of light touch of 3.5 to 4.0 mm in diameter, a midperipheral ring of fluorescein pooling, termed the "tear reservoir," under the steeper secondary curve, and a peripheral circular band of alignment tapering to the edge lift. A slitlamp lens-fitting assessment of the recommended trial lens was carried out on all subjects to ensure good centration, lens movement of 1 to 2 mm on a blink, active tear exchange without the presence of bubbles in the tear reservoir, and a clinically acceptable fluorescein fitting pattern.

Measurements

Visual Acuity.   High-contrast unaided distance visual acuity was measured at 6 m using the same internally illuminated logarithm of the minimum angle of resolution (log MAR) type chart, with luminance of 120 cd/m^2, to monitor the change in vision with OK lens wear. All visual acuity measurements were obtained under normal room illumination.

To ensure that the anticipated improvement in visual acuity for the targeted myopia reduction of 2.00 D could be monitored accurately, baseline visual acuity was "adjusted" using

trial lenses so that subjects were able to discern only letters near the top of the letter chart (approximately 20/200 or logMAR 1.0). Thus, unaided visual acuity was recorded in five subjects who were moderate myopes (range, −1.50 to −3.25 D). Three subjects had higher levels of myopia (more than −4.00 D); visual acuity in these subjects was measured with +2.00 D lenses over their habitual spectacle correction. One subject was a very low myope (−0.25 D), and uncorrected visual acuity was measured through +2.00 D lenses, creating an additional artificial myopia of 2.00 D. On all subsequent measurement occasions, log MAR visual acuity was measured through the same lenses as determined at baseline.

Corneal Topography.   Corneal topography was measured using the Medmont E300 corneal topographer Version 1.1 (Medmont, Camberwell, Victoria, Australia). Three images were captured, and data from the associated map displays were averaged on each measurement occasion. The instrument was adjusted and refocused after every image capture.

Parameters obtained from the topographic data display included apical corneal power and radius of curvature, simulated keratometry (SimK) readings, corneal sagittal depth, and the difference in apical corneal power between the pre- and post-lens wear sessions (from the difference map). The corneal sagittal depth was obtained at a chord equal to 9.34 mm and was used to calculate corneal asphericity, Q, using the following formula[12]:

$$P = (2r_o x - y^2)/x^2 \qquad (1)$$

where r_o is the apical radius of curvature, x is the sagittal depth of the cornea over a 9.34-mm chord, and y is the half chord (4.67 mm in this study). Then, $Q = 1 - p$.

On the topography map, orthokeratology treatment creates a central circular zone of corneal flattening, termed the "treatment zone," surrounded by a ring of midperipheral corneal steepening. The treatment zone diameter was measured manually from the Medmont screen displaying the difference map, which shows the change in corneal topography relative to baseline. The criterion for determining the treatment zone diameter was the horizontal distance from inner edge to inner edge of the "zero diopter change" zone inside the ring of midperipheral steepening on the difference map.

The corneal radius of curvature was also measured using a Magnon keratometer (H. Ogino & Co, Yokohama, Japan). Three readings were taken and averaged on each measurement occasion. The same keratometer was used throughout the study. The keratometer

TABLE 1.
Subject characteristics at baseline.

	Lens-Wearing Eye (OD)		Control Eye (OS)	
	Mean ± SD	Range	Mean ± SD	Range
Unaided logMAR visual acuity[a]	0.96 ± 0.22	0.40 to 1.10	0.90 ± 0.31	0.24 to 1.10
Snellen equivalent	20/200^{+2}	20/50 to 20/250	20/150	20/30^{-2} to 20/250
Best vision sphere (D)	−2.93 ± 1.57	−0.25 to −5.25	−2.83 ± 1.81	−0.25 to −5.50
Apical corneal power (D)	43.40 ± 1.16	41.23 to 45.70	43.28 ± 1.31	41.53 to 45.83
Corneal toricity (D)	0.56 ± 0.24	0.17 to 0.96	0.72 ± 0.33	0.34 to 1.29

[a] logMAR, logarithm of the minimum angle of resolution.

was calibrated using steel balls of known radius before the commencement of the study and periodically during the study.

Other Variables. Subjective refraction was performed during the baseline visit to determine the best-vision sphere (sphere + half cylinder) in each eye. A detailed biomicroscopic examination of the anterior segment, including fluorescein staining assessment, was performed before and after each session of lens wear to ensure good ocular health.

Study Design

Baseline data were collected before commencing lens wear. Subjects wore the same OK lens on the right eye only in separate sessions for 10 min, 30 min, 1 h, and 8 h. The left eye acted as a non-lens wearing control. All measurements were conducted on both eyes. The order of wearing times was not specifically randomized; all subjects began with the 10-min lens-wearing session and, in most cases, progressed to increasing wearing periods. The lens wear sessions were conducted at least 1 week apart to allow full corneal recovery, which was confirmed by comparing topographic maps obtained at baseline and before commencing each lens-wearing session.

In all lens-wearing sessions except for the 8-h session, subjects kept their eyes open and remained with the examiner during lens wear. The lenses were inserted and removed by the examiner. The measurements for all open-eye lens wear sessions were obtained at approximately the same time of the day so that diurnal variations did not confound the effects of lens wear.

For the overnight 8-h lens-wearing session, subjects inserted their own lens at night at their home and slept approximately 8 h while wearing the lens. In the morning, subjects attended the School of Optometry and Vision Science clinic within 1 h of eye opening, while still wearing the lens, for data collection.

Data Analysis

Analysis of variance (ANOVA) combined with *post hoc* paired t-tests with Bonferroni protection was used to compare parameters before and immediately after lens wear for different periods of OK lens wear. A critical p value of 0.05 was chosen to denote statistical significance.

RESULTS
Unaided logMAR Visual Acuity

At the time of lens removal, statistically significant improvement in unaided visual acuity (p < 0.001, ANOVA) relative to baseline was found for all periods of lens wear. As expected, there was a greater improvement in visual acuity with increased duration of lens wear. Fig. 1 shows the change in unaided visual acuity after different durations of OK lens wear. These results and the outcome of statistical analyses are summarized in Table 2. There was no significant change in unaided visual acuity in the non-lens wearing (control) eye.

Corneal Topography

At the time of lens removal, statistically significant reductions in apical corneal power relative to baseline were found for all periods
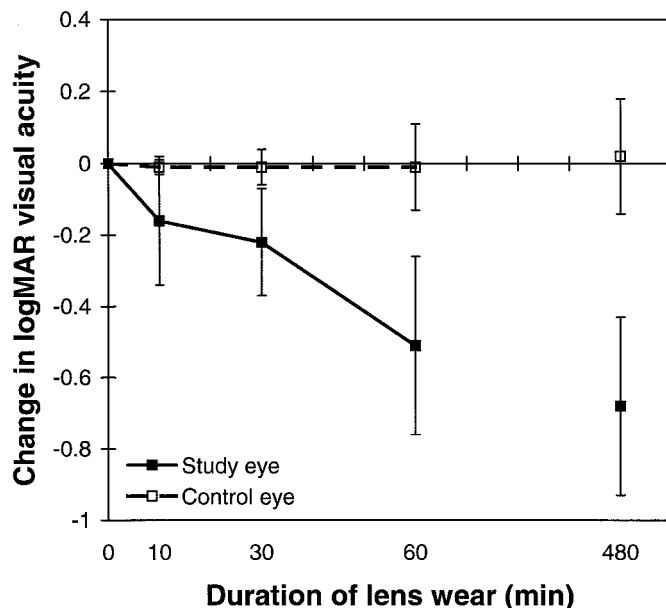

FIGURE 1.

Changes in unaided log MAR visual acuity after different durations of orthokeratology lens wear. Negative changes represent an improvement in visual acuity; error bars indicate the standard deviation.

of lens wear (p < 0.001, ANOVA), and this central corneal flattening was confirmed by changes in horizontal and vertical keratometry readings. There was a greater reduction of apical corneal power and change in keratometry readings with increasing duration of lens wear. Figs. 2 and 3 show the change in apical corneal power and keratometry readings after different durations of OK lens wear. These results and the outcome of statistical analyses performed on these data are summarized in Table 2. There were no significant changes in these variables in the non-lens wearing (control) eye.

Fig. 4 shows the change in treatment zone diameter after different durations of OK lens wear. The treatment zone averaged 3.86 ± 0.88 mm in diameter after 10 min of wear and became larger with increasing duration of lens wear to reach 5.59 ± 0.83 mm after 8 h. The treatment zone diameters after different periods of lens wear are also presented in Table 2.

There was a trend toward sphericalization of the cornea after all durations of lens wear (p < 0.001, ANOVA). However, the change was statistically significant (p < 0.001, paired t-test) only after 8 h of lens wear. Fig. 5 shows the change in asphericity, Q, after different durations of OK lens wear. The mean Q value became more positive with increasing duration of lens wear, i.e., the cornea became more spherical. Q values after different periods of lens wear are also summarized in Table 2.

DISCUSSION

One of the main advantages of reverse-geometry OK lenses is the speed with which significant corneal curvature and visual acuity changes can be achieved. The procedure that took months to induce significant reductions in myopia with conventional flat-fitting OK lenses[4–7] has been demonstrated to be effective within days[2,3] or even hours with reverse-geometry lenses. The results of

TABLE 2.

Changes from baseline (mean ± SD) in unaided logMAR visual acuity (UCVA), apical corneal power (ACP), keratometry readings in horizontal and vertical meridians (Kh, Kv), corneal toricity (cyl), treatment zone diameter (TZD), and asphericity (Q) after different durations of orthokeratology lens wear.

	Duration of Lens Wear			
	10 min	30 min	60 min	8 h
UCVA				
Change	−0.16 ± 0.18	−0.22 ± 0.15	−0.51 ± 0.25	−0.68 ± 0.25
p Value	0.005	0.001	<0.001	<0.001
ACP (D)				
Change	−0.61 ± 0.35	−0.86 ± 0.54	−1.21 ± 0.52	−1.63 ± 0.46
p Value	0.014	<0.001	<0.001	<0.001
Kh (D)				
Change	−0.35 ± 0.38	−0.49 ± 0.24	−0.77 ± 0.30	−0.90 ± 0.63
p Value	0.002	<0.001	<0.001	<0.001
Kv (D)				
Change	−0.38 ± 0.31	−0.48 ± 0.21	−0.73 ± 0.37	−0.92 ± 0.53
p Value	<0.001	<0.001	<0.001	<0.001
Cyl (D)				
Change	−0.03 ± 0.18	0.02 ± 0.25	0.03 ± 0.14	−0.01 ± 0.36
p Value	NS	NS	NS	NS
TZD (mm)				
Change	3.86 ± 0.88	4.82 ± 1.05	5.40 ± 0.61	5.59 ± 0.83
p Value	<0.001	<0.001	<0.001	<0.001
Q				
Change	0.04 ± 0.12	0.06 ± 0.26	0.14 ± 0.18	0.36 ± 0.14
p Value	NS	NS	NS	<0.001

[a] NS, not statistically significant (p > 0.05).

this study clearly demonstrate that short-term OK lens wear can induce significant, rapid changes in corneal curvature in as little as 10 min of lens wear. These lenses induced an average of 0.61 D reduction in apical corneal power after 10 min, 0.86 D after 30 min, 1.21 D after 60 min, and 1.63 D after 8 h (overnight) wear.

The change in spherical refraction (best-vision sphere) was estimated from the visual acuity change based on the assumption that one line improvement in visual acuity would result from a 0.25 D change in the spherical refraction.[13] The observed change in apical corneal power was greater than the estimated change in best-vision sphere for the 10- and 30-min lens-wearing sessions but was very similar for the longer lens-wearing sessions, as shown in Fig. 6. The discrepancy in estimated best-vision sphere for the shorter lens-wearing periods may be due to the combined effects on visual acuity of small treatment zone diameter and irregular corneal distortion, which was often noted to varying degrees within the treatment zone after 10 and 30 min of lens wear.

The overall mean changes in corneal toricity measured using keratometry were <0.05 D for all lens-wearing periods (see Table 2) and did not reach statistical significance at any timepoint. SimK (simulated keratometry) readings obtained from the Medmont topographer were also analyzed with a similar outcome and thus are not presented here. Traditional OK is known to induce significant with-the-rule corneal toricity due to decentration of the flat-fitting lenses used,[4, 5] and this undesirable effect is probably one of the reasons for the demise of traditional approaches to orthokeratology. Our study did not reveal any induction of corneal toricity in the short lens-wearing periods studied. Longer-term clinical

studies will confirm whether this is also true for prolonged wear of these lenses. To date, studies of OK using reverse-geometry lenses have not reported significant increases in corneal toricity,[2, 3, 14, 15] presumably because lens centration is maintained more reliably due to the steeper secondary curve incorporated in these lenses. Indeed, some authors have claimed that modern OK with reverse-geometry lenses can reduce with-the-rule astigmatism by up to 60%.[16] In a recent article, Mountford and Pesudovs[17] report an average reduction in corneal toricity of 50% with accelerated OK using reverse-geometry lenses.

The targeted refractive change in this study was 2.00 D reduction in myopia for all subjects. Based on changes in apical corneal power, the lenses in this study achieved 30% of this target after just 10 min of lens wear, 60% after 1 h, and 80% after 8 h of overnight wear. The apical corneal power change after overnight wear, however, ranged from 0.9 to 2.3 D (45% to 115% of target), indicating significant individual differences in the rate and amount of response. Regression analyses revealed that there was no statistically significant relationship between change in apical corneal power after 10, 30, or 60 min of lens wear and the change found after overnight wear. The potential for using a short-term lens-wearing trial to predict eventual success with OK lens wear thus requires further investigation before comments on the usefulness of such an approach can be made.

Some researchers have suggested that the endpoint of OK treatment is reached when the cornea, which is typically prolate in shape (Q < 0), has been sphericalized (Q = 0).[4, 7, 14, 18, 19] In this study, there was a trend toward less-negative asphericity values
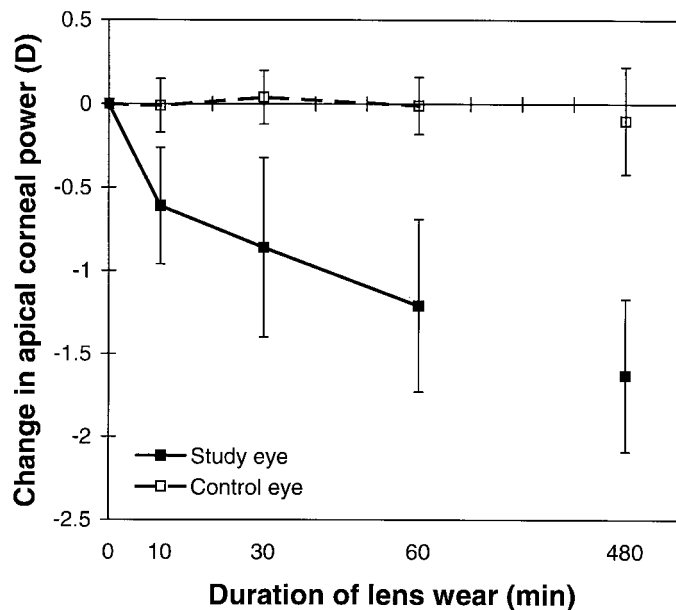
FIGURE 2.

Changes in apical corneal power (D) after different durations of orthokeratology lens wear. Negative changes represent a reduction in apical corneal power, or corneal flattening; error bars indicate the standard deviation.
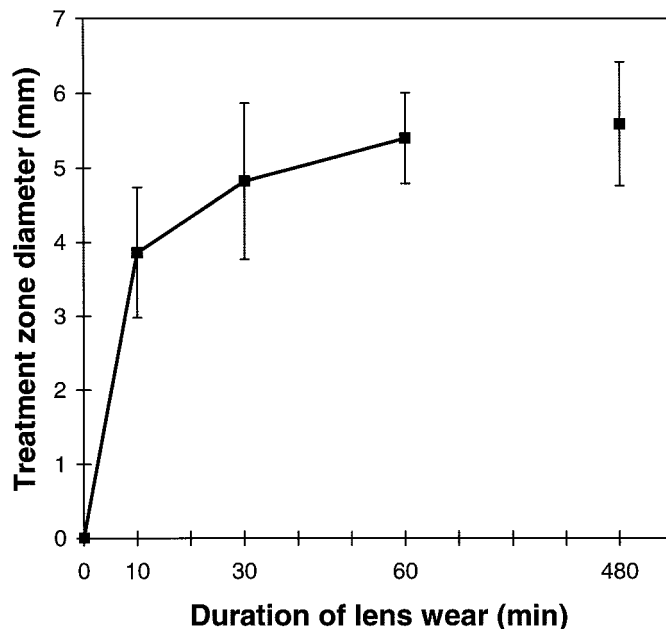

FIGURE 4.

Changes in treatment zone diameter (mm) after different durations of orthokeratology lens wear. Error bars indicate the standard deviation.
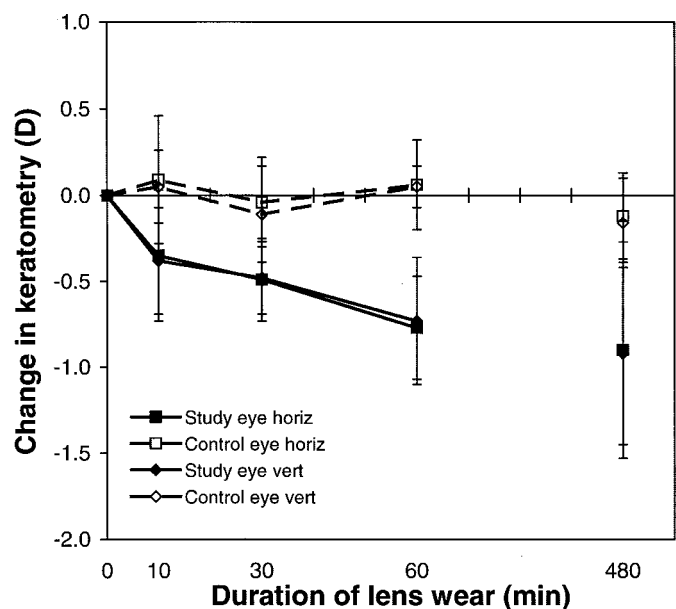

FIGURE 3.

Changes in keratometry readings (D) in horizontal (horiz) and vertical (vert) meridians after different durations of orthokeratology lens wear. Negative changes represent corneal flattening; error bars indicate the standard deviation.
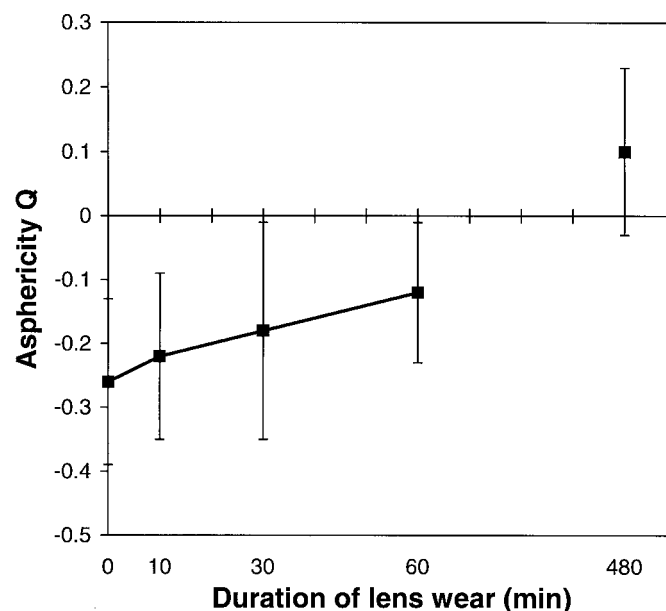

FIGURE 5.

Changes in corneal asphericity Q after different durations of orthokeratology lens wear. Positive changes indicate corneal sphericalization; error bars indicate the standard deviation.

(sphericalization) after 10, 30, and 60 min of OK lens wear, although the results did not reach statistical significance. The Q value increased significantly, becoming more positive by 0.36 ± 0.14 ($p < 0.001$), after the 8-h overnight OK lens wear session. Interestingly, the final Q value after overnight wear averaged $+0.10$, indicating an oblate corneal shape; seven of the nine subjects exhibited a positive Q value at this timepoint.

It has also been suggested that the overall myopia reduction achievable in OK can be predicted from the baseline corneal shape,[1, 14] although this hypothesis is not universally supported.[20] In this study, the correlation between the change in apical corneal power and baseline asphericity (Q) was not significant for the 10-min and 8-h lens-wearing sessions, but did reach significance after 30 and 60 min of lens wear ($r = 0.81$, $p = 0.02$ at 30 min; $r = 0.80$, $p = 0.03$ at 60 min). This suggests that patients with more
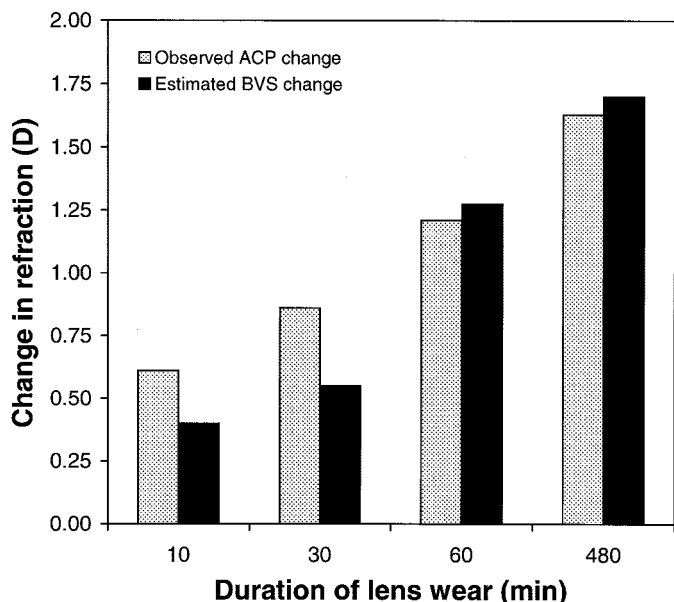
FIGURE 6.

Relationship between changes in apical corneal power (D) and refractive changes estimated from changes in logMAR visual acuity (D) for different durations of orthokeratology lens wear. ACP, apical corneal power; BVS, best-vision sphere.

prolate corneal shapes may achieve more rapid early effects with OK lenses than those with more spherical corneas. However, our data do not allow conclusions to be drawn about the relationship between baseline corneal shape and the endpoint of OK treatment.

The Q value was calculated in our study from the data output from the Medmont topographer. This topographer does give a Q value in its data display. However pilot studies using human eyes suggested that the Q value obtained from the Medmont topographer was poorly repeatable. Thus we chose to calculate the Q value using other Medmont data. The corneal shape can be approximated to a conic section of the form

$$y^2 = 2r_ox - px^2 \qquad (2)$$

where p is the corneal shape factor, r_o is the apical radius of curvature, and x is the corneal sagittal height over half chord y.[12] Rearranging this formula allows p to be calculated, and Q can then be derived from the relationship $Q = 1 - p$.[21] It should be noted that Q is related to corneal eccentricity, e, by the equation $Q = -e^2$.[21]

For convenience, in this study the chord over which the corneal sagittal height was calculated was 9.34 mm, corresponding to the chord over which sagittal height was also obtained for parameter calculation of the OK lenses used in this study. This calculation "averages" corneal shape over the selected chord diameter, an approach that may be appropriate in a normal, untreated eye. As the corneal shape changed with OK lens wear, this chord diameter typically included not only the flattened central treatment zone, but also the ring of midperipheral corneal steepening that developed under the lens tear reservoir. The selection of this chord diameter thus may have obscured central changes in Q, particularly for the shorter OK lens wear sessions where the treatment zone diameter was smaller. To better understand the effect of short-term OK lens wear on corneal shape, further studies are needed using a

topographic instrument that can provide accurate and repeatable values for corneal shape descriptors (e, p, or Q) over variable chord diameters.

For some OK lens designs, trial lens fitting is recommended with trial lenses selected on the basis of central (apical or keratometric) corneal curvature and other topographic variables. If the initial trial lens does not show appropriate fitting characteristics after a brief wearing period, patients would then be fitted with another trial lens, as recommended by the manufacturer, and so on until the desired fitting characteristics are revealed. The rapid and significant changes in central and midperipheral corneal curvature after OK lens-wearing sessions as short as 10 min, as found in this study, raises questions about the validity of this approach to trial lens fitting. Studies investigating the effect of these changes on the fit of subsequent OK trial lenses are recommended. Alternatively, a clear definition of the time taken for corneal recovery to baseline curvature after short-term OK lens wear is needed. We plan to publish the results of our analysis of corneal recovery in the near future.

Swarbrick et al.[22] have suggested that the changes in anterior corneal topography in OK are achieved through central corneal thinning and midperipheral thickening. The central thinning was mainly epithelial in origin, whereas the midperipheral thickening appeared to include a stromal contribution. The topographic thickness changes found in that study were able to explain almost all of the refractive effect of OK based on changes in corneal sagittal height. Based on this mechanism, our results suggest that the corneal epithelium is able to be remodelled very rapidly in response to the tear film forces generated behind reverse-geometry lenses.

SUMMARY

This study has demonstrated that reverse-geometry contact lenses can induce significant changes in anterior corneal topography within minutes of lens insertion. There is a corresponding rapid improvement of distance visual acuity in myopic subjects as the cornea flattens. The speed with which such large changes in corneal topography can occur has implications for other short- and long-term contact lens effects and the assessment of corneal topography after acute application of external pressures.

ACKNOWLEDGMENTS

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