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Recovery of corneal irregular astigmatism, ocular higher-order aberrations, and contrast sensitivity after discontinuation of overnight orthokeratology

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ABSTRACT

Aims: To examine prospectively the recovery of various parameters after discontinuation of overnight orthokeratology.

Methods: Seventeen subjects undergoing orthokeratology for 12 months were examined. Refraction, corneal topography, wavefront aberrometry, a visual acuity test and a contrast sensitivity test were performed at baseline, 12 months after commencement of the procedure, and 1 week and 1 month after discontinuation of the treatment. Asymmetry and higher-order irregularity components were calculated using a Fourier analysis of the corneal topography data. Contrast sensitivity was assessed at four spatial frequencies, and the area under the log contrast sensitivity function (AULCSF) was calculated.

Results: Orthokeratology significantly reduced manifest refraction (p<0.0001; Dunnett test) and significantly improved uncorrected visual acuity (UCVA) at 12 months after commencement of the procedure (p<0.0001). Asymmetry and higher-order irregularity components increased significantly (p<0.0001, p = 0.0032, respectively), and third- and fourth-order aberrations also increased significantly (p<0.0001). The treatment resulted in significant decreases in AULCSF (p = 0.0004). After discontinuing lens wear, all parameters, such as refraction, UCVA, asymmetry, higher-order irregularity, third-order aberration, fourth-order aberration and AULCSF, returned to the baseline level at 1 week.

Conclusion: This study confirmed that the effect of orthokeratology is completely reversible in light of optical quality of the eye and quality of vision as well as refraction and visual acuity.

Overnight orthokeratology is a non-surgical procedure to achieve transient reduction in refractive error and improvement of unaided vision especially in low to moderate myopic patients through a programmed application of specially designed rigid contact lenses which are worn during sleep. This procedure can provide patients with useful vision during waking hours without depending on external corrective devices, such as spectacles and daily wear contact lenses. A number of studies have demonstrated the efficacy of this procedure and orthokeratology has been widely known as a new alternative option to correct myopia. One of the proposed advantages of overnight orthokeratology is that its effect is impermanent, unlike corneal refractive surgery. Several short-term studies have reported that the influence of orthokeratology on refraction and visual acuity diminishes once lens wear is discontinued. However, no studies have confirmed complete recovery of refraction and visual acuity after discontinuing the procedure. The main reason may be that the recovery data are difficult to collect, because most successful cases in overnight orthokeratology are not willing to give up lens wear once they are adapted to the procedure, or patients, even if they quit the treatment, want to start wearing other corrective devices, such as daily-wear contact lenses, immediately after the discontinuation.

In general, contact lenses, regardless of the kinds or wearing modalities, can affect corneal shape and physiology. Ruiz-Montenegro found that contact lens-induced corneal topographic abnormalities were observed in a significant proportion of patients, and these alterations were more common and severe in rigid contact lens wearers than in soft contact lens wearers. Although such changes are considered to be reversible in most cases, several cases with irreversible changes have been reported. In addition, some reports have shown a possible relationship between contact lens wear and the development of keratoconus. In orthokeratology, the cornea is intentionally moulded by a positive pressure induced by reverse geometry lenses with a very flat base curve. Hence, some practitioners remain skeptical regarding the overall reversibility after discontinuation of the procedure.

Recently, several studies have demonstrated that overnight orthokeratology causes declines in optical quality of the eye, such as increases in corneal irregular astigmatism and higher-order wavefront aberrations (HOAs) of the cornea and the eye. There have been reports that this procedure reduces low-contrast visual acuity. Furthermore, it has been demonstrated that contrast sensitivity function decreases in parallel with the increases in HOAs following overnight orthokeratology. The recovery of these parameters after ceasing the treatment, however, has not been studied. Given the growing popularity of orthokeratology, it is crucial to know whether such declines completely recover after discontinuation of the procedure. Therefore, we conducted the current prospective study to investigate recovery of various clinical parameters including corneal irregular astigmatism, HOAs and contrast sensitivity after the use of reverse geometry contact lenses for overnight orthokeratology for 1 year.

SUBJECTS AND METHODS

A prospective study was conducted in 46 eyes of 23 subjects. They were consecutively recruited based
on the following inclusion criteria; manifest spherical equivalent refraction between $-4.00$ and $-1.00$ dioptres (D), refractive astigmatism up to $1.00$ D, best spectacle-corrected visual acuity (BSCVA) of $20/20$ or better, mean keratometry reading between $40.00$ and $46.25$ D, no previous experience with orthokeratology, and age between $20$ and $37$ years. Subjects with clinical evidence of ocular or corneal pathology including keratoconus and dry eye, with a history of ocular disease or previous ocular surgery or with systemic diseases such as diabetes mellitus were excluded from the study. Subjects were instructed to stop wearing their contact lenses for at least $3$ weeks prior to the baseline examination. Each subject had a comprehensive baseline examination including manifest refraction, keratometry, corneal topography, wavefront aberrometry, high-contrast visual acuity testing, contrast sensitivity testing and slit-lamp evaluation. All subjects participated in this study with the hope of being free from or less dependent on optical aids during waking hours by improving unaided visual acuity. No subject wished to qualify for occupations requiring specific unaided visual acuity.

Overnight orthokeratology was carried out using four-zone reverse geometry lenses manufactured from BOSTON XO material (Polymer Technology, Wilmington, Massachusetts) with a nominal Dk of $100 \times 10^{-11}$ (cm$^2$/s)/(ml O$_2$/ml-mm Hg), following the fitting guidelines recommended by the manufacturer. After confirmation of a proper trial lens fit, final lens parameters were determined, and a custom lens was then ordered for each eye. After lens dispensing, subjects started to wear their lenses on an overnight-wear basis in a consecutive manner, and thereafter continued the treatment for $12$ months. They were instructed to wear their contact lenses every night for at least $7$ h. The lens design was modified in case of poor topographical changes or insufficient improvement of uncorrected visual acuity throughout the study period.

Twelve months after starting orthokeratology treatment, they were asked to cease the lens wear. To evaluate the recovery of clinical parameters such as refraction, visual acuity, corneal irregular astigmatism, HOAs and contrast sensitivity, these data were again collected $1$ week and $1$ month after discontinuation of the treatment. During this period, they were requested to use eyeglasses, and not to wear any contact lenses. At every visit, subjects were examined between $09:00$ and $11:00$ to minimise eyeglasses, and not to wear any contact lenses. At every visit, refraction, visual acuity, corneal topography, wavefront aberrometry, high-contrast visual acuity testing, contrast sensitivity testing and slit-lamp evaluation were again collected $1$ week and $1$ month after discontinuation of orthokeratology.

RESULTS
During the study period, six subjects dropped out of the study. The reasons for discontinuation included poor improvement in uncorrected visual acuity (UCVA) (two subjects), incidence of monocular diplopia (2), poor adaptation owing to lens discomfort (1) and inability to keep follow-up appointments (1). Hence, the scheduled study was successfully carried out in $17$ subjects out of $23$ subjects who enrolled originally. They were nine males and eight females, and their mean age was $23.9$ (SD $3.5$) years. Clinical data of $34$ eyes from $17$ subjects who completed $1$-year follow-up were collected and used for the analyses. Because no significant interaction between eyes and time was present in each repeated-measures ANOVA performed ($p = 0.6805$ for manifest refraction, $p = 0.9337$ for UCVA, $p = 0.9061$ for BSCVA, $p = 0.7812$ for regular astigmatism, $p = 0.6401$ for manifest refraction, $p = 0.7828$ for the higher-order irregularity component, $p = 0.9459$ for third-order RMS, $p = 0.8538$ for fourth-order RMS and $p = 0.6500$ for AULCSF), the data of right and left eyes from a single subject
showed significant fluctuations during the study period.

The clinical parameters were monitored at 1 week and 1 month after discontinuation of overnight orthokeratology. Each time course of changes is shown in figs 1–5. Because all parameters showed significant fluctuations during the study period (p < 0.0001, repeated-measures ANOVA), a Dunnett post-hoc test was performed to assess the complete recovery to the baseline value at discontinuation of the treatment. All parameters showed rapid recovery after ceasing orthokeratology. Spherical equivalent refraction at 1 week after discontinuation (−1.95 (0.82) D) was not significantly different from the baseline value (−2.17 (0.80) D, p = 0.9291, Dunnett test). It further recovered to −2.07 (0.86) D at 1 month after discontinuing lens wear with no significant difference from the baseline (p = 0.9291) (fig 1). Similarly, UCVA at 1 week after discontinuation (0.64 (0.35) logMAR) was not significantly different from the baseline value (0.72 (0.29) logMAR, p = 0.1825), and it further recovered to 0.70 (0.30) logMAR at 1 month after discontinuing lens wear (p = 0.9931) (fig 2). Other parameters completely recovered with no significant difference from the baseline at 1 week after discontinuation (p = 0.9337 to 0.9999), such as asymmetry component, higher-order irregularity component (fig 3), third-order RMS, fourth-order RMS (fig 4) and AULCSF (fig 5). These parameters remained stable on the 1-month examinations (figs 3–5).

**DISCUSSION**

As shown in the results, the spherical equivalent refraction was significantly reduced, and UCVA was significantly improved by orthokeratology. However, the treatment led to significant increases in corneal irregular astigmatism and HOAs. Moreover, contrast sensitivity was significantly decreased by the treatment. All these parameters, however, returned to the baseline level 1 week after discontinuation of the procedure. In particular, the indices that represent corneal irregular astigmatism, HOAs and contrast sensitivity function showed complete recovery to the pretreatment level within 1 week after cessation of contact lens wear, and thereafter maintained the recovered level until 1 month. Spherical equivalent refractive errors and UCVA also returned to the baseline level at 1 week after the discontinuation, but these parameters showed a slight trend of

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**Table 1** Subjects’ clinical data at baseline and 12 months after commencement of overnight orthokeratology

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<th>Baseline (Mean, SD), range</th>
<th>12 months after treatment (Mean, SD), range</th>
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<tr>
<td>Spherical equivalent refraction (D)</td>
<td>−2.17 (0.80), −3.88 to −1.06</td>
<td>−0.17 (0.30), −1.06 to 0.00*</td>
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<tr>
<td>UCVA (logMAR)</td>
<td>0.72 (0.29), 0.22 to 1.15</td>
<td>0.06 (0.12), −0.18 to 0.15*</td>
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<tr>
<td>BSCVA (logMAR)</td>
<td>−0.10 (0.06), −0.18 to 0.00</td>
<td>−0.10 (0.07), −0.18 to 0.02</td>
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<td>Corneal regular astigmatism (D)</td>
<td>0.45 (0.29), 0.08 to 1.16</td>
<td>0.52 (0.30), 0.18 to 1.17</td>
</tr>
<tr>
<td>Corneal irregular astigmatism (D)</td>
<td></td>
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<tr>
<td>Asymmetry</td>
<td>0.23 (0.07), 0.14 to 0.42</td>
<td>0.33 (0.39), 0.12 to 1.42*</td>
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<tr>
<td>Higher-order irregularity</td>
<td>0.10 (0.02), 0.08 to 0.14</td>
<td>0.13 (0.05), 0.09 to 0.24</td>
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<td>Third-order RMS for a 4 mm pupil (μm)</td>
<td>0.074 (0.028), 0.034 to 0.120</td>
<td>0.247 (0.120), 0.103 to 0.491*</td>
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<td>Fourth-order RMS for a 4 mm pupil (μm)</td>
<td>0.037 (0.017), 0.014 to 0.092</td>
<td>0.129 (0.052), 0.057 to 0.233*</td>
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<td>AULCSF</td>
<td>1.447 (0.104), 1.191 to 1.604</td>
<td>1.316 (0.179), 0.957 to 1.598*</td>
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*p < 0.0001, †p < 0.001, ‡p < 0.005 (Dunnett test): significant differences between baseline and post-treatment values.

AULCSF, area under the log contrast sensitivity function; BSCVA, best spectacle-corrected visual acuity; D, dioptre; logMAR, logarithm of the minimum angle of resolution; RMS, root mean square; UCVA, uncorrected visual acuity.
further recovery 1 month after the discontinuation. These findings may indicate that the recovery of refraction and UCVA 1 week after the discontinuation is not enough, although there was no statistically significant difference between the values at baseline and 1 week after the discontinuation. A large sample would have been necessary to determine whether there really was a small further recovery of refraction and UCVA at 1 month after the discontinuation. Further studies should be conducted to confirm this point.

Previous studies revealed that recovery of refractive error toward the baseline after discontinuation of overnight orthokeratology was very rapid over the first 24–72 h, but complete recovery might require more than 2 weeks. Soni et al examined refractive and corneal recovery after the use of reverse-geometry contact lenses for overnight orthokeratology for 1 month, and found that spherical equivalent power and monocular uncorrected visual acuity did not recover fully until 2 weeks after discontinuing lens wear, while central corneal thickness recovered completely after just one night of no lens wear, and central corneal curvature recovered fully in 1 week. From these findings, they speculated that modification of the refractive index of epithelium or other corneal layers might have a greater influence on the refractive error and UCVA than corneal curvature. Also, in our study, the recovery of refractive error and UCVA was somewhat slower than that of other parameters.

As for the reason why corneal irregular astigmatism, HOAs and contrast sensitivity recovered more quickly than refractive error and UCVA, we have no clear explanation at present. However, the corneal surface contour is considered to recover rapidly after discontinuation of orthokeratology as the early recovery of corneal thickness and curvature was confirmed in the previous study and thus corneal irregular astigmatism, which reflects subtle changes in corneal surface shape, may have recovered quickly. Regarding ocular HOAs, the changes after orthokeratology are mainly attributed to those in corneal HOAs, because there are few or small changes in internal aberrations due to intraocular optical structures and posterior corneal curvature. Besides, corneal HOAs and irregular astigmatism are quite similar parameters representing corneal irregularity which cannot be corrected by spherocylindrical lenses. Therefore, ocular HOAs would have shown a rapid recovery in parallel with corneal irregular astigmatism in our study. As for contrast sensitivity, it is reported to be significantly correlated with ocular HOAs after orthokeratology. This relationship may have resulted in a similar recovery of contrast sensitivity within 1 week.

There is one limitation in our study. The current study was performed only for adults. Currently, there is no available information on recovery of clinical parameters after...
discontinuation of the procedure in children and young people. Many practitioners are concerned about the influence of this procedure on the development of the eye. A similar study for children and young people is certainly needed to elucidate this point.

In conclusion, we have for the first time confirmed the complete reversibility of overnight orthokeratology procedure in light of optical quality of the eye and quality of vision as well as refraction and visual acuity. On the basis of these findings, we can explain to patients that overnight orthokeratology is a reversible procedure. In addition, the current information concerning each recovery time is quite useful to consider the starting-point of the following procedure, if patients undergoing orthokeratology hope for another corrective option, such as laser refractive surgery.

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Competing interests: None.
Ethics approval: Ethics approval was provided by the institutional review board of Tsukuba University Hospital.
Patient consent: Patient consent was obtained.

REFERENCES

Figure 4  Time course of changes in ocular higher-order aberrations for a 4 mm pupil after commencement and discontinuation of overnight orthokeratology. RMS, root mean square. (A) There were significant increases in third-order RMS for a 4 mm pupil at 12 months after commencement of the procedure (p = 0.0001, Dunnett test). One week after discontinuation of the procedure, the complete recovery without significant difference from the baseline value (p = 0.9932) was observed. One month after the discontinuation, it maintained the recovered level with no significant difference from the pretreatment value (p = 0.9999). Error bars represent the SD. (B) Significant increases in fourth-order RMS for a 4 mm pupil were found at 12 months after commencement of the procedure (p < 0.0001, Dunnett test). After discontinuation of the procedure, it returned to the baseline level; there was no significant difference between values at baseline and at 1 week (p = 0.9337), and between those at baseline and at 1 month after the cessation. (p = 0.9999). Error bars represent the SD.

Figure 5  Time course of changes in area under the log contrast sensitivity function (AULCSF) after commencement and discontinuation of overnight orthokeratology. AULCSF decreased significantly 12 months after commencement of the procedure (p = 0.0004, Dunnett test). At 1 week after discontinuation of the procedure, it recovered completely to the baseline level without any significant difference from the baseline value (p = 0.9992), and thereafter remained at the recovered level until 1 month with no significant difference from the pretreatment value (p = 0.9999). Error bars represent the SD.


