Posterior Corneal Elevation Changes and Characteristic Analysis 1 Year After Corneal Collagen Cross-Linking for Keratoconus

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Research Article

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Abstract

**Purpose:** To investigate the changes in posterior corneal elevations (PCEs) in the circular areas and local points after corneal collagen cross-linking (CXL) for the treatment of keratoconus.

**Methods:** Method 1 divided the cornea into 0–2, 2–4, 4–6, and 6–8 mm regions centering on the apex. Method 2 obtained other 34 PCE values of local point that were identified on the nasal, supra-nasal, sub-nasal, superior, inferior, temporal, supra-temporal, and sub-temporal sides of the circle with diameters of 2, 4, 6, and 8 mm, and the apex and thinnest point.

**Results:** Method 1 showed a forward displacement of PCE at 1 month after CXL and then a backward displacement at 3 months. In Method 2, the points on the temporal side of 2 mm and 4 mm showed the same trend. The backward displacements of PCE on the temporal side of 2 mm at 6 months and on the temporal side of 4 mm at 12 months after CXL were both statistically different than those at 1 month after CXL (P < 0.05). The PCE of the thinnest point was correlated with other corneal points, except the points on the nasal and sub-nasal sides of 4 mm.

**Conclusion:** The PCEs in circular areas and characteristic points of different diameters in keratoconic eyes after CXL change with time. Local point assessment of the PCE is more clinically significant. In points selected in different quadrants of the cornea, the change in temporal points was more significant after CXL.

Introduction

Keratoconus (KC) is a degenerative corneal disorder characterized by progressive thinning and cone-like protrusion of the central cornea resulting in irregular astigmatism, myopia, and scarring with decreased visual acuity [1].

Conventional treatment options for KC include rigid contact lens, intracorneal ring implantation, and lamellar keratoplasty. All these techniques only correct the refractive error of the cornea with little effect on the progression of KC. The only treatment that is considered to not only improve the visual acuity but also prevent the progression of KC is corneal collagen cross-linking (CXL) [2, 3]. CXL with the photosensitizer riboflavin and ultraviolet (UV) light (365 nm) (UVA) can provide biomechanical stability through corneal stiffening by forming additional covalent connections between collagen fibers that consequently stabilize stromal collagen fibers and harden the structure of the collagen [4]. The procedure has been shown to result in increased stiffness of the cornea, improved biomechanical strength, keratocyte apoptosis, and increased resistance to enzymatic digestion [4–6]. CXL epi-on and CXL epi-off are effective in controlling the progress of KC, and CXL epi-on is preferable to CXL epi-off since CXL epi-on preserves the corneal thickness, improves visual acuity, and reduces postoperative ocular discomfort [7]. Regardless of the surgical method, the evaluation of the postoperative effect and the monitoring of postoperative progress are important.
Height data provide a more accurate representation of the true shape of the corneal surface because they are independent of the axis, orientation, and position [8, 9]. Since the posterior surface is not affected by changes in the corneal surface, and the first sign of ectasia is alteration in posterior corneal shape [10], posterior corneal elevation (PCE) is important for the diagnosis of corneal ectasia [11]. Increasing posterior elevation values might be a sign of ongoing ectatic process or CXL-related changes in the posterior corneal surface [12].

Until recently, there are few evidenced reports in the literature explaining the changes in posterior surface elevation after CXL. Moreover, few studies have focused on different posterior elevation zones and local points in different quadrants on posterior elevation. Corneal posterior elevation using the Pentacam rotating Scheimpflug camera has been reported to be highly reproducible and repeatable [13].

Here, we assessed the PCE after accelerated transepithelial CXL therapy for the treatment of KC using the high-resolution version of Pentacam. This study aimed to evaluate the changes and determine the characteristics of PCEs in circular areas and characteristic points of different diameters in the eyes with progressive KC 1 year after CXL.

Methods

Subjects and Methods

This retrospective study was conducted at the Department of Refractive Surgery Center, Xi’an People’s Hospital (Xi’an Fourth Hospital), China. The study protocol adhered to the tenets of the Declaration of Helsinki and was approved by the Xi’an People’s Hospital’s Ethics Committee.

Forty-two eyes of 34 patients with KC (23 males and 11 females; mean age, 21.0 ± 3.8 years) who received CXL at Xi’an People’s Hospital between January 2016 and March 2018 were enrolled in this study. The mean refractions were −6.79 ± 2.72 D (−14.00 to −2.50 D) of the sphere and −3.66 ± 1.77 D of astigmatism (−6.75 to 0 D). The mean axial length was 25.08 ± 1.14 (23.0 to 27.1) mm. The mean thinnest pachymetry was 458.45 ± 28.69 (386–523) µm, and the mean corneal thickness at the apex anterior was 450.02 ± 28.94 (382–511) µm. The mean flat keratometry (K1) was 47.39 ± 4.16 (40.7–59.1) D, and the mean steep keratometry (K2) was 50.89 ± 4.58 (42.3–62.3) D. KC was diagnosed based on the widely known criteria and the guidelines of the Collaborative Longitudinal Evaluation of Keratoconus Study [14]. The ocular findings that defined KC were (1) an irregular cornea determined by distorted keratometry mires and distortion of the retinoscopic or ophthalmoscopic red reflex (or a combination of the two) and (2) at least one of the following biomicroscopic signs: Vogt’s striae, Fleischer’s ring of >2 mm arc, and corneal scarring consistent with KC. According to the Amsler-Krumeich classification system, 16 (38.1%), 20 (47.6%), and 6 (14.3%) eyes had type 1, 2, and 3 KC, respectively. Subjects with any systemic or ocular pathology and any ocular surgical intervention, including intrastromal rings, were excluded. All subjects underwent CXL surgery with riboflavin and UVA in the KC eye (procedure described in the section “Cross-linking Technique”) no later than 1 month after baseline examinations. Corneal
tomography using the Scheimpflug camera (Pentacam [Oculus, Wetzlar, Germany]) was performed at baseline and at all follow-up visits (at 1, 3, 6, and 12 months).

**Posterior Corneal Elevation with Corneal Tomography (Pentacam)**

PCE was assessed using a rotating Scheimpflug imaging system (Pentacam HR; Oculus, Inc., Wetzlar, Germany). During the Scheimpflug tomography examination, the patient’s chin was placed on the chin rest and the forehead against the forehead strap. The patient was instructed to blink a few times and to open both eyes and stare at the fixation target. After attaining perfect alignment, the instrument automatically took 25 Scheimpflug images by rotating 360° around the optical axis of the eye within 2 s. Only measurements displaying the sign "OK" were accepted in the study.

Approximately 5000 raw data points from the Scheimpflug imaging system (Pentacam) during a single acquisition of a single eye were exported and further analyzed using customized MATLAB programs (Fig. 1). The corneas were divided into regions of 0–2 (Φ0–2) mm, 2–4 (Φ2–4) mm, 4–6 (Φ4–6) mm, and 6–8 (Φ6–8) mm for research centering on the apex of the cornea (Fig. 2). The mean difference of the data points in each circular area was compared before and after the operation.

Thirty-four corneal elevation values in the posterior surface of the topography maps were obtained manually and identified on the nasal (N) side, supra-nasal (NS) side, sub-nasal (NI) side, superior (S) side, inferior (I) side, temporal (T) side, supra-temporal (TS) side, and sub-temporal (TI) side of the circle with diameters of 2 mm, 4 mm, 6 mm, 8 mm, and the apex point and thinnest point (Fig. 3). Corneal elevation was calculated using a fixed floating sphere that best fit the 8.0 mm zone as the reference surface (both preoperative and postoperative measurements).

**Cross-linking Technique**

The CXL was performed without epithelial debridement. During the riboflavin imbibition period, patients were allowed to blink normally. Riboflavin 0.22% was applied every 20 s for 4 min. Subsequently, riboflavin 0.1% was applied every 20 s for 6 min. Thereafter, the cornea was exposed to 365-nm UVA light with the CXL system (UV-X; Avedro Inc., Boston, USA) for 5 min and 20 s at an irradiance level of 45 mW/cm² (total surface dose, 7.2 J/cm²) and 5-cm distance from the cornea. After treatment completion, the residual riboflavin solution was rinsed out with a balanced salt solution.

**Postoperative Care**

Postoperatively, an ophthalmologist performed slit-lamp examinations to assess treatment results and possible complications. Moreover, 0.1% fluorometholone and decreased intraocular pressure drops were administered, and a bandage soft contact lens was fitted. Therapeutic contact lenses were removed the day after surgery. Within the first 7 days, all treated patients received antibiotic drops (0.5% levofloxacin 5 mg/mL drops three times daily). After corneal re-epithelialization, a tapering dose of steroid drops (0.1%
fluorometholone, Santen, Osaka, Japan) was administered as prophylaxis to prevent the formation of significant subepithelial haze over 1 month.

Follow-up: Follow-up was first performed 1 day postoperatively. The visual acuity, pachymetric data, and PCEs were recorded at 1, 3, 6, and 12 months.

**Statistical Analyses**

The PCEs were retrieved from the topographer. The raw data from the Scheimpflug imaging system (Pentacam) were exported and further analyzed using customized MATLAB programs. A customized MATLAB algorithm was developed to calculate the changes in PCEs before and after CXL.

Statistical analysis was performed using the Statistical Package for the Social Sciences (SPSS) software version 20 (SPSS Inc., Chicago, IL, USA). Test for normal distribution of data was performed using the Kolmogorov-Smirnov test. As the parameters were not normally distributed, PCEs in the different area were compared among the groups using the Kruskal-Wallis test. A parametric repeated measures analysis of variance and protected post hoc t-tests with Bonferroni correction were used to determine changes in other normally distributed corneal parameters over time. The Pearson correlation statistical analysis was used to evaluate the association between variables. All values are presented as a mean ± standard deviation in tables. A P value less than 0.05 was considered statistically significant.

**Results**

Changes in PCE (ΔPCE; Δ values were defined by subtracting preoperative data from postoperative data) over the annular diameters Φ0–2 mm, Φ2–4 mm, Φ4–6 mm, and Φ6–8 mm after CXL were not statistically significant over the 12-month follow-up (P = 0.244, 0.377, 0.485, and 0.115, respectively) (Fig. 4).

The mean difference of the data points in each annular area was positive at 1 month after operation, which suggests that the cornea has a tendency to protrude. At 3 months after operation, the PCE change in each area was negative, and the protrusion showed a regression.

There was a statistically significant difference in the backward displacement of PCE at the T side of 2 mm at 6 months after surgery compared with that at 1 month after surgery (P = 0.026). The backward displacement of PCE at the T side of 4 mm at 12 months after surgery was also statistically different than that at 1 month after surgery (P = 0.035). There was a statistically significant difference in the forward displacement of PCE at the TI side of 6 mm and 8 mm at 6 months and 12 months after surgery compared with that at 1 month after surgery (P = 0.039, P = 0.026; P = 0.032, and P = 0.007, respectively) (Fig. 5). There were no statistically significant differences in other points before and after CXL over the 12-month follow-up (P > 0.05) (Table 1).
Table 1
Changes in posterior corneal elevation in different point after CXL (n = 42)

| Position     | Diameter | Preop     | 1 mon Postop | 3 mons Postop | 6 mons Postop | 12 mons Postop | P     |
|--------------|----------|-----------|--------------|---------------|---------------|----------------|-------|
| nasal        | 2mm      | 131.07 ± 33.29 | 132.40 ± 32.78 | 132.21 ± 32.54 | 131.60 ± 34.15 | 130.83 ± 32.07 | 0.690 |
|              | 4mm      | 43.33 ± 21.47 | 45.07 ± 21.56 | 43.48 ± 22.80 | 44.67 ± 20.10 | 44.52 ± 20.03 | 0.657 |
|              | 6mm      | -51.36 ± 27.50 | -50.17 ± 28.69 | -50.78 ± 28.36 | -49.83 ± 27.07 | -50.00 ± 26.89 | 0.912 |
|              | 8mm      | -151.52 ± 38.46 | -151.98 ± 41.28 | -151.05 ± 36.84 | -151.05 ± 37.37 | -149.90 ± 35.04 | 0.942 |
| supra-nasal  | 2mm      | 104.24 ± 25.85 | 105.83 ± 24.33 | 106.64 ± 25.30 | 104.69 ± 26.46 | 105.50 ± 25.97 | 0.362 |
|              | 4mm      | 7.55 ± 24.60 | 8.76 ± 22.12 | 9.50 ± 21.72 | 7.62 ± 23.01 | 7.17 ± 22.37 | 0.336 |
|              | 6mm      | -81.90 ± 25.97 | -81.55 ± 28.69 | -84.00 ± 29.10 | -80.50 ± 29.41 | -81.88 ± 30.17 | 0.423 |
|              | 8mm      | -180.83 ± 36.37 | -178.10 ± 36.13 | -181.64 ± 34.27 | -176.60 ± 38.77 | -176.21 ± 37.16 | 0.118 |
| sub-nasal    | 2mm      | 150.69 ± 38.32 | 152.14 ± 36.53 | 151.12 ± 35.71 | 150.26 ± 37.81 | 149.45 ± 34.99 | 0.260 |
|              | 4mm      | 43.81 ± 22.13 | 43.95 ± 18.52 | 43.38 ± 18.69 | 42.12 ± 20.46 | 40.05 ± 18.60 | 0.225 |
|              | 6mm      | -81.95 ± 32.36 | -86.05 ± 29.57 | -86.64 ± 32.15 | -83.40 ± 35.74 | -88.07 ± 34.04 | 0.135 |
|              | 8mm      | -207.93 ± 48.85 | -216.05 ± 53.61 | -216.07 ± 50.10 | -212.69 ± 50.86 | -215.12 ± 50.86 | 0.082 |
| superior     | 2mm      | 93.81 ± 24.52 | 93.83 ± 24.15 | 95.86 ± 25.89 | 94.31 ± 24.85 | 95.14 ± 23.96 | 0.459 |
|              | 4mm      | -11.74 ± 25.37 | -15.55 ± 27.32 | -12.12 ± 23.47 | -12.43 ± 24.48 | -11.79 ± 25.20 | 0.078 |
|              | 6mm      | -106.05 ± 29.62 | -110.24 ± 31.00 | -109.76 ± 30.49 | -105.64 ± 28.01 | -106.71 ± 31.31 | 0.155 |
|              | 8mm      | -210.40 ± 40.39 | -213.21 ± 48.09 | -205.00 ± 38.57 | -206.17 ± 44.38 | -204.29 ± 41.12 | 0.111 |
| inferior     | 2mm      | 159.76 ± 35.35 | 159.98 ± 31.49 | 160.67 ± 34.60 | 159.64 ± 32.92 | 160.00 ± 33.08 | 0.879 |

*P < 0.05 is statistically significant
| Position      | Diameter | Preop       | 1 mon Postop | 3 mons Postop | 6 mons Postop | 12 mons Postop | P     |
|--------------|----------|-------------|--------------|---------------|---------------|----------------|-------|
|              |          | 31.48 ± 19.91 | 31.33 ± 22.91 | 33.38 ± 24.20 | 31.62 ± 24.20 | 31.83 ± 21.21 | 0.986 |
| 4mm          |          | -126.33 ± 38.18 | -125.26 ± 39.92 | -125.67 ± 46.23 | -124.17 ± 42.81 | -125.76 ± 44.45 | 0.937 |
|              |          | -259.05 ± 55.74 | -254.57 ± 65.91 | -257.64 ± 63.26 | -260.93 ± 62.06 | -258.07 ± 57.82 | 0.481 |
| temporal     | 2mm      | 151.93 ± 36.02 | 154.95 ± 36.18 | 152.55 ± 35.50 | 151.10 ± 35.06 | 151.31 ± 35.64 | 0.013*|
|              |          | 56.02 ± 18.01  | 61.64 ± 23.15  | 57.12 ± 20.79  | 56.43 ± 19.14  | 54.98 ± 19.78  | 0.006*|
|              |          | -58.02 ± 30.63 | -56.31 ± 35.01 | -59.50 ± 31.34 | -60.24 ± 31.56 | -58.19 ± 30.50 | 0.603 |
|              | 8mm      | -170.38 ± 42.67 | -172.38 ± 44.22 | -174.29 ± 41.13 | -171.90 ± 40.06 | -171.36 ± 39.77 | 0.630 |
| supratemporal| 2mm      | 117.45 ± 31.80 | 118.29 ± 30.00 | 118.67 ± 31.34 | 116.14 ± 30.31 | 116.79 ± 30.24 | 0.230 |
|              |          | 14.60 ± 18.21  | 13.38 ± 17.83  | 13.69 ± 20.65  | 12.17 ± 18.83  | 12.00 ± 17.84  | 0.422 |
|              |          | -84.52 ± 25.40 | -84.74 ± 24.33 | -84.86 ± 28.56 | -85.71 ± 25.60 | -87.05 ± 25.55 | 0.701 |
|              | 8mm      | -181.86 ± 34.86 | -183.02 ± 35.95 | -182.33 ± 37.02 | -185.62 ± 33.88 | -186.31 ± 32.00 | 0.172 |
| subtemporal  | 2mm      | 167.93 ± 34.38 | 169.95 ± 32.58 | 168.88 ± 34.86 | 169.12 ± 33.81 | 169.24 ± 34.93 | 0.437 |
|              |          | 58.33 ± 25.46  | 58.79 ± 22.83  | 60.29 ± 21.89  | 60.64 ± 21.52  | 62.67 ± 22.22  | 0.296 |
|              |          | -86.21 ± 49.51 | -90.31 ± 47.81 | -85.60 ± 48.02 | -81.98 ± 41.63 | -81.14 ± 40.19 | 0.023*|
|              | 8mm      | -232.31 ± 57.47 | -238.38 ± 57.78 | -229.45 ± 58.39 | -226.43 ± 48.33 | -221.48 ± 47.96 | 0.003*|
| thinnest     |          | -190.62 ± 48.70 | -189.17 ± 47.73 | -188.95 ± 47.12 | -190.50 ± 48.48 | -191.50 ± 47.95 | 0.339 |
| point        |          | 181.55 ± 50.06 | 182.12 ± 48.07 | 180.57 ± 46.99 | 180.69 ± 48.36 | 180.90 ± 48.03 | 0.748 |
| apex         |          | -190.62 ± 48.70 | -189.17 ± 47.73 | -188.95 ± 47.12 | -190.50 ± 48.48 | -191.50 ± 47.95 | 0.339 |

*P < 0.05 is statistically significant
PCE of the thinnest point was significantly correlated with other corneal points, except the points at the N and NI sides of 4 mm (Table 2).
Table 2
Relationship Between the PCE in Corneal Thinnest Point and in Other Corneal Points

| Corneal Point     | Diameter  | r       | P      |
|-------------------|-----------|---------|--------|
| Nasal             | 2mm       | 0.869   | < 0.001* |
|                   | 4mm       | 0.058   | 0.403  |
|                   | 6mm       | -0.478  | < 0.001* |
|                   | 8mm       | -0.464  | < 0.001* |
| supra-nasal       | 2mm       | 0.765   | < 0.001* |
|                   | 4mm       | -0.524  | < 0.001* |
|                   | 6mm       | -0.722  | < 0.001* |
|                   | 8mm       | -0.580  | < 0.001* |
| sub-nasal         | 2mm       | 0.911   | < 0.001* |
|                   | 4mm       | 0.004   | 0.948  |
|                   | 6mm       | -0.675  | < 0.001* |
|                   | 8mm       | -0.516  | < 0.001* |
| Superior          | 2mm       | 0.677   | < 0.001* |
|                   | 4mm       | -0.583  | < 0.001* |
|                   | 6mm       | -0.680  | < 0.001* |
|                   | 8mm       | -0.474  | < 0.001* |
| Inferior          | 2mm       | 0.934   | < 0.001* |
|                   | 4mm       | -0.317  | < 0.001* |
|                   | 6mm       | -0.607  | < 0.001* |
|                   | 8mm       | -0.305  | < 0.001* |
| Temporal          | 2mm       | 0.922   | < 0.001* |
|                   | 4mm       | 0.207   | < 0.001* |
|                   | 6mm       | -0.472  | < 0.001* |
|                   | 8mm       | -0.495  | < 0.001* |

*P < 0.05 is statistically significant
| Comical Point | Comical Thinnest Point |
|---------------|------------------------|
| supra-temporal | 2mm 0.847 < 0.001*     |
|               | 4mm -0.163 < 0.001*    |
|               | 6mm -0.540 < 0.001*    |
|               | 8mm -0.361 < 0.001*    |
| sub-temporal  | 2mm 0.949 < 0.001*     |
|               | 4mm -0.356 < 0.001*    |
|               | 6mm -0.755 < 0.001*    |
|               | 8mm -0.701 < 0.001*    |
| apex point    | - 0.986 < 0.001*       |

*P < 0.05 is statistically significant

Discussion

CXL with riboflavin and UVA is used for slowing or halting the progression of KC and is shown to be effective [15, 16]. However, the long-term efficacy of epi-on CXL on progressive KC treatment is not fully understood, especially that there are only few studies demonstrating the stability of the PCE.

Changes in PCE can represent the shape of the posterior cornea and provide an evaluation of the shape and corneal stability in the post-CXL stage. Posterior elevation is a sensitive parameter to monitor corneal remodeling after CXL [17]. A positive change in the posterior corneal surface indicates an ectatic change in the cornea.

In the present study, PCE was analyzed, and this study aimed to determine whether or when corneal posterior morphology was stable following CXL. To the best of our knowledge, only few studies have reported the safety and efficacy of CXL by PCE in different corneal zones and local points in different quadrants.

We analyzed PCEs using elevation maps provided by Scheimpflug tomography. In this study, no significant forward displacement of PCE was found in different corneal annular areas and local points in different quadrants, which suggests that cross-linking surgery is safe and effective. Grewal et al. [18] and Henriquez et al. [19] have also analyzed the corneal changes after CXL with Scheimpflug imaging and found no significant changes in the PCE. Moreover, Steinberg has demonstrated a statistically significant increase in the posterior elevation at the apex 2 years after CXL [12]. At 36 months, the posterior elevation of the thinnest point did not change significantly [20]. Both of these studies mainly focus on the corneal curvature and corneal anterior surface, but studies assessing the description of PCE are rare.
In this study, we analyzed the changes and characteristics of PCEs in circular areas and compass points of different diameters after CXL to determine the effectiveness of the operation and evaluate the stability after the operation.

In the current study, some characteristic changes in PCE were found after the cross-linking surgery. In Method 1, apart from the mean $\Delta$PCE values at 1 month after CXL and that of the annular diameters $\Phi_{0-2}$ mm at 6 months being positive after CXL, the values of all areas were negative at all times. This suggests that there is a backward displacement in the PCE 1 month after CXL. Moreover, Method 2 showed a forward displacement of PCE at the T side of 2 mm and 4 mm 1 month after surgery and then a backward displacement of PCE. This is possibly due to the rarefaction of keratocytes associated with stromal edema at 1 month after treatment [21]. After 2 to 3 months, the population of cell increased, and the edema decreased gradually [21].

Except for a 4 mm point on the T side, there was no significant change in PCE at the other 33 points involved in this study after CXL compared with before CXL. For the 4 mm point on the T side, the PCE at 1 month after CXL showed a forward displacement compared with that before CXL, and the PCE at 12 months after operation showed a backward displacement compared with that at 1 month after CXL. There was no significant difference in PCE at 12 months after CXL compared with before CXL. This is consistent with Magli's findings that no significant difference was found in the posterior elevation at the thinnest location and at the apex from preoperative value at 1 year after treatment [22]. However, Magli's study mainly evaluates the safety of cross-linking surgery. Except for the thinnest point and apex, it does not involve the study of the changes in the PCE at other different points. In addition, the PCE at the TI side of 6 mm and 8 mm at 6 and 12 months after surgery showed a significantly forward displacement than that at 1 month after surgery. The PCE at the T side of 2 mm shows a backward displacement at 6 months after CXL compared with 1 month after CXL. The overall change was not significant. Consistent with KC development, our study found that the PCE at the T and TI side changes evidently.

The abovementioned study results show that the PCE in the local point can be more sensitively detected before and after CXL than that in the circular area. The possible reason is that the annular area is the mean value of the PCE difference of the raw data points, which will reduce the sensitivity of detection.

The PCE of the thinnest point was correlated with other corneal points, except the points at the N and NI sides of 4 mm. Previous studies have found that the flattening effect of CXL is augmented in the eyes with thinner corneas. CXL may affect deeper stromal tissues of thinner corneas compared to cases with thicker corneas [17]. This may be attributed to the fact that changes in corneal biomechanics after cross-linking surgery cause more collagen fibers in the deep corneal stroma that can be cross-linked. Based on our study and previous studies, we found that the cone of KC tends to occur on the T side [23]. Therefore, the corneal thickness of the T side is thinner than that of the nasal side; thus, the cross-linking effect of the temporal cornea is stronger than that of the nasal cornea.
The main limitation of this study is that we did not analyze the PCE at the thinnest corneal point, the cone apex, and the maximum K point.

In summary, our data confirm that transepithelial corneal CXL is a potent treatment for preventing corneal ectasia progression in KC eyes. The PCEs of KC after CXL had certain characteristic changes at 1 year in the studied cohort. The local point assessment of the PCE of KC is more valuable than that of the circular area. Compared with the nasal points of the cornea, the change in temporal points was more significant after CXL. CXL surgery may cause different degrees of cross-linking effect in different parts of the cornea. The cross-linking effect of the temporal cornea is stronger than that of the nasal cornea. The changes of corneal collagen fiber structure in different areas after CXL need further observation.

Declarations

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Conflicts of interest/Competing interests

The authors have no conflicts of interest to declare that are relevant to the content of this article.

Availability of data and material

The data used to support the findings of this study are available from the corresponding author upon request.

Code availability

Not applicable

Authors’ contributions

Concept and design (JL and YW); analysis of the data (JL and SSW); writing the article (JL and YHZ); critical revision of the article (JL, SSW, and YW); data collection (JL, SSW, YHZ, and YL); provision of materials, patients, or resources (YW); and administrative, technical, or logistic support (YL, JGL and YW). All authors have reviewed the manuscript. All authors read and approved the final manuscript.

Ethics approval

The study protocol adhered to the tenets of the Declaration of Helsinki and was approved by the Xi’an People’s Hospital’s Ethics Committee.

Consent to participate
Written informed consent was obtained from at least one parent or legal guardian of each subject.

Consent for publication

Not applicable

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Figure 1

Distribution map of the raw data points before surgery

Figure 2

Difference in posterior corneal elevation before and after surgery in each circular area—Method 1

Method 1: The cornea was divided into 0–2 mm (Φ0–2 mm), 2–4 mm (Φ2–4 mm), 4–6 mm (Φ4–6 mm), and 6–8 mm (Φ6–8 mm) regions centering on the apex of the cornea. The posterior corneal elevation difference was calculated and compared in each circular area before and after the operation.
Figure 3

Local point position on radial lines in different quadrants of posterior corneal elevation—Method 2

Method 2: Thirty-four posterior corneal elevation values of local point in the Scheimpflug topography maps were obtained and identified on the nasal side (N), supra-nasal side (NS), sub-nasal side (NI), superior side (S), inferior side (I), temporal side (T), supra-temporal side (TS), and sub-temporal side (TI) of the circle with diameters of 2 mm, 4 mm, 6 mm, 8 mm, and the apex and thinnest point.

Figure 4

$\Delta$PCE values at different follow-up times

$\Delta$PCE: posterior corneal elevation; $\Delta$ values were defined by subtracting preoperative data from postoperative data.
Figure 5

Mean and standard deviation of PCE