Original Article

Anterior segment optical coherence tomography evaluation of early corneal changes following corneal collagen cross-linking for progressive keratoconus

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ABSTRACT

Background: Keratoconus is a progressive corneal ectatic disorder characterized by stromal thinning, corneal protrusion, and progressive visual impairment. Corneal collagen cross-linking (CXL) is an established treatment for halting disease progression by enhancing corneal biomechanical stability. This study evaluated early corneal structural and functional changes following accelerated epithelium-off CXL in eyes with progressive keratoconus using anterior segment optical coherence tomography (AS-OCT). Specifically, epithelial thickness and central corneal thickness (CCT) were assessed one month after treatment and correlated with stromal demarcation line depth.

Methods: In this prospective study, eyes with progressive keratoconus underwent accelerated epithelium-off CXL. All participants underwent comprehensive ophthalmic examination before treatment and one month postoperatively. Assessments included uncorrected distance visual acuity (UDVA), corrected distance visual acuity (CDVA), intraocular pressure (IOP), corneal tomographic parameters, CCT, epithelial thickness, and AS-OCT measurement of stromal demarcation line depth.

Results: Thirty eyes of 15 patients with progressive keratoconus underwent accelerated epithelium-off CXL. Mean (standard deviation) age of participants was 26.5 (4.5) years (range 19–35), and 53.3% (n = 8) were female. At one month, modest but statistically significant improvements were observed in both UDVA and CDVA (both $P < 0.05$). A slight but statistically significant reduction in IOP was also observed ($P < 0.05$). Keratometric parameters yielded modest but significant reductions following treatment (all $P < 0.05$), consistent with early corneal flattening. Significant decreases were observed in both CCT and epithelial thickness (both $P < 0.05$). The median (interquartile range) stromal demarcation line depth measured by AS-OCT was 214.5 (171.0–274.3) μm, with 143–322 μm value ranges. Demarcation line depth showed significant positive correlations with both preoperative CCT ($\varrho = 0.368$, $P = 0.045$) and postoperative CCT ($\varrho = 0.433$, $P = 0.017$), whereas no significant associations were observed with preoperative ($\varrho = -0.197$, $P = 0.298$) or postoperative ($\varrho = -0.093$, $P = 0.625$) epithelial thickness.

Conclusions: Accelerated epithelium-off CXL was associated with early corneal structural changes, including reductions in CCT and epithelial thickness, accompanied by mild corneal flattening and modest improvements in visual acuity. Stromal demarcation line depth was positively correlated with CCT, suggesting an association between corneal thickness and treatment penetration. AS-OCT provided detailed, non-invasive assessment of postoperative demarcation line depth and may serve as a useful tool for monitoring early response to CXL. Further studies with larger sample sizes, longer follow-up periods, and multicenter recruitment are warranted to validate these findings in our population.

KEYWORDS

keratoconus, corneal collagen cross-linking, epithelium-off corneal cross-linking, anterior eye segments, optical coherence tomography, corneal topographies, visual acuities, intraocular pressures, corneal thickness measurement

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INTRODUCTION

Keratoconus is a progressive non-inflammatory corneal ectatic disorder characterized by stromal thinning and protrusion, resulting in irregular astigmatism and visual deterioration [1]. The disease typically manifests during the second decade of life and may continue to progress over several years [2, 3]. If left untreated, progressive corneal deformation can lead to substantial visual impairment and, in advanced cases, may necessitate corneal transplantation [4, 5].

Corneal collagen cross-linking (CXL) has become an established treatment for halting keratoconus progression by enhancing corneal biomechanical stability through the formation of additional covalent bonds within stromal collagen fibers [6, 7]. The procedure employs riboflavin (vitamin B2) as a photosensitizer in combination with ultraviolet-A (UVA) irradiation to induce collagen cross-linking within the corneal stroma [8, 9]. Although CXL has demonstrated efficacy in stabilizing ectatic progression, postoperative assessment remains important for evaluating treatment-related corneal changes [10]. Advances in CXL protocols, including accelerated treatment approaches, together with developments in corneal imaging technologies, have enhanced the safety and efficacy of the procedure and facilitated the assessment of treatment-induced corneal structural changes [11].

Anterior segment optical coherence tomography (AS-OCT) provides high-resolution, non-contact imaging of the cornea and has become an important modality for evaluating corneal changes after CXL [12]. The technique allows quantitative assessment of corneal structural parameters, including epithelial thickness, stromal thickness, and treatment-induced stromal alterations [13, 14]. A distinct interface between the treated anterior stroma and the untreated posterior stroma, referred to as the stromal demarcation line, can be visualized using AS-OCT, and is considered an indicator of the depth of stromal treatment penetration following CXL [12, 15, 16].

This study aimed to investigate early corneal structural changes after accelerated epithelium-off CXL in eyes with progressive keratoconus using AS-OCT. Specifically, epithelial thickness and central corneal thickness were evaluated 1 month after treatment and correlated with stromal demarcation line depth.

METHODS

This prospective study enrolled consecutive eligible patients presenting to the ophthalmology outpatient clinics of Port Said Ophthalmology Hospital, Port Said, Egypt, between February 2025 and February 2026. Participants were recruited after meeting the predefined eligibility criteria. The study protocol received approval from the Research Ethics Committee of the Faculty of Medicine, Port Said University (Approval No. 243/OPT824_007; approved 9 February 2025). Written informed consent was obtained from all participants before study enrollment. The study adhered to the tenets of the Declaration of Helsinki and its subsequent amendments. All data were de-identified prior to analysis to maintain participant confidentiality. Separate consent for publication was obtained from participants whose clinical images were included in this report.

Consecutive sampling was employed, whereby all eligible patients fulfilling the predefined inclusion criteria were enrolled sequentially throughout the study period until the required sample size was attained. Sample size calculation was performed during protocol development using G*Power software (version 3.1; Heinrich Heine University, Dusseldorf, Germany). Based on the postoperative changes in corneal thickness reported by Barakat et al. [17], a paired-samples design was adopted to assess longitudinal within-subject changes. Assuming a two-sided significance level of 0.05, a statistical power of 80%, and an effect size derived from the published data, the minimum required sample size was estimated at 30 eyes. Accordingly, 30 eyes from 15 patients were included in the final analysis. Inclusion of both eyes from the same participant enabled assessment of bilateral treatment effects and maximized the use of available clinical data. However, the potential for inter-eye correlation and the resulting departure from statistical independence should be considered when interpreting the findings.

Eligibility criteria included age between 18 and 35 years and a diagnosis of progressive keratoconus. Progression was defined by the presence of one or more of the following changes documented over the preceding 12 months: an increase ≥ 1.00 diopter (D) in the steepest keratometric value (Ksteep), an increase ≥ 1.00 D in manifest refractive cylinder, an increase ≥ 0.50 D in manifest spherical equivalent refraction, or a reduction in corneal thickness > 25 μm [1, 18]. Only eyes with stage I–III keratoconus according to the Amsler-Krumeich classification [19] and a clinically clear cornea were considered eligible. If both eyes met the inclusion criteria, both were enrolled in the study. Exclusion criteria comprised a history of ocular trauma, previous intraocular surgery, central corneal thickness (CCT) < 400 μm, prior herpetic ocular disease, post-refractive surgery ectasia [20], and the presence of other corneal ectatic disorders

Preoperative and postoperative evaluations included visual acuity, intraocular pressure (IOP), corneal tomographic parameters, CCT, epithelial thickness, and AS-OCT assessment of stromal demarcation line depth. All participants underwent a comprehensive ophthalmic examination, including measurement of uncorrected and corrected distance visual acuity (UDVA and CDVA, respectively) using a Snellen chart and recorded in decimal notation, slit-lamp biomicroscopy of the anterior and posterior segments (SL-3G; Topcon Corporation, Tokyo, Japan), IOP measurement using a non-contact tono-pachymeter (CT-1P; Topcon Corporation, Tokyo, Japan), and corneal tomography with the Pentacam HR (Oculus Optikgeräte GmbH, Wetzlar, Germany). AS-OCT imaging was performed using a spectral-domain device (REVO FC 130;

Optopol Technology, Zawiercie, Poland) to evaluate CCT, epithelial thickness, and postoperative stromal demarcation line depth. To ensure measurement consistency and minimize interobserver variability, all examinations and image acquisitions were performed by the same experienced examiner using standardized protocols and identical instrumentation throughout the study.

CXL was performed under sterile conditions using an accelerated epithelium-off protocol. On the day of surgery, topical gatifloxacin 0.3% ophthalmic solution (Gatistar®, Orchidia Pharmaceutical Industries, Cairo, Egypt) was administered prophylactically four times before the procedure. Topical anesthesia was achieved with benoxinate hydrochloride 0.4% (Benox®, Epico, Inc., Cairo, Egypt), instilled at 5-minute intervals for a total of three applications. Following anesthesia, the central 7.0–9.0 mm of corneal epithelium was mechanically removed using a hockey spatula. A photosensitizing solution containing 0.1% riboflavin in 1.0% hydroxypropyl methylcellulose (Ribocross®, SERVImed, Rome, Italy) was then applied every 5 minutes for 20 minutes to ensure adequate stromal saturation. UVA irradiation was subsequently delivered at a wavelength of 370 nm using a solid-state cross-linking system (CCL-365; Peschke Meditrade GmbH, Huenenberg, Switzerland). The irradiance was set at 9 mW/cm² for 10 minutes at a working distance of 5 cm. Throughout UVA exposure, riboflavin instillation was repeated every 3 minutes to maintain stromal saturation [21, 22]. All procedures were performed by a single experienced corneal surgeon following a standardized surgical protocol. At the conclusion of the procedure, a bandage soft contact lens (SofLens® bandage contact lens; Bausch & Lomb, Rochester, NY, USA) was applied and retained until complete corneal re-epithelialization was confirmed by slit-lamp biomicroscopy.

Postoperatively, patients received topical gatifloxacin 0.3% (Gatistar®, Orchidia Pharmaceutical Industries) four times daily for one week and a combined tobramycin 0.3%/dexamethasone 0.1% ophthalmic suspension (Tobradex®, Alcon Laboratories, Fort Worth, Texas, USA) four times daily for one week. Ocular surface lubrication was maintained with sodium hyaluronate 0.2% artificial tears (Hyfresh®, Jamjoom Pharma, Jeddah, Saudi Arabia) administered four times daily for six weeks. Oral ibuprofen (400 mg; Brufen®, Abbott Laboratories, Abbott Park, IL, USA) was prescribed as required for postoperative pain control.

Participants were evaluated on postoperative days 1, 3, and 7, and one month following treatment. Early follow-up visits focused on monitoring epithelial healing and detecting procedure-related complications. At each visit UDVA and CDVA were assessed, and slit-lamp biomicroscopy was performed according to a standardized examination protocol. Corneal tomographic parameters were obtained using the Pentacam HR. AS-OCT was performed to evaluate postoperative corneal structural changes, including CCT, epithelial thickness, and stromal demarcation line depth. Postoperative tomographic and AS-OCT findings were compared with baseline measurements to assess the anatomical response to CXL.

Statistical analyses were performed using IBM SPSS Statistics for Windows (version 24.0; IBM Corp., Armonk, NY, USA). Data distribution was assessed using the Shapiro-Wilk test. Continuous variables are presented as median (interquartile range [IQR]), categorical variables as frequency (percentage). Comparisons between preoperative and postoperative measurements, including visual acuity, keratometric indices, CCT, epithelial thickness, and IOP, were performed using the Wilcoxon signed-rank test, as several variables did not satisfy the assumption of normality. Associations between stromal demarcation line depth and corneal tomographic parameters were evaluated using Spearman's rank correlation coefficient (ϱ). All statistical tests were two-tailed, and a P-value < 0.05 was considered statistically significant.

RESULTS

Thirty eyes of 15 patients with progressive keratoconus underwent accelerated epithelium-off CXL. Mean (standard deviation) age of participants was 26.5 (4.5) years (range 19–35 years). Eight patients (53%) were female and seven (47%) were male (Table 1).

The median (IQR) stromal demarcation line depth measured by AS-OCT was 214.5 (171.0–274.3) μm, with 143–322 μm value ranges. Changes in functional, tomographic, and corneal structural parameters are summarized in Table 2. Both UDVA and CDVA showed modest but statistically significant improvements one month after treatment (both $P < 0.05$). A slight but statistically significant reduction in IOP was observed ($P < 0.05$). Keratometric indices evidenced modest yet significant decreases (all $P < 0.05$), consistent with early corneal flattening following CXL. Significant reductions were also observed in CCT and epithelial thickness (both $P < 0.05$), reflecting early postoperative corneal remodeling (Table 2).

There was no significant correlation between demarcation line depth and preoperative epithelial thickness ($\varrho = -0.197$, $P = 0.298$) or postoperative epithelial thickness ($\varrho = -0.093$, $P = 0.625$). However, significant positive correlations were observed between demarcation line depth and both preoperative CCT ($\varrho = 0.368$, $P = 0.045$) and postoperative CCT ($\varrho = 0.433$, $P = 0.017$). The strength of these associations was weak-to-moderate and moderate, respectively, suggesting that eyes with greater corneal thickness tended to exhibit deeper stromal demarcation lines (Figure 1). Because both eyes were included when eligible, inter-eye correlation may have influenced variance estimates.

Representative AS-OCT findings obtained 1 month after treatment are shown in Figure 2. The cross-sectional scan reveals a distinct stromal demarcation line within the anterior corneal stroma at a depth of approximately 177 μm. Corresponding epithelial thickness and pachymetry maps showed a central epithelial thickness of 49 μm and a minimum corneal thickness of 450 μm, respectively.

Table 1. Demographic characteristics of enrolled patients

Variable	Value
Age (y), Mean ±SD (Range)	26.5 ± 4.5 (19 to 35)
Sex (Male / Female), n (%)	7 (47) / 8 (53)

Abbreviations: y, year; SD, standard deviation; n, number of participants; %, percentage.

Table 2. Functional, tomographic, and structural corneal parameters before and one month after accelerated corneal collagen cross-linking

Variable	Baseline	1-month post CXL	Mean Difference (Post – Pre)	*P*-value
UCDVA (decimal), Mean ± SD, Median (IQR)	0.46 ± 0.23, 0.50 (0.30 to 0.60)	0.49 ± 0.30, 0.50 (0.30 to 0.60)	+ 0.03	**0.007**
CDVA (decimal), Mean ± SD, Median (IQR)	0.56 ± 0.23, 0.60 (0.40 to 0.78)	0.58 ± 0.24, 0.60 (0.40 to 0.78)	+ 0.02	**0.025**
IOP (mmHg), Mean ± SD, Median (IQR)	19.3 ± 1.1, 20.0 (19.0 to 20.0)	19.2 ± 1.2, 19.0 (18.3 to 20.0)	- 0.1	**0.025**
Kflat (D), Mean ± SD, Median (IQR)	44.3 ± 2.3, 43.9 (43.3 to 46.0)	44.2 ± 2.3, 43.8 (43.0 to 45.9)	- 0.1	**0.001**
Ksteep (D), Mean ± SD, Median (IQR)	49.6 ± 3.4, 50.2 (47.4 to 51.5)	49.5 ± 3.3, 50.0 (47.4 to 51.4)	- 0.1	**0.007**
Kmean (D), Mean ± SD, Median (IQR)	46.7 ± 2.3, 47.1 (44.7 to 48.0)	46.5 ± 2.2, 47.1 (45.3 to 48.0)	- 0.2	**0.002**
CCT (µm), Mean ± SD, Median (IQR)	495.9 ± 39.5, 487.5 (464.0 to 534.0)	484.1 ± 35.5, 485.0 (459.0 to 517.3)	- 11.8	**0.001**
Epithelial thickness (µm), Mean ± SD, Median (IQR)	47.2 ± 3.0, 47.0 (45.0 to 50.0)	46.4 ± 2.9, 46.0 (45.0 to 49.0)	- 0.8	**0.002**
Demarcation line depth (µm), Mean ± SD, Median (IQR)	-	226.3 ± 57.6, 214.5 (171.0 to 274.3)	-	-

Abbreviations: CXL, corneal collagen cross-linking; UCDVA, uncorrected distance visual acuity; CDVA, corrected distance visual acuity; IQR, interquartile range; SD, standard deviation; IOP, intraocular pressure; mmHg, millimetres of mercury; Kflat, flat keratometry; Ksteep, steep keratometry; Kmean, mean keratometry; D, diopters; CCT, central corneal thickness; µm, micrometre.

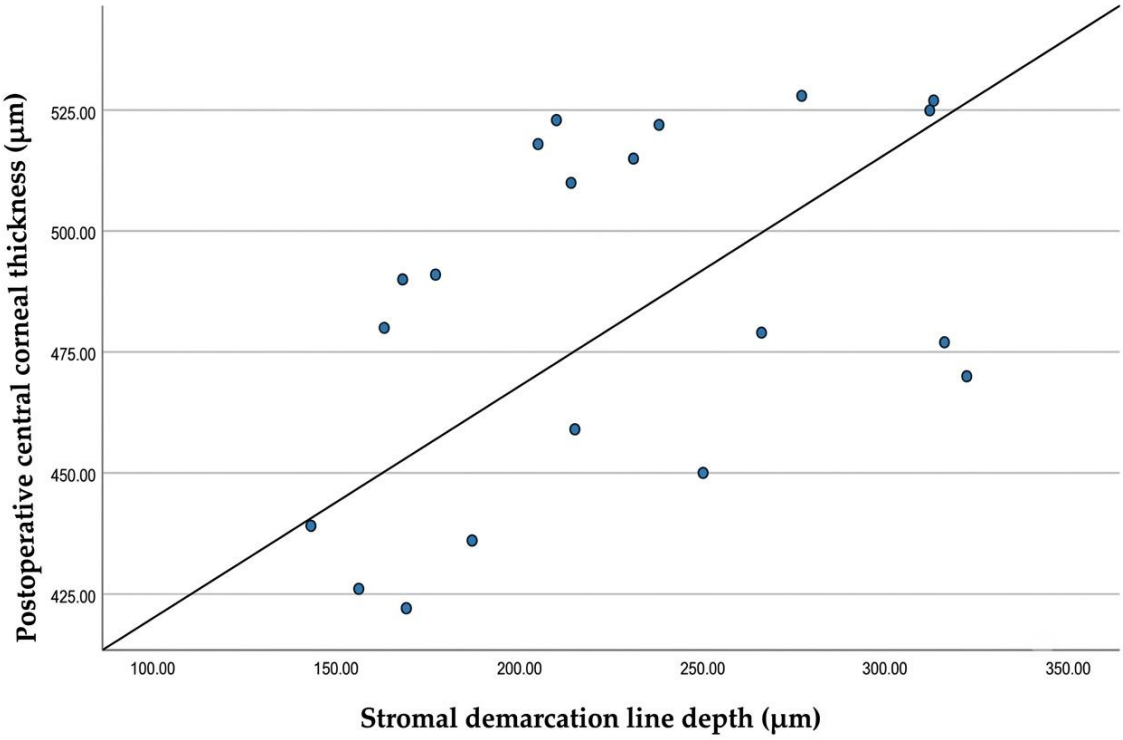

Figure 1. Association between stromal demarcation line depth and postoperative central corneal thickness (CCT) one month following accelerated epithelium-off corneal collagen cross-linking. A significant moderate positive association was observed between stromal demarcation line depth and postoperative CCT (Spearman's ϱ = 0.433, *P* = 0.017), indicating that eyes with greater corneal thickness tend to exhibit deeper stromal demarcation lines.

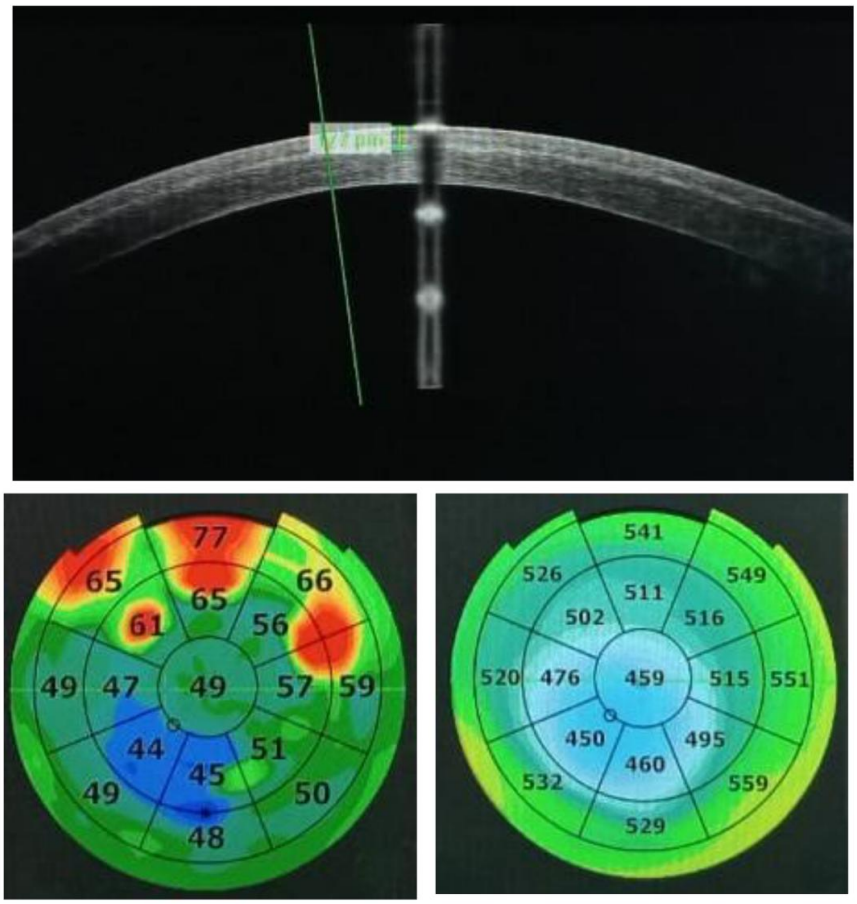

Figure 2. Representative anterior segment optical coherence tomography (AS-OCT) image obtained using a spectral-domain device (REVO FC 130; Optopol Technology, Zawiercie, Poland), randomly selected from among the study eyes to illustrate the typical postoperative appearance, acquired one month after accelerated epithelium-off corneal collagen cross-linking (CXL) in an eye with progressive keratoconus. A distinct stromal demarcation line is visible at a depth of approximately 177 μm. Corresponding epithelial thickness and pachymetry maps show a central epithelial thickness of 49 μm and a minimum corneal thickness of 450 μm, respectively.

DISCUSSION

The present study evaluated early corneal changes following accelerated epithelium-off CXL in progressive keratoconus using AS-OCT. At one month, treatment was associated with significant reductions in CCT and epithelial thickness, modest improvements in visual acuity, and minimal changes in corneal curvature. Median stromal demarcation line depth was 214.5 μm, and deeper demarcation lines were significantly associated with greater preoperative and postoperative CCT, suggesting an association between corneal thickness and the extent of stromal treatment penetration following CXL. These findings provide further insight into the early structural response of the cornea following accelerated CXL.

The median (IQR) stromal demarcation line depth in the present study was 214.5 (171.0–274.3) μm one month following accelerated epithelium-off CXL. This value is comparable to the 209.1 (49.6) μm reported by Ng et al. [23], who used AS-OCT to assess eyes with progressive keratoconus treated with an accelerated protocol employing the same irradiance (9 mW/cm² for 10 minutes) after a mean follow-up of 12 months—although both studies evidenced shallower demarcation lines than those observed following the conventional Dresden protocol (282.9 [66.9] μm) [23]. Similarly, Kirgiz et al. [24] reported a mean AS-OCT demarcation line depth of 228.03 (36.74) μm 12 months following accelerated CXL with 18 mW/cm² for 5 minutes, whereas a significantly deeper demarcation line (279.86 [31.95] μm) was observed in eyes treated with 9 mW/cm² for 10 minutes [24]. Tomita et al. [25], using AS-OCT one month postoperatively, reported a mean demarcation line depth of 294.38 (60.57) μm following accelerated CXL (30 mW/cm² for 3 minutes), compared with 380.78 (54.99) μm after conventional CXL, although the difference between the two treatment groups did not reach statistical significance [25]. Likewise, Kymionis et al. [26] reported greater AS-OCT demarcation line depths one month postoperatively, measuring 337.00 (46.46) μm and 322.91 (48.28) μm following conventional and modified accelerated protocols, respectively, for eyes with progressive keratoconus, with no significant difference between treatment groups [26]. Differences among studies may reflect variations in irradiation protocols, riboflavin formulations, postoperative assessment intervals, and baseline corneal characteristics, suggesting that stromal demarcation line depth is influenced by multiple procedural and patient-related factors and should be interpreted within the context of the specific CXL protocol employed.

In the present study, stromal demarcation line depth displayed a significant positive correlation with both preoperative and postoperative CCT, whereas no significant associations were observed with preoperative or postoperative epithelial thickness. These findings suggest that greater CCT may be associated with deeper stromal treatment penetration following accelerated CXL. Direct comparison with previous studies is challenging because the variables examined have differed considerably. Ng et al. [23] reported a significant correlation between demarcation line depth and changes in Kmean, but not Kmax, suggesting that deeper stromal treatment effects may be associated with greater corneal flattening [23]. In contrast, despite observing differences in demarcation line depth among treatment protocols Bouheraoua et al. [27] found no significant correlations between demarcation line depth and changes in best spectacle-corrected visual acuity, Kmax, or CCT 6 months following CXL. Similarly, Yam et al. [16] reported no significant associations between demarcation line depth and changes in CDVA or steepest keratometry, although shallower demarcation lines were associated with thinner corneas, older age, more advanced ectasia, and longer disease duration [16]. The discrepancy among studies may reflect differences in CXL protocols, patient characteristics, follow-up duration, and outcome measures. Nevertheless, although stromal demarcation line depth is widely regarded as an indirect measurement of treatment penetration [15, 28], its association with postoperative clinical and tomographic outcomes remains a subject of debate.

Modest improvements in UCDVA and CDVA were observed one month after accelerated epithelium-off CXL in the present study. Although the degree of visual improvement was modest, our findings concord with those of Kirgiz et al. [24], who showed significant improvements in both uncorrected and best-corrected visual acuities 12 months following accelerated CXL using either 9 mW/cm² for 10 min or 18 mW/cm² for 5 min. Similarly, Ng et al. [23] showed a significant improvement in CDVA following conventional CXL, although no significant visual improvement was observed in their accelerated CXL cohort after a mean follow-up of approximately 12 months. Ozgurhan et al. [29] also reported improvements in both UCDVA and CDVA after accelerated CXL in thin keratoconic corneas during 12 months of follow-up, though the magnitude of these changes was limited [29]. Regarding corneal curvature, the present study demonstrated modest reductions in keratometric parameters at one month. This limited early topographic response is not unexpected, given the short follow-up period. In contrast, studies with longer follow-up have reported more pronounced keratometric flattening, including significant reductions in Kmean and Kmax after conventional CXL [23]; significant improvements in Kflat, Ksteep, and average keratometry following accelerated CXL [24]; and reductions in flat, steep, and apex keratometry after 12 months of follow-up [29]. Collectively, these findings suggest that visual and topographic improvements may continue to evolve beyond the early postoperative period.

A significant reduction in CCT and epithelial thickness was observed one month after treatment in our study. Early postoperative corneal thinning has been reported following CXL and is generally considered part of the corneal healing and remodeling response, with an initial decrease in corneal thickness followed by partial recovery over subsequent months [30]. Although the present study lacked long-term follow-up, the observed decrease in corneal thickness is consistent with previous evidence indicating dynamic structural changes during the early postoperative phase. In a meta-analysis of 22 studies including 1158 eyes, Shajari et al. [31] reported no significant difference in CCT between conventional and accelerated CXL at final follow-up, suggesting that corneal thickness may partially recover over time despite early postoperative thinning [31]; moreover, accelerated CXL was associated with less corneal thinning than conventional treatment, supporting the notion that different irradiation protocols may influence the extent of postoperative stromal remodeling. More recently, a systematic review and meta-analysis by Qureshi et al. [28] found no significant differences in CCT between pulsed and continuous CXL protocols at 12 months, despite differences in ultraviolet irradiation delivery, further suggesting that long-term corneal thickness outcomes may converge across treatment modalities [28]. The observed changes in corneal and epithelial thickness likely reflect early postoperative tissue remodeling after CXL and are consistent with the expected healing response of the cornea.

Strengths of this study include its prospective design and the use of AS-OCT to provide detailed quantitative assessment of early corneal structural changes following accelerated epithelium-off CXL. Several limitations should be acknowledged. The relatively small sample size and 1-month follow-up period limit evaluation of long-term structural and visual outcomes. In addition, the inclusion of both eligible eyes may have introduced inter-eye correlation and affected statistical independence. Finally, the absence of effect size estimates and 95% confidence intervals limits assessment of the magnitude and precision of the observed effects. Future multicenter studies with larger cohorts, extended follow-up, and appropriate statistical methods accounting for within-subject correlation are warranted. Further investigation is also needed to clarify the relationship between stromal demarcation line depth and long-term clinical and tomographic outcomes, which remains a subject of ongoing debate.

CONCLUSIONS

Accelerated epithelium-off CXL was associated with early corneal structural changes in eyes with progressive keratoconus, including reductions in CCT and epithelial thickness, accompanied by modest improvements in visual acuity and minimal changes in corneal curvature. AS-OCT enabled detailed visualization and quantitative assessment of the stromal demarcation line, with a median depth of 214.5 μm one month postoperatively. The positive correlation observed between

demarcation line depth and both preoperative and postoperative CCT suggests that corneal structural characteristics may influence the extent of stromal treatment penetration. These findings support the utility of AS-OCT as a non-invasive modality for monitoring early postoperative corneal changes following CXL, and provide further insight into early corneal response to treatment. Further studies in similar populations with larger sample sizes, longer follow-up periods, and appropriate comparison groups are warranted to validate these preliminary findings.

ETHICAL DECLARATIONS

Ethical approval: The study protocol received approval from the Research Ethics Committee of the Faculty of Medicine, Port Said University (Approval No. 243/OPT824_007; approved 9 February 2025). Written informed consent was obtained from all participants before study enrollment. The study adhered to the tenets of the Declaration of Helsinki and its subsequent amendments. All data were de-identified prior to analysis to maintain participant confidentiality. Separate consent for publication was obtained from participants whose clinical images were included in this report.

Conflict of interests: None.

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