Contact Lens and Anterior Eye 49 (2026) 102688

Contents lists available at ScienceDirect

Contact Lens and Anterior Eye

journal homepage: www.elsevier.com/locate/clae

Comparison of corneoscleral topographic consistency in eyes with low-to-moderate and high astigmatism

Ziwei Xiang [e,1], Danjie Han [f,1], Dantong Gu [g,1], Yishan Qian [a,b,c,d,*], Zhi Chen [a,b,c,d,*]

[a] Eye Institute and Department of Ophthalmology, Eye and ENT Hospital, Fudan University, Shanghai 200031, China
[b] NHC Key Laboratory of Myopia (Fudan University), Key Laboratory of Myopia, Chinese Academy of Medical Sciences, Shanghai 200031, China
[c] Shanghai Research Center of Ophthalmology and Optometry, Shanghai 200031, China
[d] Shanghai Key Laboratory of Visual Impairment and Restoration, Shanghai 200031, China
[e] Shanghai Medical College, Fudan University, Shanghai, China
[f] School of Health Science and Engineering, University of Shanghai for Science and Technology, Shanghai 200093, China
[g] Clinical Research Unit of Eye & ENT Hospital, Fudan University, Shanghai, China

ARTICLE INFO

Keywords:
Corneoscleral topography
Astigmatism
Scleral lenses

ABSTRACT

Purpose: This study aimed to compare the corneoscleral topographic consistency between eyes with low-to-moderate and high refractive astigmatism (RA).

Methods: A total of 131 eyes of 69 participants with astigmatism (51 females and 18 males) and no ocular diseases or history of ocular surgery were included in this study. Participants were divided into a low-to-moderate astigmatism (LMA) group ($|RA| \leq 2.50$ D; mean 1.57 ± 0.71 DC; $n = 94$ eyes) and a high astigmatism (HA) group ($|RA| > 2.50$ D; mean 3.72 ± 1.08 DC; $n = 37$ eyes). Corneoscleral topography was acquired via Anterior Segment Analyzer (Scansys TA517). The measurement repeatability at 8-mm and 14-mm chord lengths was examined using Bland-Altman approach. Intraclass correlation coefficient (ICC) between the corneal and scleral shapes was used to calculate corneoscleral topographic consistency. Inter-eye ICC of corneoscleral shape were compared in participants exhibiting a marked interocular astigmatic asymmetry (≥ 1.50 DC).

Results: The 8-mm chord lengths demonstrated superior repeatability, with narrower limits of agreement (LoA: 0.356 ± 0.029 mm; range 0.312 to 0.406 mm) compared to the 14-mm chord (LoA: 0.541 ± 0.058 mm; range 0.429 to 0.648 mm). The eyes with HA showed stronger corneoscleral topographic consistency (mean ICC = 0.54 ± 0.19) than those with LMA (mean ICC = 0.34 ± 0.37, $t = -3.96$, $p < 0.001$). In participants with interocular astigmatic asymmetry, the eye with greater astigmatic power exhibited a significantly higher corneoscleral topographic consistency (mean ICC = 0.67 ± 0.20) than the contralateral eye (mean ICC = 0.32 ± 0.24, $t = 3.09$, $p = 0.01$).

Conclusion: Eyes with HA exhibited greater corneoscleral topographic consistency than those with LMA. This finding may help with scleral lens fitting in participants with corneal and refractive astigmatism in the absence of scleral shape data.

1. Introduction

The morphology of the cornea and sclera is interdependent given their shared role in maintaining ocular shape. Under certain pathological conditions involving corneal deformation, the sclera also exhibits morphological alterations. The sclera appears to be more irregular and steeper in eyes with keratoconus and corneal ectasia [1–3]. Also, differences between the nasal and temporal sagittal height of sclera were remarkably higher in eyes of participants with keratoconus [4]. It is also noteworthy that the orientation and severity of deformation in cornea and sclera are highly associated. Previous research has found that in astigmatic eyes, asymmetry of cornea and sclera is highly correlated, whereas in normal eyes, this is not the case [5]. The flat corneal and scleral meridians were highly consistent in eyes with high astigmatism

* Corresponding authors.
E-mail addresses: 20301050259@fudan.edu.cn (Z. Xiang), 13917852240@163.com (Y. Qian), peter459@aliyun.com (Z. Chen).
[1] These authors have contributed equally to this work and share first authorship.

https://doi.org/10.1016/j.clae.2026.102688
Received 24 March 2026; Received in revised form 15 May 2026; Accepted 4 June 2026
Available online 16 June 2026
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[6]. In keratoconus, the steepest corneal and scleral regions share spatial consistency [7]. Therefore, it may be speculated that corneoscleral topographic consistency was related to corneal deformation severity.

Scleral lenses are widely used for visual rehabilitation in eyes with irregular corneal optics, such as keratoconus [8], corneal ectasia [9], and post-keratoplasty corneas [10], because they vault the corneal surface and create a tear reservoir that improves optical quality. Under these circumstances, scleral lenses emerge as the best option that can markedly improve visual acuity [11].

However, the fitting of scleral lenses still presents many difficulties. The human sclera exhibits morphological variability among individuals, which can be roughly classified into four distinct types: spherical (5.7%), regular toric (28.6%), quadrant-specific (40.7%) and irregular (26%) [12], making it important to fit scleral lenses based on parameters of scleral structure, including toricity, sagittal height and radius of curvature [13]. Although optical coherence tomography and scleral topographers can provide objective measurements of ocular surface anatomy beyond the corneal area, these devices are still not widely used in clinical practice worldwide [14]. Current fitting strategy relies heavily on clinical experience, which often leads to prolonged chair times and multiple lens trials. Improper scleral lens fit can result in complications such as lens decentration [15], impingement, and mid-day fogging [16]. Therefore, there is an urgent need for a more convenient way to predict the scleral shape by obtaining corneal topographic data.

Hence, this study aimed to explore the corneoscleral topographic consistency in participants with high astigmatism (HA) compared to those with low-to-moderate astigmatism (LMA).

2. Methods

2.1. Participants

This cross-sectional study was performed at the Eye and ENT Hospital of Fudan University, Shanghai, China. This study adhered to the principles of the Declaration of Helsinki. The research protocol was reviewed and approved by the Ethics Committee of the Eye & ENT Hospital of Fudan University (No. 2021004). Participants aged 17 to 42 years with refractive astigmatism were enrolled and further divided into LMA ($|RA| \leq 2.50$ D; mean 1.57 ± 0.71 DC; $n = 94$ eyes) group and HA ($|RA| > 2.50$ D; mean 3.72 ± 1.08 DC; $n = 37$ eyes) group (Fig. 1). This threshold was aligned with a commonly used classification ~~that defined LMA as >– 2.75 DC and HA as ≤– 2.75 DC~~ based on previously published studies [17,18]. Interocular astigmatic asymmetry was defined as an interocular difference of astigmatism ≥1.50 DC between the two eyes of one participant.

All participants were free of ocular diseases and had no history of ocular surgeries. Eyes with irregular astigmatism (e.g., keratoconus, pellucid marginal degeneration) or corneal scarring were excluded. Those who wore rigid contact lenses were excluded and soft contact lens wearers were required to discontinue lens wear for at least 1 day before examination. All participants underwent a comprehensive ophthalmic examination, including slit-lamp examination, uncorrected visual acuity (UCVA), non-cycloplegic autorefraction and subjective refraction, and corneoscleral topography. No formal sample size calculation was performed because this was an exploratory cross-sectional study. All eligible participants with qualified corneoscleral topography data during the study period were included.

2.2. Data collection

Corneoscleral topography was measured with a novel Anterior Segment Analyzer (Scansys TA517, MediWorks, Shanghai, China). This equipment adopts an ultra-high-definition Scheimpflug camera. The scleral lens module employed can generate 60 high-definition anterior segment Scheimpflug images within 2 s and cover a 16-mm-diameter corneoscleral area centered on the corneal vertex normal. Scansys was reported to have high agreement with an anterior segment optical coherence tomographer (CASIA 2) in the measurements of the ocular anterior segment [19]. It has also been reported that Scansys measurements of certain ocular biometric parameters, such as anterior chamber depth, pupil-center pachymetry, central corneal thickness and keratometry were interchangeable with the Pentacam HR tomography (Oculus, Wetzlar, Germany) [20].

Before measurements, eyelids of participants were held open gently and manually by examiners while ensuring no pressure was applied to the eyeball. Each eye was scanned three times at 5-min intervals by the same examiner. Qualified images were identified as coverage >90% within 16-mm diameter. The scan with the largest coverage was included for corneoscleral topographic consistency analysis. For repeatability test, at least two qualified scans had to be available for one eye, with the best-fit-sphere difference < 0.1 mm between scans.

2.3. Corneoscleral data processing

The coordinates and sagittal height of each point were exported into

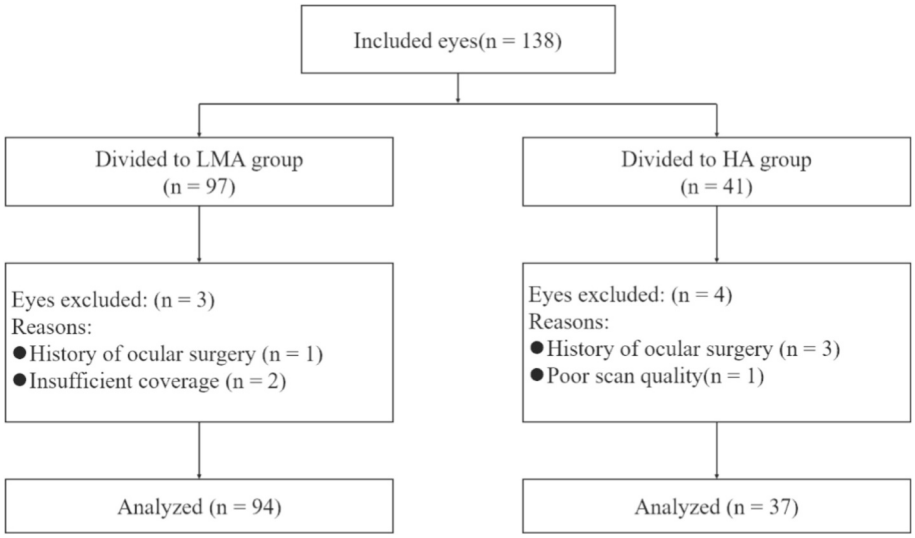


Fig. 1. Inclusion and exclusion flowchart.

a spreadsheet. The sagittal height data at the chord lengths of 8-mm and 14-mm were extracted and connected using curves (Fig. 2), representing the contour of cornea and sclera. The 8-mm chord was often used to represent the contour of mid-peripheral cornea, e.g., in orthokeratology contact lens fitting [21]. The 14-mm chord extends beyond the limbus into the anterior sclera, providing partial morphological information of the scleral shape with acceptable repeatability. Because the Scansys TA517 acquires 60 Scheimpflug images, sagittal height values at every 1° meridian were not directly measured. The exported sagittal height data were therefore processed in R, where smoothed interpolation was performed along each chord length to reconstruct continuous sagittal-height curves. These reconstructed curves were subsequently resampled at 1° intervals from 0° to 359° for repeatability and corneoscleral topographic consistency analyses.

The repeatability of sagittal height measurements using Scansys at 8-mm and 14-mm chord lengths was examined in 87 eyes with at least two qualified images. Among the 131 eyes included in the final analysis, 87 eyes had at least two qualified scans meeting the predefined image-quality criteria and were therefore included in the repeatability analysis. The remaining eyes had only one qualified scan as the other repeated scans did not qualify due to insufficient coverage, motion artifacts, blinking, etc. Because 360 points were sampled along each chord, repeatability was calculated on an angle-by-angle basis. For each meridian, the upper and lower 95% Limits of Agreement (LoA) were calculated as the mean difference ± 1.96 SD. The LoA span was defined as the distance between the upper and lower LoA, and the LoA half-width (LoA HW) was defined as half of this span using the Bland-Altman approach.

2.4. Statistical analysis

The statistical analysis was performed using IBM SPSS Statistics (version 20.0; IBM Corp, Armonk, NY). To quantify corneoscleral topographic consistency, intraclass correlation coefficients (ICCs) between the sagittal height curves at the 8-mm and 14-mm chords were calculated. The ICCs were estimated using a generalized linear model framework, with higher values indicating better agreement between the corneal and scleral contours. Differences in ICC values between the low-to-moderate astigmatism (LMA) and high astigmatism (HA) groups were assessed using Welch's *t*-test. For participants with interocular astigmatic asymmetry, a paired t-test was used to compare the ICCs of the two eyes. The normality of the paired differences was verified with the Shapiro-Wilk test. A *p*-value <0.05 was considered statistically significant.

3. Results

3.1. Baseline demographics

The baseline data of this study are presented in Table 1. Measurements were taken in 131 eyes of 69 participants who met the inclusion criteria. The remaining 7 eyes were excluded due to a history of ocular surgery, insufficient coverage or poor scan quality. The mean age of LMA and HA groups were 28.3 ± 5.3 and 25.8 ± 6.1 years respectively ($t = 2.17$, $p = 0.034$). The flat keratometry (K1) and steep keratometry (K2) were 42.70 ± 1.40 D and 44.55 ± 1.68 D for the LMA group, 42.59 ± 1.40 D and 45.71 ± 1.44 D for the HA group, respectively. The mean refractive astigmatism was significantly lower ($t = 11.25$, $p < 0.001$) in the LMA group (1.57 ± 0.71 DC) than in the HA group (3.72 ± 1.08 DC), while the spherical equivalent was comparable between the two groups (−8.77 ± 2.82 DS and − 8.69 ± 2.11 DS, respectively; $t = 0.19$, $p = 0.850$).

3.2. Repeatability of Scansys measurements of sagittal height at 8-mm and 14-mm chord lengths

When repeatability was assessed using the Bland-Altman approach, the 8-mm chord consistently demonstrated superior repeatability. For the 8-mm chord lengths, the mean LoA span was 0.356 ± 0.029 mm (median 0.356 mm; range 0.312–0.406 mm), and the LoA half-width was 0.178 ± 0.014 mm (median 0.178 mm; range 0.156–0.203 mm) across 360°. For the 14-mm chord lengths, the mean LoA span increased to 0.541 ± 0.058 mm (median 0.543 mm; range 0.429–0.648 mm), with a corresponding LoA half-width of 0.271 ± 0.029 mm (median 0.272 mm; range 0.215–0.324 mm). These results indicated that Scansys provided better absolute repeatability at the 8-mm chord. Detailed angle-by-angle profiles of LoA span and LoA half-width were shown in Fig. 3.

Table 1
Baseline demographics.

	Total	LMA group	HA group	*p* value
Sample size (eyes included)	131	94	37	
Age (years), mean ± SD		28.3 ± 5.3	25.8 ± 6.1	0.034
Flat keratometry (K1, D), mean ± SD		42.70 ± 1.40	42.59 ± 1.40	
Steep keratometry (K2,		44.55 ± 1.68	45.71 ± 1.44	
Refractive astigmatism (DC), mean ± SD		1.57 ± 0.71	3.72 ± 1.08	<0.001
Spherical equivalent (DS), mean ± SD		−8.77 ± 2.82	−8.69 ± 2.11	0.85

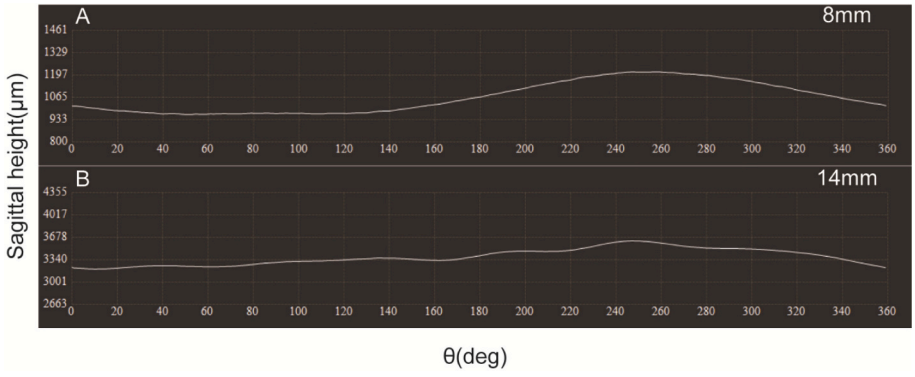


Fig. 2. The sagittal height along 360° at two chord lengths (A. 8-mm representing the mid-peripheral cornea, and B. 14-mm representing the sclera). Sagittal height data was sampled at 1° interval and connected as two curves.

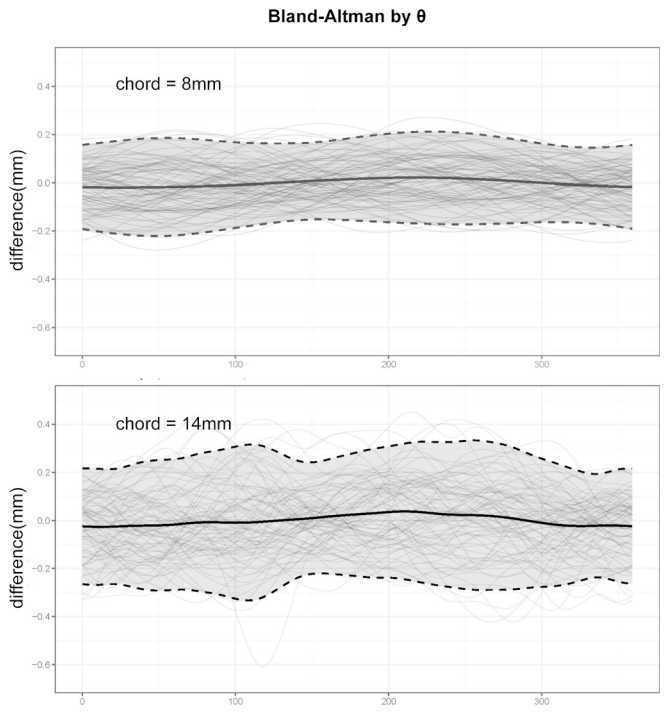


Fig. 3. Bland-Altman results of how repeatability varied with θ across 360° at the 8-mm and 14-mm chord lengths measured by Scansys. The light-gray curves represented the Bland-Altman results for each eye. The thick black curve represented the mean difference at each θ. The shaded gray area indicated the 95% limits of agreement.

3.3. *Corneoscleral topographic consistency of eyes with LMA and HA*

The HA eyes exhibited significantly higher corneoscleral topographic consistency (mean ICC = 0.535 ± 0.190) than the LMA eyes (mean ICC = 0.339 ± 0.371; $t = -3.96$; $p < 0.001$) as shown in Fig. 4.

3.4. *Interocular comparison of corneoscleral topographic consistency in participants with interocular astigmatic asymmetry*

A total of 9 participants exhibited interocular astigmatic asymmetry of ≥1.50 D and were included in the paired-eye analysis. In these participants, the eyes with higher astigmatic power showed significantly greater corneoscleral topographic consistency (mean ICC = 0.67 ± 0.20) than the fellow eyes (mean ICC = 0.32 ± 0.24; $t = 3.09$; $p = 0.01$, Fig. 5).

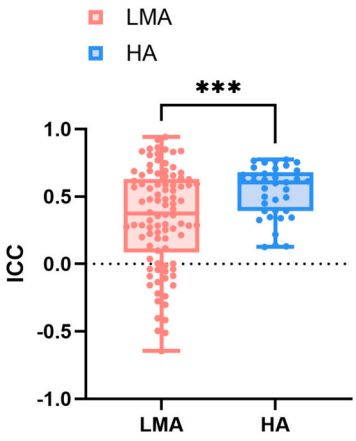


Fig. 4. Box plot comparing corneoscleral topographic consistency (ICC) between low-to-moderate (LMA) and high astigmatism (HA) groups. *** $p < 0.001$.

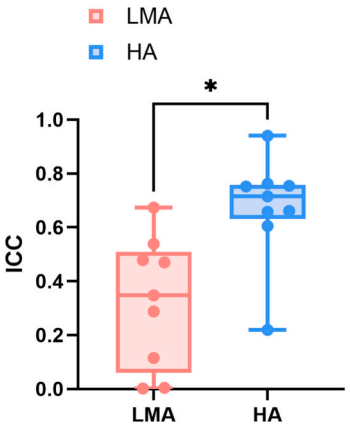


Fig. 5. Interocular comparison of corneoscleral topographic consistency (ICC) in participants with interocular astigmatic asymmetry. * $p = 0.01$.

4. Discussion

This study investigated the consistency between corneal and scleral sagittal height curves at 8-mm and 14-mm chords. The results demonstrated that eyes with HA (|RA| > 2.50 D) exhibited significantly stronger corneoscleral topographic consistency than those with LMA (|RA| ≤ 2.50 D). Furthermore, in participants with interocular astigmatic asymmetry, the eyes with higher astigmatic power showed greater corneoscleral topographic consistency compared to the fellow eyes. These findings suggested that corneal topography may reliably predict scleral shape in HA but not in LMA.

In this study, a novel device, Scansys TA517 Anterior Segment Analyzer (MediWorks, Shanghai, China), was used to measure corneal and scleral shape. Scansys was reported to show high agreement with anterior segment optical coherence tomographer (CASIA 2) and another Scheimpflug-based tomographer (Pentacam HR, Oculus, Wetzlar, Germany) in the measurements of the anterior segment with excellent repeatability [22,23]. Given that the anterior segment measurements of Fourier-based profilometry and Scheimpflug imaging are not interchangeable [24,25], the agreement between Scansys and ESP remains to be explored. The 14-mm chord length was adopted to represent scleral morphology because sagittal heights at 13–15-mm chord lengths have been used in corneoscleral profilometry studies to quantify scleral asymmetry [26]. Moreover, measurement repeatability at the 14-mm chord is generally acceptable but tends to decline in the more peripheral scleral region [27,28].

The current study is consistent with previous researches indicating corneoscleral topographic consistency in eyes with corneal pathology or significant refractive error [1,3–7]. However, other studies argued that it was difficult to predict the scleral shape from corneoscleral topography [29]. One study pointed out that corneal parameters incompletely predict the sagittal height of sclera at the chord length ≥ 14–15 mm, with clinically significant discrepancies between sagittal heights computed from corneal parameters and those measured directly by ocular profilometry [30]. These differences may be explained by differences in measurement devices, analytical methods, and participant ethnicity. The current study measured and analyzed resampled 360° sagittal-height profiles, while other studies mostly focused on sagittal elevation or absolute sagittal height at certain points [5,7]. The participants of the current study were recruited from a Chinese population, representing an Asian cohort, therefore the findings may not be directly generalizable to non-Asian populations such as Caucasian populations. [31].

The stronger corneoscleral topographic consistency in HA may be attributed to biomechanical coupling of the anterior eye segment. It was reported that a patient with keratoconus exhibited a significant change in the scleral elevation pattern at 16-mm chord lengths after collagen

crosslinking [32]. The reduced consistency in LMA may reflect a more independent variation between corneal and scleral shapes, possibly due to milder biomechanical influences or greater anatomical individual variability. The interocular comparison in participants with interocular astigmatic asymmetry, which showed different degrees of corneoscleral topographic consistency within the same individual, suggested that discrepant developmental patterns may exist between the two eyes.

For scleral lens fitting, the high corneoscleral topographic consistency in HA suggested that corneal topography can serve as a feasible reference for estimating scleral shape, particularly in institutions where scleral imaging is unavailable or impractical. This approach may reduce dependence on invasive scleral exposure maneuvers (e.g., eyelid retractor use), shorten chair time, decrease the number of trial lenses required, improve fitting efficiency and patient comfort, especially in primary care or resource-limited communities.

This study has a few limitations. Firstly, it focused on sagittal height consistency along two chord lengths of the ocular surface. A more comprehensive analysis encompassing multiple chord lengths would provide a holistic understanding of corneoscleral topography. Secondly, this study only included participants without ocular disease or surgery. Hence, results may not be generalized to pathological conditions such as keratoconus or post-surgical cases. Lastly, given the well-documented ethnic variations in corneal and scleral shape [33], the findings may not be directly generalizable to other ethnic groups.

In conclusion, in this Chinese population, adults with HA had significantly higher corneoscleral topographic consistency than those with LMA. This structural feature may support the potential use of corneal topography as a predictive tool for scleral shape in patients with HA, thereby improving the efficiency of scleral lens fitting.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors thank Bingjie Wang for language edit.

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