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Corneoscleral junction angle in healthy eyes assessed objectively

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ABSTRACT

Purpose: To introduce a fully objective method to measure corneoscleral junction (CSJ) angle and evaluate the CSJ angle in healthy eyes.
Methods: Corneoscleral topography (Eye Surface Profiler, ESP) was acquired from the right eye of 105 healthy Caucasian subjects, ranging from 18 to 59 years old. From the raw anterior eye height data, the topographic limbus was automatically demarcated in 360 semi-meridians. Further, in limbal location, the CSJ angle was automatically calculated from corneoscleral height data using neighbouring auxiliary points for angle calculation. Additionally, CSJ angle was statistically analysed regionally.
Results: The mean CSJ angle was $177.5 \pm 1.1^\circ$. There is a mean difference of $7.7 \pm 3.7^\circ$ between the steepest (smallest) and flattest (largest) CSJ angle within the same eye. There exist statistically significant differences between temporal ($178.2 \pm 1.4^\circ$) and nasal ($176.4 \pm 1.1^\circ$) regions (paired *t*-test, $p < 0.001$), and between superior ($178.1 \pm 1.1^\circ$) and inferior ($177.9 \pm 1.1^\circ$) regions ($p = 0.038$). CSJ angle is correlated with limbus position ($r = 0.43$, $p < 0.001$).
Conclusion: CSJ angle is rotationally asymmetric. CSJ varies regionally, being the smallest (steepest) in the nasal region. Significant rough changes in CSJ angle were observed for some healthy individuals.

1. Introduction

The transition from the cornea to the sclera has been defined as a clinically non-obvious sulcus of 1.5 to 2 mm where both structures meet. Anatomically and histologically, this sulcus consists of overlying episclera and conjunctiva externally and the limbus internally. The latest is a very important structure from a physiological perspective since it contains adult stem cell populations for the cornea and the conventional outflow pathway for the aqueous humour at the trabecular meshwork [1].

Geometric differences between the cornea and the sclera have been documented, with the radius of curvature of both structures being significantly different [2–6]. Such geometrical differences compose the transition area. Since the sclera is significantly flatter than the cornea [2–6], the use of tangent angles has been proposed to describe the corneoscleral transition [7] Therefore, the term corneoscleral junction (CSJ) angle has been commonly used to describe the transition between the cornea and the sclera, specifically in the contact lens field [8].

When fitting contact lenses, the CSJ angle is relevant for all those lenses that land beyond the cornea, which specifically happens with soft, hybrid, and scleral lenses [8]. The CSJ angle has some impact on the sagittal height of the anterior eye, which cannot be predicted based on a mere extrapolation from the cornea [9]. Consequently, large contact lenses designed with sagittal values derived from corneal parameters may not provide an optimal fit [9,10]. A regression equation or a former measurement of the corneoscleral geometry is needed to obtain a reliable value of sagittal height [9,10]. Apart from that, when scleral lenses are designed, a transition zone between the optic zone and the landing zone is needed to fit the CSJ angle [11]. When fitting hybrid and soft lenses, in addition to being designed with transition zones as well (often

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bicurve, tricurve, or with aspherical designs) [12], some lens flexure is expected in the corneoscleral area to fit the CSJ profile [13].

Several authors have attempted to measure the CSJ angle using Optical Coherence Tomography (OCT) [14–17] and Scheimpflug imaging [18]. Using OCT, Seguí-Crespo et al and Hall et al measured the angle by means of a point-and-click calliper that an observer manually manipulated to locate the CSJ and measure the angle [14,15]. Tan et al went a step further and developed an algorithm to automatically measure the angle, although the CSJ was still located manually by an observer [16]. They described good inter-observer repeatability, but found some differences in reproducibility between different observers [16]. Moreover, measurements of the CSJ angle in these studies were taken at a single point of each quadrant.

The aim of this work was to introduce a fully objective and automated methodology to measure CSJ angle in 360°at the limbal position, assessed from 3-dimensional corneoscleral topography [19,20], and use this methodology to evaluate the mean CSJ angle in healthy eyes objectively. This novel method intends to obtain a more complete and realistic description of the transition from the cornea to the sclera than the current standards, as well as to avoid the loss of accuracy inherent to subjective criteria [21].

2. Methodology

2.1. Participants

This study was approved by the ethics committee for medical research of the Health Department of Alicante (General Hospital, Alicante, Spain) (CEIm 2021-105, ISABIAL 2021-0224) and adhered to the tenets of the Declaration of Helsinki. Fully anonymised records from 105 healthy Caucasian subjects (67 % women and 33 % men) aged between 18 and 59 years, (mean ± SD 29.8 ± 12.1 years) were collected for this retrospective study. All participants were free of ocular disease and current use of topical ocular medications. Exclusion criteria also included the presence of corneal, conjunctival, or scleral pathology or history of ocular surgery.

All participants underwent a comprehensive ophthalmologic examination, including corneoscleral topography using ESP (Eye Surface Profiler, Eaglet Eye BV, Netherlands) [22]. A single drop of Blink single dose artificial tears (Johnson & Johnson Vision, Santa Ana, CA, California, United States) was used to moisten a fluorescein strip and then the inferior, superior, and temporal bulbar conjunctiva were gently stained. An experienced technician assisted in holding up the patient's eyelids while the examiner focused and took the measurement. Only the right eyes were considered in this study to avoid any artefact in the study outcomes due to the natural correlation between fellow eyes. A single measurement per participant was considered. In addition to raw anterior eye height data, corneoscleral parameters directly acquired from ESP software were also considered: mean keratometry (K_{mean}), mean HVID ($HVID_{mean}$, Horizontal Visible Iris Diameter), BFS_{cornea} (Best Fit Sphere), and BFS_{sclera}.

2.2. Calculation of CSJ angle

The raw anterior eye height data (*x*, *y*, and *z* coordinates) were exported from the corneoscleral topographer to build three-dimensional corneoscleral topography maps [20,23]. CSJ angle measurement was calculated in 360 semi-meridians. To calculate the CSJ angle is necessary to know the limbus position. The limbus position was calculated in 360 semi-meridians using a purpose-designed algorithm as the point corresponding to a certain amount of change in the curvature between the cornea and the sclera [19,20]. The relative error for the proposed limbus demarcation method was below 0.05 % and below 1.1 % for a simulated test surface and an artificial bi-sphere, respectively [20]. Fig. 1 illustrates the methodology followed for CSJ angle calculation for each semi-meridian. After limbus demarcation, auxiliary points were

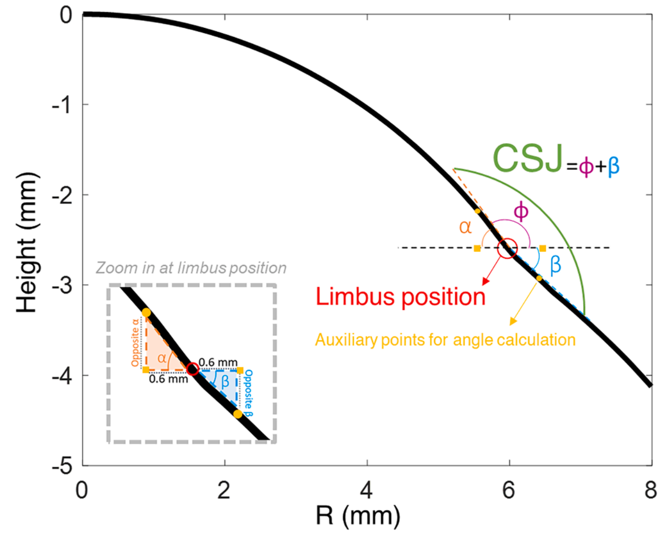

Fig. 1. Methodology for corneoscleral junction (CSJ) angle calculation. The solid black line corresponds to the corneoscleral profile in one out of 360 semi-meridians. For details on angle calculation, see text.

placed 0.6 mm horizontally away from the limbus (yellow squares in Fig. 1). The distance of the auxiliary points from the limbus position was investigated as a part of a preliminary study using a specially manufactured PMMA (poly(methyl) methacrylate)) bi-sphere test surface optimized for a blue light fringe projection system. The surface was manufactured with 1 μm accuracy. The same artificial bi-sphere test surface was previously used to assess the accuracy of the measuring instrument [22] and the algorithm for limbus position [20]. According to the manufacturer, in the artificial bi-sphere test surface the transition between spheres occurs at 6.0 mm (equivalent to limbal position) at an angle of 143.4° (equivalent to CSJ angle). The distance of the auxiliary points from the limbus for CSJ angle calculation was chosen according to this premise. Distances from 0.01 mm to 1.2 mm in steps of 0.05 mm were tested, as shown in Fig. 2. A distance of 0.6 mm resulted to be

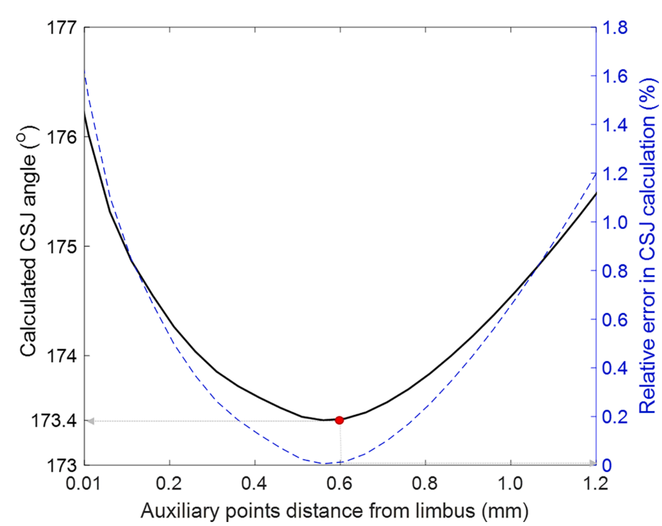

Fig. 2. Variation of the calculated CSJ angle as a function of the distance from the limbus chosen for the auxiliary points needed for CSJ angle calculation (black curve and left y-axis), along with the relative error in CSJ angle calculation depending on the distance from the limbus of the auxiliary points (blue dashed curve and right y-axis). Data was calculated from an artificial bi-sphere test surface with a known CSJ angle (173.4°). The red circle along with the gray dashed arrows indicate the distance from the limbus of the auxiliary points that optimizes CSJ angle calculation (i.e., 0.6 mm). The definition of auxiliary points for CSJ angle calculation is available in the text and illustrated in Fig. 1.

optimal for CSJ angle calculation. However, as presented in Fig. 2, the distance of the auxiliary points from the limbus is not a critical parameter for CSJ angle calculation; only if this distance is too small (<0.1 mm) or too large (>1 mm) the relative error in CSJ angle calculation is >1 %. Following auxiliary points placement, the corresponding sagittal height at the auxiliary points was measured, demarcated with yellow points in Fig. 1. Further, angle α (see Fig. 1) was evaluated as the arctangent of the adjacent, i.e., 0.6 mm, and the opposite α, calculated as the distance between the corresponding auxiliary points. The same procedure was repeated to estimate angle β (see Fig. 1). In the following, angle ϕ (see Fig. 1) was calculated as $\phi = 180°\text{-}\alpha$ (see Fig. 1). Finally, the CSJ angle was calculated as $CSJ = \phi + \beta$ (see Fig. 1). This process, illustrated in Fig. 1 for a single meridian, was custom-coded in MATLAB (MathWorks, mathworks.com) and repeated for every 360 semi-meridians.

To assess the repeatability of the proposed method, a randomly chosen participant was asked to have their right eye measured with ESP 15 times. The subject had break between measurements, ensuring new positioning and alignment for every measurement. Fluorescein instillation was added when needed. Additionally, to estimate the level of accuracy of the proposed method for CSJ angle calculation 10 measurements were performed using the artificial bi-sphere test surface previously defined.

2.3. Statistical analysis

Statistical analysis was performed using IBM SPSS software for Windows version 25.0 (IBM, ibm.com). The normality of all parameters was not rejected (Shapiro–Wilk test, $p > 0.05$). For statistical analysis, the limbus position and CSJ angle values were grouped into four 90° sectors: nasal, superior, temporal, and inferior.

Paired *t*-test was used to assess differences in CSJ angle between opposite sectors. Pearson correlation coefficient was applied to assess correlations between CSJ angle per quadrant and limbus position per quadrant, and between mean CSJ angle and age, mean limbus position (calculated using custom-made software [19,20]), and corneoscleral parameters acquired from ESP software: mean keratometry (K_{mean}), mean HVID ($HVID_{mean}$, Horizontal Visible Iris Diameter), BFS_{cornea} (Best Fit Sphere), and BFS_{sclera}. Throughout this manuscript, the terms ‘mean CSJ angle’ and ‘mean limbus position’ refer to the mean value of the corresponding parameter in 360 semi-meridians. The level of significance was set to 0.05.

To assess the repeatability of the proposed method (repeatability test in one participant and the artificial bi-sphere test surface) the coefficient of variation (CV) was calculated for limbus position and CSJ angle.

3. Results

CSJ angle is rotationally asymmetric (Fig. 3). There was a mean difference of 7.7 ± 3.7° between the steepest (smallest) and flattest (largest) angle within the same eye. However, this difference greatly depended on the individual, as it ranged from 3.5° (participants with minimal rotational variation in their CSJ angle) to 17.8° (participants with large variation in their CSJ angle; examples of such individuals can be seen in Fig. 3).

The group mean CSJ angle was 177.5 ± 1.1°, calculated as the mean of 360 semi-meridians for all participants. However, regional differences were observed. Fig. 3 shows that the CSJ angle was smaller (steeper) in the nasal region than in the remaining sectors. Table 1 shows the mean CSJ angle per quadrant. There was a significant statistically significant difference in CSJ angle between nasal and temporal quadrants (paired *t*-test, $p < 0.001$) and between superior and inferior quadrants (paired *t*-test, $p = 0.038$). Similarly, when considering the mean limbus position per quadrant (Nasal: 5.9 ± 0.3 mm, Superior: 5.8 ± 0.4 mm, Temporal: 6.0 ± 0.3 mm, Inferior: 6.2 ± 0.3 mm) a significant statistically significant difference in limbus position between nasal and temporal quadrants (paired *t*-test, $p < 0.001$) and between superior and inferior quadrants (paired *t*-test, $p < 0.001$) was found.

Mean CSJ angle and mean limbus position were moderately correlated ($r = 0.43$, $p < 0.001$). The correlation remains for every quadrant

Table 1
Mean CSJ angle per quadrant from 105 healthy participants.

Quadrant	Mean CSJ angle ± SD (°)	Range (°)	p-value (paired *t*-test)
Nasal	176.4 ± 1.1	[172.9, 178.7]	<0.001
Temporal	178.2 ± 1.4	[171.4, 180.6]	
Superior	178.1 ± 1.1	[173.3, 180.6]	0.038
Inferior	177.9 ± 1.1	[173.9, 180.9]	

>180° angle signifies a convex corneoscleral junction profile.

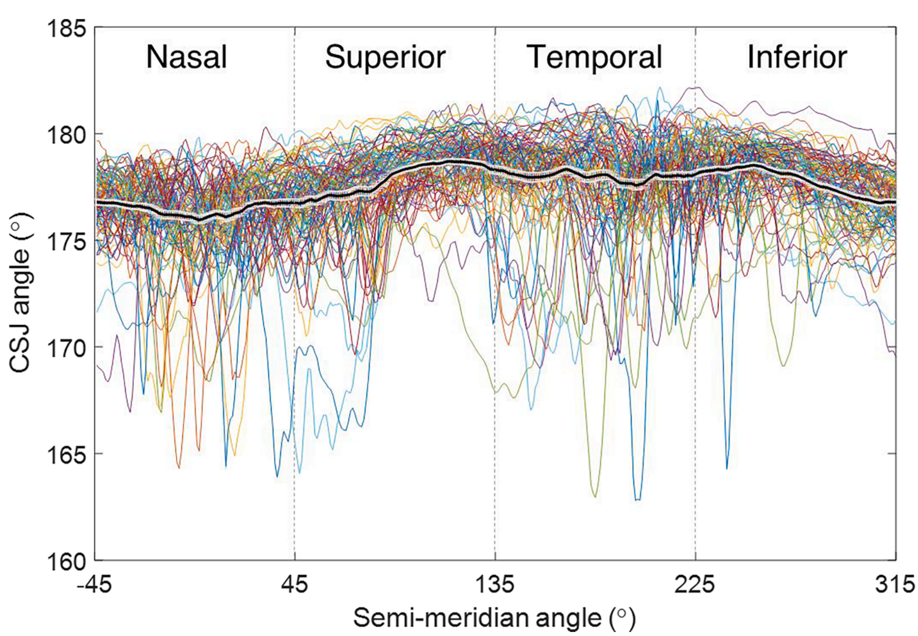

Fig. 3. Individual CSJ angle in each sector in all 105 eyes (color lines). Corresponding mean CSJ angle (black line) and error bars (in light gray) indicating ± standard error are also shown.

(Nasal: $r = 0.30$, $p < 0.001$; Superior: $r = 0.29$, $p = 0.001$; Temporal: $r = 0.37$, $p < 0.001$; Inferior: $r = 0.43$, $p < 0.001$). No correlation was found between mean CSJ and age ($r = 0.04$, $p = 0.32$), K_{mean} ($r = 0.13$, $p = 0.08$), $HVID_{mean}$ ($r = 0.12$, $p = 0.10$), BFS_{cornea} ($r = 0.16$, $p = 0.06$), or BFS_{sclera} ($r = 0.03$, $p = 0.37$). The lack of correlation between CSJ and aforementioned parameters remains when considering CSJ per quadrant.

The results from the repeatability test, where a single eye was measured 15 times, showed CV values of 0.83 % for the mean limbus position and 0.20 % for the mean CSJ angle, indicating high repeatability of the parameters. Similar results were obtained in CV for quadrant-specific CSJ angle calculation (Nasal: 0.15 %, Temporal 0.14 %, Superior 0.20 %, and Inferior 0.17 %). Similarly, when measuring the artificial bi-sphere test surface a mean limbal position of 6.0 ± 0.1 mm and CSJ angle of $(173.4 \pm 0.2)^\circ$ were achieved, in agreement with the manufacturer's indications. These results were consistent across quadrants. For the measurements performed on the artificial bi-sphere test surface, a CV of 0.10 % and 0.08 % for limbus position and CSJ angle were achieved, respectively.

4. Discussion

The CSJ angle influences sagittal height, a key parameter for ensuring a successful lens fit, specifically in large-diameter lenses such as soft and sclerals [24]. However, to date, there are only a few works characterising this parameter [6,15], and those are based on manually positioning virtual callipers on an image, making the process subjective and poorly repeatable [18]. To overcome the inherent limitations of point-and-click-based methods, in the current work we proposed a methodology for the calculation of the CSJ angle automatically and objectively from 3-dimensional corneoscleral topography data.

In the current work, the CSJ angle was calculated for each participant in 360 semi-meridians. Even though the mean CSJ angle calculated ($177.5 \pm 1.1^\circ$) was comparable to that reported in previous studies [6,14], it is important to realise that for some participants a rough transition between semi-meridians occurred, as shown in Fig. 3. The roughest (largest) transition recorded between two consecutive semi-meridians was 4°. These meaningful differences for contact lens fit would be lost if CSJ angle was calculated only in a few chosen points. Consequently, for a complete CSJ angle characterization, it is important not to restrict the calculation to a few isolated points or semi-meridians.

Using OCT and point-and-click callipers, Ritzmann et al. reported a mean CSJ angle of 178.1° analysing eight semi-meridians at a fixed chord of 12.8 mm. According to their findings, the corneoscleral angles at 12.8 mm are steeper in the nasal hemisphere than in the temporal [17]. Similarly, Hall et al. reported a mean CSJ angle of $173.7 \pm 3.1^\circ$ horizontally, and $178.3 \pm 3.1^\circ$ vertically [15]. Likewise, Seguí-Crespo et al., who exclusively analysed CSJ angle horizontally with OCT and point-and-click callipers, reported $172.4 \pm 2.8^\circ$ nasally and $177.2 \pm 2.6^\circ$ temporally [14]. In agreement with those previous works, in the current study, the mean CSJ angle nasally was statistically significantly smaller ($176.4 \pm 1.1^\circ$) than temporally ($178.2 \pm 1.4^\circ$), $p < 0.001$. Even though there exist significant methodological differences between those previous works and the current work due to the measuring principle (OCT vs Fourier profilometry) and data analysis protocol (subjective based on manual callipers vs objective based on an automatic routine), the results are still consistent. CSJ angle varies regionally, showing the smallest (steepest) value nasally.

Contrarily, Bergmann and colleagues [18], in a recent work based on Scheimpflug imaging and point-and-click callipers, did not report regional differences in CSJ angle estimated in four semi-meridians. These authors considered that this absence of differences could be attributed to the participants' young age, as some age-related differences in CSJ angle have been previously reported [14]. In the current study, no correlation was found between mean CSJ angle and age ($r = 0.04$, $p = 0.32$), even when considering mean quadrant-specific CSJ angle (all $p > 0.05$). Even though differences in imaging technology (OCT vs Fourier profilometry), methodology (point-and-click vs automatic routine), and statistical analysis (age groups vs age as a continuous variable) may justify these differences, further work based on a large age range continuous dataset should be conducted to clarify whether there exists a correlation of CSJ angle with age. Furthermore, in their work, Bergmann et al. [18] mentioned that the analysis of the CSJ angle based on Scheimpflug images is a more cost-effective alternative than OCT-based estimations. However, they also commented on the strong light backscatter at the corneoscleral region as an important inherent limitation of using Scheimpflug images to estimate CSJ angle. Corneoscleral topography based on Fourier profilometry shares with Scheimpflug imaging the affordability, but as it does not suffer from spurious backscatter at corneoscleral transition it might be a more suitable platform to calculate CSJ angle. One of the limitations of Fourier profilometry is the need for fluorescein instillation. However, according to the repeatability test performed (CV = 0.20 %), fluorescein instillation does not seem to be a limitation of the proposed method for CSJ angle calculation.

CSJ angle is not strongly correlated with other biometry parameters. Seguí-Crespo and colleagues found a weak but statistically significant correlation of the temporal CSJ angle with some biometry parameters, such as anterior chamber depth ($r = 0.25$, $p = 0.024$) or anterior chamber volume ($r = 0.25$, $p = 0.016$) [14]. In the current work, a moderate correlation between mean CSJ angle and mean limbus position was found ($r = 0.43$, $p < 0.001$). In previous work, Consejo et al. characterized the limbal position in 360 semi-meridians [19]. Their results indicated that there is a statistically significant difference between nasal and temporal limbal radial distance. An equivalent result was found between the superior and inferior quadrants [19]. In the current work, statistically significant differences between opposite quadrants were also found (Table 1). Consequently, limbus position and CSJ angle are rotationally asymmetric. These results are likely a consequence of the fact that, in opposition to the healthy cornea, the healthy sclera shows an asymmetric topography [25].

The measuring device, ESP, based on Fourier profilometry, offers consistent measurements of sagittal height data for different chord diameters [26]. The proposed method for CSJ angle calculation showed to be highly repeatable on a single participant (CV = 0.20 %) and for an artificial bi-sphere test surface (CV = 0.08 %).

In conclusion, a methodology to fully objectively measure the CSJ angle was presented in the current work. CSJ varies regionally, being the smallest (steepest) in the nasal region. Significant rough changes in CSJ angle were observed for some healthy individuals.

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.

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