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ORIGINAL PAPER

Geometrical characterization of the corneo-scleral transition in normal patients with Fourier domain optical coherence tomography

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Abstract
Purpose To characterize the geometry at the corneo-scleral transition for a normal population and its correlation with other anatomic parameters of the eyeball.
Methods Transversal epidemiologic study on a sample of 100 individuals (right eye) in different ethnic groups (Africans and Caucasians). All of them were examined with Fourier domain optical coherence tomography, auto-refractometer, topographer, and biometer to obtain the corneo-scleral angle (CSA) and additional clinical parameters. The dataset was analyzed to determine correlations between different anatomical parameters and nasal (CSAn) and temporal CSA (CSAt) values.
Results The CSAt presents a significant but low correlation with the anterior chamber depth—ACD ($r = 0.25$; $p = 0.024$), the white-to-white (W–W) distance ($r = 0.27$; $p = 0.022$), and the anterior chamber volume ($r = 0.25$; $p = 0.016$). CSAn did not correlate significantly with any clinical variable, with all values being lower than 179° (concave). Ethic groups presented significant differences for pachymetry (Pac) and corneal volume ($p = 0.033$ and $p = 0.014$), being greater for Caucasians, and temporal corneo-iridial angle ($p = 0.006$), being greater for Africans. CSA presented and inverse correlation with age.
Conclusions The CSAn presents a more concave profile for the normal population, whereas the CSAt presents a planar-convex profile with a great influence of age. In particular, the older the patient, the more convex the CSAt is. This age-related evolution of the CSAt and the concavity on the nasal direction must be considered when prescribing scleral contact lenses or when performing limbal incisions during refractive interventions.

Keywords Corneo-scleral angle · Scleral contact lenses · Optical coherence tomography · Corneal topography

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Introduction

The study of the corneo-scleral profile is of extreme importance for surgeries with limbal incisions (e.g., cataract surgeries) and for the fitting of soft and rigid scleral contact lenses [1]. Daniel Meier [2] described in 1992 five feasible transition profiles between the sclera and the cornea: (1) gradual corneo-scleral transition with convex sclera; (2) gradual corneo-scleral transition with tangential sclera; (3) steep corneo-scleral transition with convex sclera; (4) mid corneo-scleral transition with tangential sclera; and (5) convex cornea with concave sclera. In 2011, Van der Worp et al. [3] compared different corneo-scleral profiles and the feasibility of scleral contact lens fitting using time-domain optical coherence tomography (OCT) (Visante, Carl Zeiss Meditec, Jena, Germany), videokeratoscopy, and conventional keratometry. They concluded that the most suitable device for the evaluation of the corneo-scleral profile was the OCT, as it provided the most complete and detailed 360° information. Furthermore, they found that the nasal corneo-scleral profile was different with respect to the other quadrants due to the influence of the insertion of the medial rectus muscle [3]. Hall et al. (2013) [4] studied the corneo-scleral profiles for Caucasian British and Asian British subjects using time-domain OCT, suggesting that age could be the unique factor affecting the morphology of the corneo-scleral angle (CSA) as it decreased with age.

Besides the relationship of CSA with age, differences between CSAs were found to be larger on the horizontal meridian (temporal and nasal) rather than on the vertical (superior and inferior) [4]. However, there are still some relationships that have not been addressed yet such as the relation between anatomic parameters of the eyeball and the magnitude of the CSA. Furthermore, to date, all studies evaluating the CSA used time-domain OCT, but not Fourier-domain OCT which provides more repeatable measurements of the anatomical parameters of the anterior segment [5–7]. Our goal was to characterize the geometry of the corneo-scleral surface for a normal ethnic-dependent population using a Fourier-domain OCT system and to analyze the correlation between the CSA and other anatomical or demographic characteristics.

Methods

Patients and clinical protocol

The target population had no previous known ocular pathology, with a balanced sample in terms of gender and age. Exclusion criteria were individuals with anterior or posterior pathologies, wearing contact lenses, or with previous refractive surgery. The optimal sample size (n) for drawing conclusions with enough statistical power (at least 85%, p value < 0.05) was found to be 100. Thus, a total of 100 right eyes were included in the current series.

All measurements were carried out during three months at the Optometry Clinic of the University of Alicante (Alicante, Spain) in the mornings (from 9:00 to 14:00 a.m.). The study was approved by the ethics committee of the University of Alicante (BioEye Project 2016) and adhered to the tenets of the Declaration of Helsinki. All participants were informed previously and signed an informed consent to take part in the study. Personal data were encoded with a numeric label to comply with data protection legislation.

The clinical protocol was applied sequentially as follows. First, refraction was measured in a central 3-mm pupillary diameter with the multidiagnostic platform VISIONIX VX120 (Luneau Technologies, Chartres, France). Second, topographic and tomographic data of the anterior segment were obtained using the Pentacam HR system (Oculus Optikgeräte GmbH, Wetzlar, Germany). Third, the CSA was measured with the anterior segment module of the Fourier-domain OCT system Copernicus HR (Optopol Technology Sp. z.o.o., Zawiercie, Poland). The measurement was obtained with the angular caliper of the software of the OCT system, as displayed in Fig. 1. Finally, the axial length (AL) of the eyeball was measured using the IOL Master 500 optical biometer (Carl Zeiss Meditec, Jena, Germany). Variables measured for the study were the following: nasal/temporal corneo-scleral angle ($CSA_{n/t}$), anterior/posterior corneal asphericity ($Q_{a/p}$), nasal/temporal corneal-irido angle ($CIA_{n/t}$), corneal volume (CV), anterior chamber volume (ACV), anterior/posterior horizontal corneal radius ($HCR_{a/p}$), anterior/posterior vertical corneal radius ($VCR_{a/p}$), anterior/posterior average corneal radius ($ACR_{a/p}$), pachymetry (Pac), anterior chamber

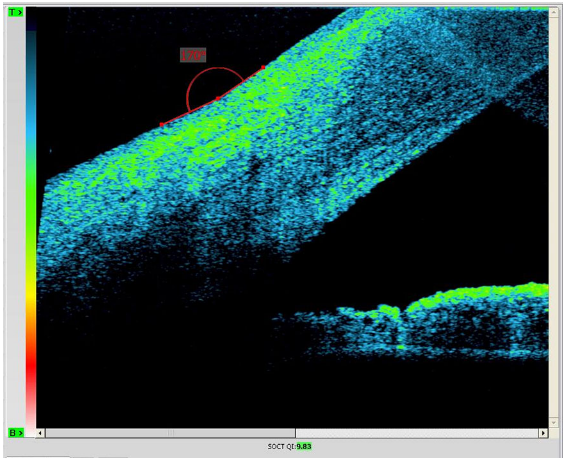

Fig. 1 Corneo-scleral section obtained with the anterior segment module of the Fourier domain optical coherence tomography (OCT) system Copernicus HR (Optopol Technology Sp. z.o.o., Zawiercie, Poland). The measurement of CSA was obtained with an angular caliper as displayed in the figure in the nasal and temporal positions

depth (ACD), white-to-white distance (WTW), and axial length (AL).

Statistical analysis

Descriptive statistics was used for quantitative variables, including the calculation of the arithmetic mean, standard deviation, and median. For the qualitative variables, the absolute frequency and relative percentages were calculated. Two different statistical tests were used to determine the normality in the distribution of the variables: the Chi-squared and the Lilliefors tests [8], which evaluate whether the sample comes from a normal distribution $N(\mu, \sigma)$. To determine differences between continuous distributions with equal medians, a nonparametric Wilcoxon rank-sum test was used. To identify possible relations between the CSA and the rest of the anatomical variables evaluated, the nonparametric Spearman's correlation coefficient (ρ) was calculated.

Finally, linear regression models were used to analyze the strength of the relationship between variables (R^2 of 0.10–0.29: low; 0.30–0.49: moderate; 0.5–1.0: high). All the analysis was performed using MATLAB 2016 (MathWorks, USA) and double-checked with IBM SPSS 21 (IBM, USA) at a level of significance of 5% (α).

Results

In the evaluated sample, women's and men's group size was equal, presenting an average age of 34.6 ± 13.1 (19–69 years). Caucasians were the most predominant ethnic group (83%), and myopia the most relevant ametropy (77%). The CSA_n presented a mean value of 172.5° ± 2.8° (163.0°–178.3°), being classified all of them within the *concave* category. The CSA_t presented a mean value of 177.2° ± 2.6° (170.0°–181.0°), following the empirical distribution presented in Fig. 2. Importantly, several variables could not be assumed as normally distributed (see *Normality Test* i Table 1).

Regarding the anatomical differences between genders subgroups (see Table 2), only HCR_p (male 6.80 ± 0.56 vs. female 6.55 ± 0.39 mm, $p = 0.022$), ACV (male 175.70 ± 39.37 vs. female 159.12 ± 37.12 mm^3, $p = 0.032$), and AL (male 24.30 ± 1.18 vs. female 23.63 ± 0.99 mm, $p = 0.002$) presented significant differences. When the comparison was done between ethnic subgroups (Caucasian vs. African), there were significant differences in CIA_t (Caucasian 38.27 ± 5.72 vs. African 44.33 ± 6.39°, $p = 0.002$), ACD (Caucasian 2.90 ± 0.48 vs. African 3.12 ± 0.22 mm, $p = 0.044$), W–W (Caucasian 11.48 ± 0.74 vs. African 12.00 ± 0.74 mm, $p = 0.022$), VCR_p (Caucasian 6.22 ± 0.35 vs. African 6.42 ± 0.27 mm, $p = 0.014$), ACR_p (Caucasian 6.38 ± 0.35 vs. African 6.57 ± 0.27 mm, $p = 0.016$), CV (Caucasian 63.19 ± 3.53 vs. African 60.01 ± 3.55 mm^3, $p = 0.008$), Pac (Caucasian 561.60 ± 29.52 vs. African 535.75 ± 27.23 µm, $p = 0.008$) and AL (Caucasian 23.84 ± 1.15 vs. African 24.64 ± 0.91 mm, $p = 0.009$). Although several anatomical differences were detected between Africans and Caucasians, the CSA did not present significant differences ($p \geq 0.111$). In terms of age, only the CSA_t presented a significant difference between young and old patients (Young 177.47 ± 2.64 vs. Old 175.84 ± 3.10°, $p = 0.034$). The rest of the anatomical differences between age subgroups mainly correspond to refraction and corneal features ($p \leq 0.042$). The comparison between myopic and hyperopic patients only revealed the presence of significant differences for some anatomical parameters (CIA_n, $p = 0.009$; CIA_t, $p = 0.007$; HCR_a, $p = 0.037$; AL, $p = 0.013$), but not in terms of CSA_n (0.999) or CSA_t ($p = 0.515$).

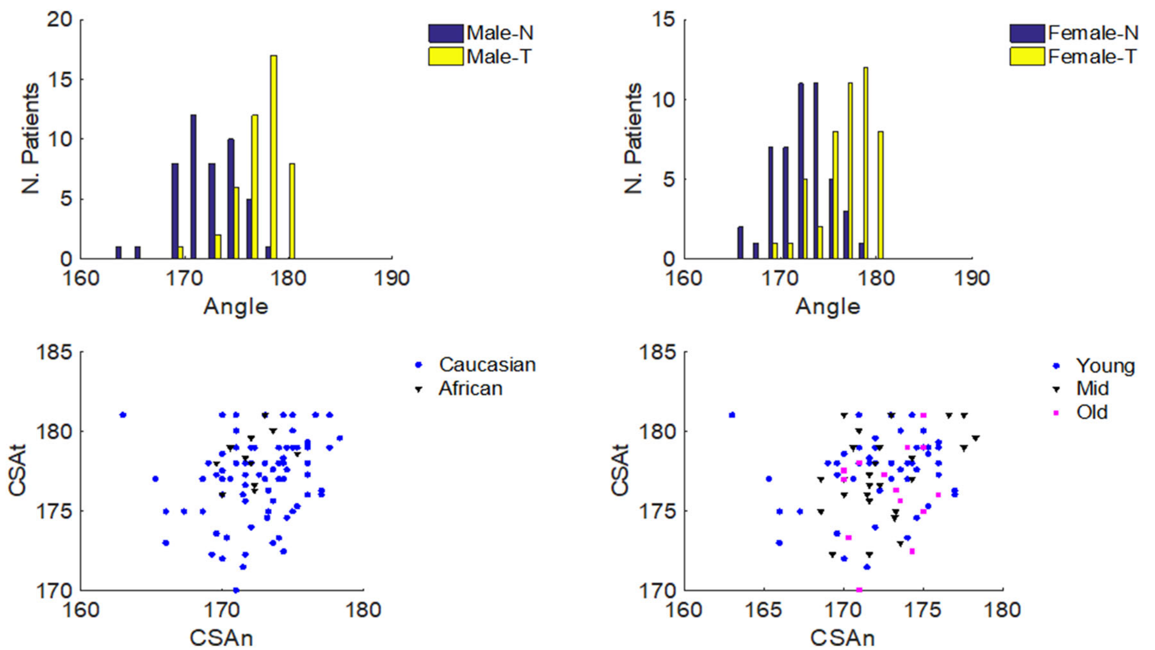

Fig. 2 Distribution of nasal and temporal corneo-scleral angle according to gender, ethnic group (African vs. Caucasian) and age. No significant differences were found between male–female, age subgroups and African–Caucasian groups

Table 1 General statistics and result of the tests of normality (Chi-squared and Lilliefors tests)

Descriptive analysis						Normality test*			
Variable	Mean (μ)	STD (σ)	Median	Max.	Min.	Chi-S		Lilliefors	
						h	*p*	*h*	*p*
Refraction	− 0.105	2.395	− 0.750	4.625	− 7.875	1	< 0.001	1	0.001
CIAn	39.950	5.958	40.000	55.000	20.000	1	0.009	1	0.001
CIAt	39.370	6.237	38.500	61.000	22.000	**0**	**0.293**	1	0.046
ACD	2.936	0.453	2.965	4.370	1.070	1	0.036	0	0.213
W–W	11.540	0.744	11.000	14.000	10.000	1	< 0.001	1	0.001
Qa	− 0.279	0.143	− 0.270	0.430	− 0.700	**0**	**0.125**	**0**	**0.191**
Qp	− 0.316	0.179	− 0.300	0.440	− 0.800	1	0.038	1	0.020
HCRa	7.934	0.297	7.920	8.830	7.450	**0**	**0.161**	**0**	**0.098**
HCRp	6.674	0.499	6.555	8.000	6.030	1	< 0.001	1	0.001
VCRa	7.647	0.492	7.715	9.610	6.060	1	0.001	1	0.001
VCRp	6.233	0.337	6.200	7.500	5.650	1	0.013	1	0.001
ACRa	7.853	0.285	7.865	8.720	7.360	**0**	**0.447**	**0**	**0.115**
ACRp	6.392	0.334	6.360	7.630	5.840	1	0.005	1	0.001
ACV	167.410	38.968	168.500	292.00	77.000	**0**	**0.674**	**0**	**0.289**
CV	62.751	3.675	62.600	73.400	52.400	**0**	**0.365**	**0**	**0.500**
Pac	557.340	30.864	556.000	649.00	488.00	**0**	**0.411**	**0**	**0.500**
CSAn	172.458	2.813	172.300	178.300	163.000	0	0.684	0	0.446
CSAt	177.168	2.602	177.550	181.000	170.000	0	0.108	1	0.005

Associated *p*-values below 0.05

*Null hypothesis: the sample comes from a normal distribution ($h = 0$, hypothesis accepted with a 5% of confidence)

Table 2 Pair-wise comparison of variables based on the Wilcoxon rank-sum test* according to gender, ethnic and age subgroups

Variable	Gender		Ethnic group		Age (young: < 31 years; mid: 31–50 years; old: > 50 years)					
	Male–female		Caucasian–African		Young–mid		Young–old		Mid–old	
	h	*p*	*h*	*p*	*h*	*p*	*h*	*p*	*h*	*p*
Refraction	0	0.847	0	0.821	0	0.091	**1**	**0.004**	0	0.074
CIAn	0	0.529	0	0.270	**1**	**0.000**	**1**	**0.001**	0	0.281
CIAt	0	0.724	**1**	**0.002**	**1**	**0.040**	**1**	**0.000**	0	0.149
ACD	0	0.221	**1**	**0.044**	**1**	**0.000**	**1**	**0.000**	0	0.107
W–W	0	0.284	**1**	**0.022**	0	0.063	**1**	**0.017**	0	0.284
Qa	0	0.212	0	0.119	0	0.540	0	0.797	0	0.817
Qp	0	0.450	0	0.398	**1**	**0.002**	**1**	**0.000**	0	0.341
HCRa	0	0.177	0	0.169	0	0.079	0	0.797	0	0.317
HCRp	**1**	**0.022**	0	0.084	0	0.202	0	0.850	0	0.435
VCRa	0	0.986	0	0.056	0	0.223	0	0.215	0	0.990
VCRp	0	0.593	**1**	**0.014**	0	0.101	0	0.529	0	0.855
ACRa	0	0.180	0	0.076	0	0.210	0	0.615	0	0.705
AVRp	0	0.147	**1**	**0.016**	**1**	**0.026**	0	0.473	0	0.634
ACV	**1**	**0.032**	0	0.717	**1**	**0.000**	**1**	**0.000**	0	0.464
CV	0	0.400	**1**	**0.008**	**1**	**0.024**	0	0.134	0	0.817
Pac	0	0.918	**1**	**0.008**	0	0.553	0	0.547	0	0.435
AL	**1**	**0.002**	**1**	**0.009**	0	0.585	**1**	**0.042**	0	0.176
CSAn	0	0.871	0	0.427	0	0.747	0	0.423	0	0.304
CSAt	0	0.245	0	0.111	0	0.620	**1**	**0.034**	0	0.186

Associated *p*-values below 0.05

*Null hypothesis (*h*) states that the variables come from the same distribution (with same median); $h = 0$ ($p < 0.05$) accepts that there are no significant differences between variables; $h = 1$ implies that there are significant differences between variables

In terms of correlation, only poor although statistically significant correlations of temporal CSA_t with ACD ($r = 0.25, p = 0.02$), W–W ($r = 0.27, p = 0.02$), and the ACV ($r = 0.25$, $p = 0.02$) were found (see Table 3). Although there is a correlation between parameters, it cannot be regarded only as linear. CSA_n did not present any significant correlation with any anatomical parameter.

Table 3 Spearman's correlation between CSA_t and the most important anatomical parameters

Variable	Spearman's ρ	*p*-value
Spherical equivalent	0.10	0.60
CIAn	0.12	0.62
CIAt	0.16	0.62
ACD	**0.25**	**0.02**
W–W	**0.27**	**0.02**
Qa	0.04	0.88
HCRa	0.12	0.12
VCRa	0.13	0.18
ACV	**0.25**	**0.02**
CV	− 0.02	0.70
Pac	0.04	0.91
AL	0.07	0.45

Associated *p*-values below 0.05

Discussion

To date, there are few studies that evaluate the distribution of the corneo-scleral transition in healthy eyes. Likewise, all of them used time-domain OCT technology and did not use Fourier domain technology as in our study. Our main findings outline that $CSA_{n/t}$ does not seem ethnic dependent nor gender dependent. Also, $CSA_{n/t}$ does not clearly correlate with other anatomical factors that could help to estimate it when OCT is not available. Not only that, but demographic variables do not correlate with CSA, except the significant difference found in CSA_t between young and old individuals, which supports the previous finding reported by Hall et al. using time-domain OCT [4, 9].

In the nasal quadrant, the corneo-scleral profile was concave (< 179°) in 97% of the eyes, which agrees with previous results [4]. Regarding the temporal quadrant, there is a predominance of concave angles (69%), with respect to the flattened and convex angles (16% and 15%, respectively). In fact, the temporal profile was always more planar/convex than the nasal profile as the trend reported by Hall et al. [4]. This is of great importance as the higher the asymmetry between profiles, the more difficult will be the stabilization of a scleral contact lens when fitted. This is a crucial aspect when defining the design of the peripheral bands of a scleral contact lens, which was acknowledged in studies evaluating CSA with OCT [4] and evaluating corneo-scleral topography with profilometers [10, 11]. This horizontal asymmetry in the corneo-scleral transition angle could be related to the insertion of the medial rectus muscle, as suggested by Van der Worp [3]. In our population, supero-inferior asymmetry was not studied due to the technical limitations of the system, as happened in the previous studies using Fourier transform profilometers [10].

Regarding the ethnic group, both $CSA_{n/t}$ did not show statistically significant differences between Africans or Caucasians, despite clear anatomical differences (CIA_t, ACD, W–W, VCR_p, ACV, CV, and Pac). This fact suggests an insensitivity of the corneo-scleral profile to the ethnicity, which could be advantageous when designing contact lenses as their design would be ethnic independent. Nevertheless, the sample size for Africans was yet small to withdraw a definitive conclusion and a larger study would be required including also other ethnicities.

No pattern was found on the CSA when analyzing the influence of gender. Clinically, both genders presented a temporal profile mainly convex, with a higher planar predominance for women (20%) with respect to men (12%), whereas men presented a higher convex predominance (20% vs 10%). However, this trend did not reach statistical significance. The rest of the anatomical parameters followed the previously reported trends, with higher values of AL and ACV as well as lower values of HCR_p in men [12]. Concerning refraction, no clear differences in CSA between myopic and hyperopic individuals were observed, which agrees with the previous findings of Hall et al. [4].

The relationships between CSA and the different anatomical variables evaluated were also investigated. CSA_n did not present a correlation with any anatomical parameter, whereas CSA_t correlated significantly with ACD, W–W, and ACV, although these correlations were very weak. Thus, there is a trend of finding higher CSAt in individuals with higher values of ACD, W–W, or ACV. However, this should be evaluated in future studies, including also an analysis of additional variables, such as the intraocular pressure or the scleral radius. Apart from OCT for evaluating the corneo-scleral junction [13], new devices have been developed to analyze the scleral curvature and irregularity [14, 15] and should be considered in new investigations on the characterization of the transition between cornea and sclera.

Conclusions

The CSA does not seem predictable just based on anatomical features of the eyeball. It is remarkable, though, that the corneo-scleral transition in the nasal profile is concave and similar in Caucasians and Africans, which points toward the difference between CSA_t and CSA_n as the most important factor when designing scleral contact lenses.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the ethics committee of the University of Alicante (Alicante, Spain) and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards.

Informed consent Informed consent was obtained from all individual participants included in the study.

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