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Mean shape of the human limbus

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Purpose: To characterize the mean topographic shape of the limbus of a normal human eye and determine whether it depends on age or refractive power.

Setting: University of Manchester, Manchester, United Kingdom.

Design: Prospective case series.

Methods: Participants with no previous ocular surgeries were included in this study. The left eye was measured with a corneoscleral topographer (Eye Surface Profiler). From the raw anterior eye height data, the topographic limbus was demarcated and fitted in 3 dimensions to a circle, an ellipse, and a Fourier series. The root mean square error was calculated to evaluate the goodness of fit. In addition, the white-to-white (WTW) corneal diameter was taken from the readings of the measuring device. For statistical analysis, participants were grouped according to their age and their spherical equivalent correction.

Results: The study comprised 74 participants aged 20 to 84 years. From the considered models, the 2nd-order Fourier series was the most accurate model to describe the shape of the human limbus. The mean difference between the topographic limbus diameter and the WTW corneal diameter was 0.33 mm ± 0.24 (SD). There were statistically significant differences between eye quadrants ($P < .001$); however, there were no statistically significant differences in the horizontal and vertical meridians between age groups ($P = .71$ and $P = .082$, respectively) or between eyes with myopia and eyes with emmetropia ($P = .78$ and $P = .68$, respectively).

Conclusion: The human limbus is not symmetrical and although its shape is person-dependent, it is not related to age or the eye's refractive power.

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The cornea and the sclera are the main structures that comprise the anterior eye surface. The change in the curvature at the junction of these 2 structures is the limbus. The anterior limbus is formed by the junction of the corneal and conjunctival epithelia, where the epithelium gradually becomes thicker toward the sclera. Anatomically, the limbus contains important features related to eye functions including corneal stem cells for nourishing the cornea. It also contains the principal conventional pathways of aqueous humor outflow, which, among other functions, are necessary for the maintenance of intraocular pressure.[1]

The corneal diameter is defined as the limbus-to-limbus distance, and clinically the horizontal and vertical dimensions are important because they are necessary in the diagnosis of diseases such as macrocornea, microcornea, macrophthalmia, microphthalmia, or relative anterior microphthalmia.[2] Delimiting corneal borders is also essential for refractive cataract surgeons as a useful approximation for sizing some types of anterior chamber intraocular lenses (IOLs).[3]

The white-to-white (WTW) corneal diameter, horizontal visible iris diameter, and vertical visible iris diameter are the parameters usually used to estimate the corneoscleral transition. Manual and automated techniques are used in the clinic to make these estimates. Table 1 shows, in chronological order, the results of WTW corneal diameter estimates evaluated in previous studies.[2–21]

Most estimates of the WTW corneal diameter in Table 1 are based on imaging the colored transition from the iris to the sclera. The estimates that considered topographic transition from cornea to sclera used manual calipers. However, the corneoscleral topographic transition does not necessarily correspond to the color transition observable with en face imaging.[22,23] In the past, the limitations of technology restricted the study of the anterior eye topography to the corneal region. Keratometers, keratoscopes, Scheimpflug-based topographers, and optical coherence tomography have been used to assess the shape of the human cornea.[24,25] On the other hand, the shape of the limbus, understood as the transition between the cornea and the sclera, has been conventionally

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Table 1. White-to-white corneal diameter evaluated in previous studies.

Study*/Year & Measuring Device	Eyes (N)	Mean WTW (mm) ± SD
Martin[4]/1982		
Videotapes and photographs	50	11.64 ± 0.49
Edmund[5]/1988		
Slitlamp	56	11.86 ± 0.55
Pop[6]/2001		
Caliper	43	11.87 ± 0.49
Werner[3]/2004		
Surgical caliper	12†	11.77 ± 0.40
Digital caliper		11.75 ± 0.43
Baumesiter[7]/2004		
Caliper	100	11.91 ± 0.71
Holladay-Godwin gauge		11.80 ± 0.60
Orbscan II		11.78 ± 0.43
IOLMaster		12.02 ± 0.38
Goldsmith[8]/2005		
Holladay-Godwin gauge	40	11.78 ± 0.57
Rüfer[9]/2005		
Orbscan II	743	11.71 ± 0.42
Kohnen[10]/2006		
IOLMaster	52	12.17 ± 0.45
Orbscan II		11.84 ± 0.41
Lim[11]/2006		
Orbscan II	724	11.56 ± 0.36
Ronneburger[12]/2006		
Calipers	65‡	10.75 ± 0.81
Microscope		10.65 ± 0.65
Piñero[13]/2008		
Digital caliper, by CSO topographer	36	12.25 ± 0.49
Salouti[14]/2009		
Galilei 4.01	74	12.01 ± 0.61
Orbascan II		11.67 ± 0.29
Nemeth[16]/2010		
IOLMaster	91	11.99 ± 0.47
Sanchis-Gimeno[15]/2012		
Orbscan II	379	11.90 ± 0.20
Zha[17]/2013		
Orbscan II	231§	11.49 ± 0.36
Martin[18]/2013		
Orbscan II	328	11.69 ± 0.37
IOLMaster		12.19 ± 0.40
Hall[19]/2013		
Slitlamp	199	11.70 ± 0.50
Domínguez-Vicent[20]/2014		
Galilei G4	80	11.84 ± 0.31
Pentacam HR		11.90 ± 0.43
Hickson-Curran[21]/2014		
Digital camera	255	11.75 ± 0.50
Chen[2]/2015		
Calipers	729	12.22 ± 0.52
IOLMaster	977	12.12 ± 0.42

WTW = white-to-white
*First author
†Cadaver eyes
‡Children's eyes
§Eyes with myopia

considered circular. Although the importance of the topography of corneoscleral transition has been recognized,[26] no accurate description of the human limbal shape has been reported. Today, it is possible to overcome the technical limitations that constrained the topographic studies to the corneal region with noncontact commercially available instruments, such as corneoscleral profilometers that cover the corneoscleral area far beyond the limbus.[27]

The aim of this study was to characterize the mean topographic shape of the limbus of a normal human eye and determine whether it depends on age or refractive power.

PARTICIPANTS AND METHODS

This study was approved by the University of Manchester Human Research Ethics Committee and adhered to the tenets of the Declaration of Helsinki. All participants gave written informed consent to participate after receiving an explanation of the nature and possible consequences of the study. All participants were free of ocular disease, and current use of topical ocular medications was specified by the participants as part of a background questionnaire. Exclusion criteria also included the presence of corneal, conjunctival, or scleral pathology; history of ocular surgery; or contact lens wear.

The study was performed in a single visit for each participant. First, the refractive power was measured in monocular conditions (nontested eye occluded with an eyepatch) using an open-view autorefractometer (Shin Nippon SRW-500, Ajinomoto Trading, Inc.). Participants were asked to focus on a fixed 6 m distant target (Maltese cross) positioned on a flat wall, and the autorefractometer was aligned with the center of the pupil. Five measurements were acquired from the left eye of each participant. The average value of the 5 measurements provided by the autorefractometer were considered as the valid refractive spherocylindrical power in each eye.

Further, topographic data were obtained using a noncontact corneoscleral topographer (Eye Surface Profiler, Eaglet Eye BV), a height profilometer with the potential to measure the corneoscleral topography far beyond the limbus. To determine surface heights, algorithms used in the noncontact corneoscleral topographer achieve levels of accuracy similar to those reached in keratoscopy-based instruments such as Placido-disk videokeratoscopes.[27] The scleral data were obtained after fluorescein staining was instilled into each participant's eye. Accurate measurements of the anterior eye surface using the noncontact corneoscleral topographer require instillation of fluorescein with a more viscous solution than saline.[27] The ophthalmic strips (Bioglo, HUB Pharmaceuticals, Inc.) were used to gently touch the upper temporal ocular surface. They were infused with 1 mg of fluorescein sodium moistened with 1 drop of an eye lubricant (Hylo-Parin, 1 mg/mL sodium hyaluronate). Four measurements were taken of the left eye of each participant. Participants were instructed to open their eyes wide (not forcefully) before the measurements were taken with the noncontact corneoscleral topographer to ensure full coverage of the corneoscleral area. Measurements in which the corneoscleral area was affected by eyelids were excluded.

After the data acquisition was complete, the raw anterior eye height data (x, y, and z coordinates) were exported from the noncontact corneoscleral topographer for further analysis. The limbal transition was calculated in 360 semimeridians using a purpose-designed algorithm as the point corresponding to a certain amount of change in the curvature between the cornea and the sclera.[22] Furthermore, 3 parametric models—a best-fit-circle (3-parameter model), best-fit-ellipse (5-parameter model), and a best-fit-Fourier-series—were applied to the limbal transition points demarcated earlier. The Fourier series is a sum of sine and cosine functions that describes a periodic signal as follows:

$$y = a_0 + \sum_{i=1}^{n} a_i \cos(iwx) + b_i \sin(iwx) \quad (1)$$

where a_0 models a constant term in the data, a_i and b_i are the Fourier coefficients, w is the fundamental angular frequency of the signal, and n is the number of terms in the series. The 2nd-order ($n = 2$) Fourier series was used because preliminary analysis showed that a higher-order series would not result in a model that has a statistically significant higher correlation coefficient ($P > .05$, Fisher test). The 2nd-order Fourier series limits the