• Clinical Research •

Changes in endothelial morphology and ocular aberrations in pterygium

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Abstract

● **AIM:** To compare changes in the corneal surface and endothelium, and to investigate their relationship with the horizontal length (HL), vertical length (VL), and depth of pterygium.

● **METHODS:** This study analyzed 34 eyes with unilateral primary pterygium and compared them to the 34 fellow eyes. Topographic values, wavefront aberrations, and specular microscopy findings were assessed. In addition, correlation analyses were conducted between the HLs and VLs, as well as the depth of pterygium.

● **RESULTS:** The mean age of the patients was 60.18±11.36y (38.2% females). Uncorrected visual acuity (UCVA) was lower, and corneal astigmatism was higher in the pterygium group (P=0.006 and P<0.001, respectively). Simulated keratometry 1 (simK1) measurements showed significant corneal flattening in the pterygium group (P=0.038). Notably, the HL of the pterygium (r=0.646, P<0.001) demonstrated a stronger correlation with corneal astigmatism than the VL (r=0.449, P=0.008). No significant correlation was observed between depth (r=-0.007, P=0.971) and corneal astigmatism. Furthermore, significant increases were noted in total higher-order aberrations (HOA; P=0.013), trefoil (P=0.002), tetrafoil (P=0.001), and high-order astigmatism (P<0.001) in the pterygium group. Mean point spread function (PSF) values were also significantly impaired in the pterygium group (P=0.007). Regarding endothelial parameters, the median endothelial cell density (ECD) was 2448.50 (2176.00-2750.25 cells/mm²) in pterygium group, and 2554.00 (2252.50-2890.00 cells/mm²) in the control group (P=0.289). No correlation was found between HS or VL and specular microscopy findings. However, a negative correlation was observed between depth and hexagonality (r=-0.381, P=0.026), and between depth and central corneal thickness (CCT; r=-0.422, P=0.013).

● **CONCLUSION:** The effect of pterygium on corneal aberrations is more strongly associated with its HL than with its VL. Depth do not affect aberrations, and pterygium has no significant effect on the ECD.

● **KEYWORDS:** pterygium; corneal astigmatism; corneal aberrations; root mean square; endothelial cell density

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INTRODUCTION

Pterygium is a fibrovascular growth of the nasal conjunctiva and the underlying subconjunctival tissue, extending onto the cornea. It typically assumes a wing-like appearance within the interpalpebral space. Despite the lack of clarity regarding its etiology, the impact of pterygium on corneal parameters is well-documented. Beyond compromising visual quality, it can lead to motility disorders, recurrent inflammation, foreign body sensation, excessive tearing, and cosmetic concerns. These symptoms are often accompanied by changes in the corneal curvature and endothelial structure[1-2]. Given its influence on both corneal curvature and morphology, pterygium affects refractive indices, topographic parameters, and endothelial morphology[1-3]. Over time, these changes may lead to complications that necessitate surgical intervention. Some studies have explored the association of pterygium with ocular wavefront, corneal morphology, and endothelium[4-8]. However, the advent of anterior segment optical coherence tomography (AS-OCT) has allowed for more detailed assessments, including depth measurements. Pterygium has been shown to significantly increase corneal higher-order aberrations (HOAs), with both its horizontal length (HL) and width correlating with these changes[4-5]. Changes in corneal curvature are linked to the percentage of corneal surface affected, rather than the length of the pterygium[6]. Additionally, a decrease in the number of endothelial cells in pterygium has also been reported[7]. One important issue that remains to be

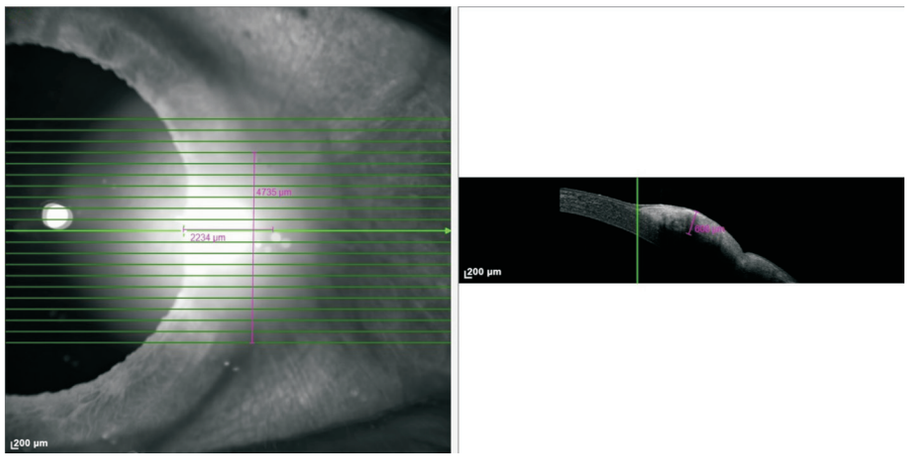

Figure 1 Pterygium dimensions (horizontal length, vertical length and depth of pterygia) measured by anterior segment optical coherence tomography.

clarified is the simultaneous evaluation of the horizontal and vertical dimensions and depth of the pterygium. Specifically, it is unclear which of these parameters has the greatest effect on corneal curvature and endothelial morphology. This could lead to the inclusion of an additional factor in the follow-up and treatment guidelines. The present study was designed to comprehensively examine the impact of pterygium on corneal topographical parameters and endothelial morphology. In addition, it was planned to elucidate the effect of the HL, vertical length (VL) and depth of pterygium on these values, providing potential novel insights for clinical follow-up.

PARTICIPANTS AND METHODS

Ethical Approval This prospective observational study received approval from the non-interventional clinical research ethics committee of Kocaeli University, Faculty of Medicine (GOKAEK, 2023/14.03 2023/182). Furthermore, the study adhered to the principles outlined in the Declaration of Helsinki. Informed consent was obtained from all participants.

Study Participant Selection Our study included 68 eyes from 34 patients with unilateral primary pterygium. The fellow eyes of these unilateral pterygium patients (34 eyes) were used as controls. All patients, seeking diagnosis and treatment at our outpatient clinic for symptoms like redness, itching, burning, stinging, and cosmetic concerns, were evaluated. These patients all had primary nasal pterygium in one eye.

We excluded individuals with a history of eye trauma, prior eye surgery, use of topical drugs, contact lens wear, severe blepharitis, conjunctivitis, dry eye, glaucoma, retinal disorders, refractive errors >3 diopters, other ocular surface or corneal disorders, and systemic conditions, such as diabetes, hypertension, and rheumatological diseases, that could effect endothelial function and corneal aberrations.

Ophthalmic Examination The 34 patients with unilateral primary pterygium underwent a comprehensive ophthalmic examination conducted by the same examiner (Celikoglu D). This exam included assessments of uncorrected visual acuity (UCVA), best corrected visual acuity (BCVA), biomicroscopic evaluation of the anterior and posterior segments, axial length using non-contact ocular biometry (IOL Master 500, Carl Zeis Meditec, Germany), and objective refraction. Determination of refractive spherical and astigmatic values, as well as the spherical equivalent (calculated as the average of spherical and cylindrical errors) using an autorefractometer keratometer (Canon RK-F2, Japan). All detailed ophthalmic examinations were performed by the same person (Celikoglu D).

Additionally, the dimensions of the pterygium were meticulously measured using the caliper feature of the anterior segment (AS) module of the Heidelberg Spectralis OCT (wavelength 870 nm, Heidelberg Engineering GmbH, Heidelberg, Germany). Specifically, we manually measured the HLs and VLs, as well as the depth of the pterygium in microns using AS-OCT calipers during the analysis process. HL was measured as the distance from the limbus to the apical part of pterygium. The VL of the pterygium was determined by measuring the distance between the superior and inferior points of intersection with the limbus[3]. The maximum thickness or depth of the pterygium was quantified as the greatest depth of anterior stromal hyperreflectivity (Figure 1)[3]. The values were derived by calculating the average of the measurements taken by two independent investigators (Subasi S and Celikoglu D). Any discrepancies between the reviewers were addressed through consensus, or by a decision from the third investigator (Pirhan D) if the difference between the two measurements exceeded 10% of the average.

The pterygium cases were categorized into three subgroups based on their size: small, medium, and large, as previously described[4]. First, HL and VL were evaluated and categorized into three subgroups (HL: ≤2.0, 2.0-3.5, and >3.5 mm and VL: ≤5.0, 5.1-7.0, and >7.0 mm). Then, using HL and VL categorizations, three subgroups were created

(small pterygium: HL=2.0 mm+VL=5.0 mm and HL=2.0 mm+VL=5.1–7.0 mm and HL=2.0–3.5 mm+VL=5.0 mm, medium pterygium: HL=2.0–3.5 mm+VL=5.1–7.0 mm; large pterygium: HL=2.0–3.5 mm+VL=7.0 mm and HL=3.5 mm +VL=5.1+7.0 mm and HL=3.5 mm+VL=7.0 mm)[4]. This classification was established using corneal photographs obtained *via* slit-lamp microscopy (TOPCON 703963, DC-4 digital camera, Tokyo, Japan), with a slit beam of light measured in millimeters. The severity of pterygium was graded according to the visibility of the underlying episcleral vessels during slit lamp examination, as proposed by Tan *et al*[8]. The grading system included three levels: grade 1 (atrophic), grade 2 (intermediate), and grade 3 (fleshy). In addition, Stoker lines were assessed in slit-lamp microscopy images.

To evaluate corneal endothelial morphology, noncontact specular microscope (TOPCON SP-1P, Tokyo, Japan) was used. The fixed frame analysis located the centre of the cornea. The auto-tracking system then took over an area with precise focusing and centering automatically. The captured image was transferred to a computer, where cell count software provided a very precise analysis of the endothelial cell layer. Endothelial cell density (ECD) was determined by counting the number of endothelial cells within a standardized evaluation frame, expressed in cells per square millimeter. The average cell area (AVG) was calculated by dividing the total area within the frame by the number of cells, providing an estimate of the mean cell size. The maximum and minimum cell areas (CAmax and CAmin) were recorded to reflect the range of cell sizes within the endothelial layer. The standard deviation (SD) of the cell area was calculated to evaluate size variability among the cells. The coefficient of variation (CV) was derived using the formula CV=(SD/AVG)×100%, indicating the extent of variation in cell size. The percentage of hexagonal cells (6A) was measured as an indicator of pleomorphism, reflecting the proportion of cells that maintained a regular hexagonal shape. Central corneal thickness (CCT) was also measured in micrometers as part of the overall corneal assessment. Three measurements were obtained for each patient, and the average was used to determine the mean ECD. It is important to note that ECD measurement accuracy can vary (typically ranging from 2% to 4%) depending on image quality, cell selection, and the technician's experience[9].

A Scheimpflug camera integrated with placido-disk corneal topography (Sirius, Costruzione Strumenti Oftalmici Inc., Florence, Italy) was used for corneal surface analysis. Corneal reference surfaces were evaluated, including 9-mm spherical reference surfaces (which is the standard map in the 4-map display). The following topographic parameters were measured: corneal astigmatism, simulated keratometry 1 (simK1), simulated keratometry 2 (simK2), maximum keratometry (K-max), mean keratometry (K-mean), horizontal visible iris diameter (HVID), iridocorneal angle (ICA), corneal volume (Cvol), symmetry index of frontal surface curvature map (SIf), symmetry index of back surface curvature map (SIb), and total Baiocchi Calossi Versaci index (BCV).

Zernike polynomials were employed to quantify ocular aberrations and analyzed at the 4 mm optic zone by the Sirius (Costruzione Strumenti Oftalmici Inc., Florence, Italy) device. Recorded aberration parameters included: root mean square (RMS) values of total high-order aberrations (HOAs), total coma, total trefoil, total tetrafoil, total spherical aberations, and high-order astigmatism. The subject's eye movement was continuously tracked by the imaging system. An automated quality factor assessment was performed. In addition, the software calculated the Strehl ratio based on point spread function (PSF) values within a 4-mm corneal optic region, derived from corneal wavefront aberrations.

Statistical Analysis All statistical analyses were performed using SPSS for Windows version 20.0 (IBM Corp., Armonk, NY, USA). The Shapiro-Wilk test was used to assess the normality assumption. Continuous variables are presented as mean±SD or median (interquartile range; IQR). Categorical variables are summarized as counts and percentages. Comparisons between groups were performed using independent samples *t* test for normally distributed variables, Mann-Whitney *U* test and Kruskal-Wallis test for non-normally distributed variables. Dunn's test was used for multiple comparisons. Associations between categorical variables were examined using the Chi-square test. Associations between continuous variables were examined using Spearman's correlation analysis. A *P*-value <0.05 was considered statistically significant.

RESULTS

A total of 34 eyes from 34 patients with unilateral primary pterygium, along with the 34 fellow eyes, were included in the study. The mean age of the patients was 60.18±11.36y. Sex distribution comprised 13 females (38.2%) and 21 males (61.8%). Based on pterygium size, 17 eyes (50%) were classified as small, 9 eyes (26.5%) were medium-sized, and 8 (23.5%) as large. In terms of pterygium type, 8 eyes (23.5%) were atrophic, 15 eyes (44.1%) were intermediate, and 11 eyes (32.4%) were fleshy. Stocker lines were observed in 19 eyes (55.9%). The mean HL, VL, and depth of the pterygium as measured by AS-OCT, were 2523.0±1153.2, 4641.5±1525.8, and 481.0±98.8 μm, respectively.

Both topographic and refractive astigmatic values were higher in the pterygium group but only the topographic corneal astigmatic value showed a statistically significant difference (*P*<0.001). UCVA was significantly lower in the pterygium group (*P*=0.006) and significant corneal flattening was also observed in the pterygium group (*P*=0.038; Table 1).

Table 1 Topographic and refractive values of pterygium and control groups median (IQR), mean±SD

Parameters	Pterygium group (*n*=34)	Control group (*n*=34)	*P*
UCVA	0.75 (0.50-1.0)	1.0 (0.775-1.0)	0.006[a]
BCVA	1.00	1.00	1.00
simK1	42.78 (40.48-44.00)	43.72 (42.70-44.21)	0.038[a]
simK2	44.34 (43.29-46.02)	44.63 (43.54-45.15)	0.878[a]
Topographic astigmatism	1.28 (0.49-3.22)	0.82 (0.52-1.31)	0.042[a]
K-mean	43.23 (41.99-44.60)	43.92 (43.26-44.71)	0.053[a]
K-max	48.31 (46.65-53.65)	46.00 (45.06-47.39)	0.119[a]
HVID	11.33±0.77	11.83±0.61	0.004[b]
ICA	44.88±10.67	43.32±9.14	0.520[b]
Cvol	56.25 (51.97-58.75)	56.25 (54.24-58.72)	0.606[a]
SIf	-0.18±1.06	-0.23±0.81	0.814[b]
SIb	0.06 (-0.08 to 0.18)	0.06 (-0.01 to 0.17)	0.632[a]
BCV	0.21 (0.14-0.49)	0.17 (0.02-0.31)	0.029[a]
Refractive spherical value	0.62 (-0.31 to 1.31)	0.25 (-0.50 to 0.81)	0.226[a]
Refractive astigmatic value	-1.00 (-2.50 to -0.50)	-0.75 (-1.62 to -0.43)	0.110[a]
Refractive spherical equivalent	0.06 (-0.90 to 1.00)	0.00 (-1.12 to 0.28)	0.341[a]
Type of astigmatism, *n* (%)			
With the rule astigmatism	18 (52.9)	17 (50)	
Against the rule astigmatism	9 (56.5)	10 (29.4)	
Oblique astigmatism	7 (20.6)	7 (20.6)	
Axial length	23.45 (23.03-23.76)	23.20 (22.71-23.77)	0.524[a]

UCVA: Uncorrected visual acuity; BCVA: Best corrected visual acuity with decimal fraction; simK1: Simulated keratometry 1; simK2: Simulated keratometry 2; K-mean: Mean keratometry; K-max: Maximum keratometry; HVID: Horizontal visible iris diameter; ICA: Iridocorneal angle; Cvol: Corneal volume; SIf: Symmetry index of frontal surface curvature map; SIb: Symmetry index of back surface curvature map; BCV: Baiocchi Calossi Versaci index; IQR: Interquartile range; SD: Standard deviation. [a]Mann-Whitney *U* test; [b]Independent samples *t* test.

Table 2 Root mean square values of ocular aberrations in the pterygium and control groups median (IQR)

Parameters	Pterygium group (*n*=34)	Control group (*n*=34)	*P*
Total high order aberration	1.87 (1.50-3.33)	1.55 (1.27-1.92)	0.013[a]
Total coma	0.97 (0.65-1.43)	1.08 (0.61-1.27)	0.754[a]
Total trefoil	1.02 (0.49-2.39)	0.45 (0.26-0.91)	0.002[a]
Total tetrafoil	0.81 (0.38-1.60)	0.39 (0.12-0.69)	0.001[a]
Total spherical	-0.76 (-1.04 to -0.47)	-0.66 (-0.87 to -0.53)	0.367[a]
High order astigmatism	0.48 (0.25-0.74)	0.20 (0.15-0.35)	<0.001[a]
Point spread function, mean±SD	0.066±0.0287	0.085±0.028	0.007[b]

IQR: Interquartile range; SD: Standard deviation; [a]Mann-Whitney *U* test; [b]Independent samples *t* test.

The RMS values of corneal aberrations for both the pterygium and control groups were shown in Table 2. The RMS values of total HOA (P=0.013), trefoil (P=0.002), tetrafoil (P=0.001) and high order astigmatism (P<0.001) showed a statistically significant increase in the pterygium group (Table 2, Figure 2). The mean PSF values indicated significant impairment in the pterygium group (P=0.007).

Correlation analysis of corneal aberrations and topographic corneal astigmatism were presented in Table 3. HL showed positive correlation with trefoil (r=0.577, P<0.001), tetrafoil (r=0.428, P=0.012), high order astigmatism (r=0.496, P=0.003), and negative correlation with PSF (r=-0.547, P=0.001). A significant positive correlation was also detected between VL and trefoil (r=0.391, P=0.022), and spherical aberration (r=0.345, P=0.046). No correlation was found between pterygium depth and aberrations. Horizontal pterygium length showed a stronger correlation with topographic corneal astigmatism (r=0.646, P<0.001) than VL (r=0.449, P=0.008). There was no correlation between pterygium depth and corneal astigmatism (Table 3). Multiple comparisons revealed that the difference was particularly evident in the large pterygium group (Table 4).

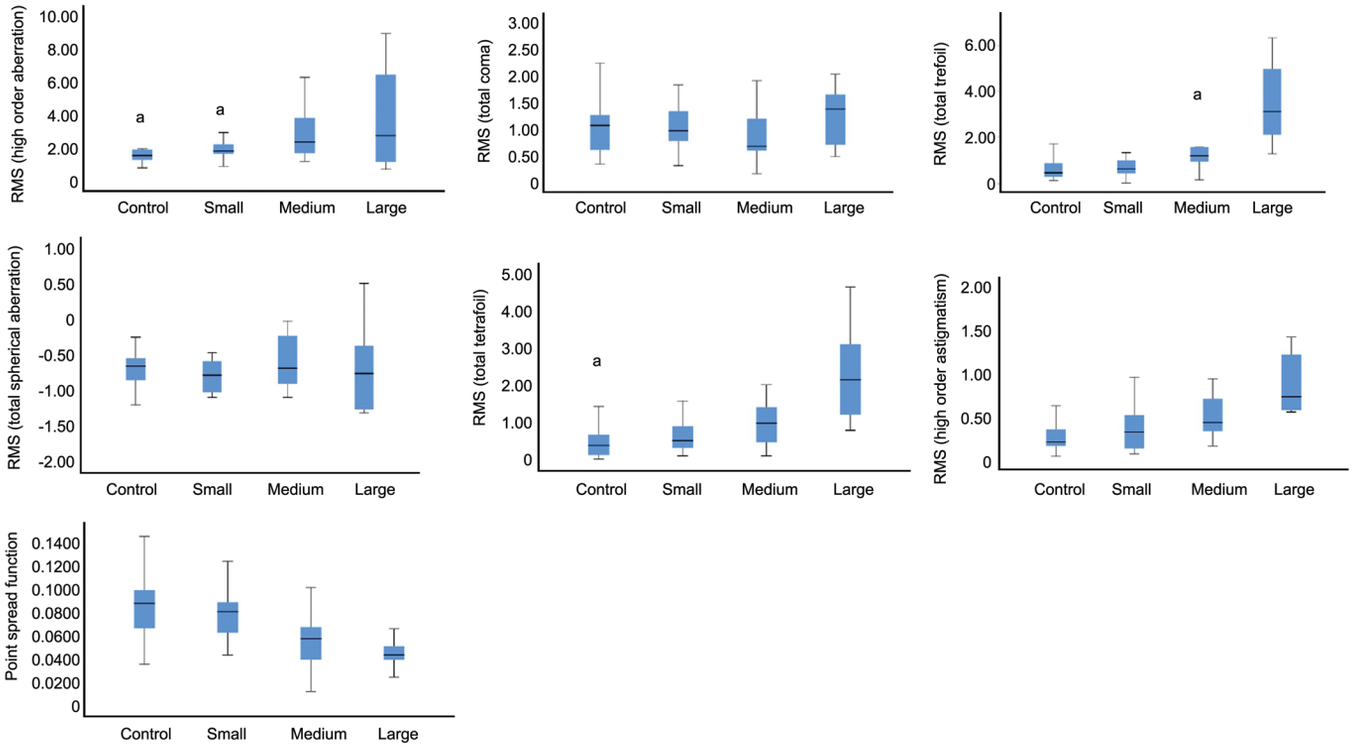

Figure 2 Box plots representing RMS values of corneal aberrations and PSF in pterygium, control and subgroups PSF: Point spread function; RMS: Root mean square; IQR: Interquartile range. [a]Extreme outliers (>3×IQR).

Table 3 Correlation between root mean square values of ocular aberrations, topographic corneal astigmatism and HL, VL and pterygium depth

Parameters	Correlation with HL		Correlation with VL		Correlation with depth	
	r	*P*	*r*	*P*	*r*	*P*
High order aberration	0.023	0.898	0.102	0.564	0.164	0.355
Total coma	0.024	0.893	-0.008	0.965	-0.011	0.949
Total trefoil	0.577	<0.001	0.391	0.022	-0.202	0.252
Total tetrafoil	0.428	0.012	0.269	0.124	-0.117	0.510
Total spherical	0.090	0.612	0.345	0.046	-0.038	0.829
High order astigmatism	0.496	0.003	0.336	0.052	-0.007	0.971
Point spread function	-0.547	0.001	-0.307	0.078	0.086	0.630
Topographic corneal astigmatism	0.646	<0.001	0.449	0.008	-0.007	0.971

r: Spearman's correlation coefficient. HL: Horizontal length; VL: Vertical length.

The mean ECD in pterygium eyes was 2448.50 (2176.00-2750.25) cells/mm^2, compared to 2554.00 (2252.50-2890.00) cells/mm^2 in control eyes (P=0.289). Subgroup analysis showed no significant changes in ECD (P=0.517; Table 5). Interestingly, there was no correlation between HL and VL and specular microscopy findings. However, a negative correlation was observed between depth and hexagonality (r=-0.381, P=0.026), as well as with CCT (r=-0.422, P=0.013).

DISCUSSION

Pterygium is a common ocular surface disease that affects visual acuity and quality by altering the anterior corneal surface. It is characterized by changes in corneal curvature, ocular aberrations, and topographic indices, which can lead to a decrease in visual functions[4,10-11]. The effects of pterygium on posterior surface astigmatism, corneal layers, and the endothelial level are still being investigated[7,11-13]. This aim of the present study was to evaluate the topographical and aberrational measurements of corneal surface parameters and endothelial effects using AS-OCT to determine whether these suspected changes are most dependent on the morphological features of pterygium, such as HL, VL, or depth, or not. The results encompass a comprehensive corneal profile by integrating surface topography and aberration analysis. It is hoped our findings will enhance clinical understanding of corneal health, guide decision-making, and offer valuable insights into the clinical characteristics of pterygium.

Previous studies have shown that pterygium decreased visual acuity and ocular quality by changing corneal curvature and

Table 4 Multiple comparisons of pterygium grades according to corneal aberrations median (IQR)

Parameters	Control	Small	Medium	Large	*P*	Multiple comparisons
Total high order aberration	1.555 (1.272-1.920)	1.830 (1.590-2.255)	2.370 (1.655-5.015)	2.740 (1.102-6.895)	0.052	
Total coma	1.080 (0.617-1.270)	0.980 (0.745-1.375)	0.690 (0.575-1.555)	1.380 (0.632-1.665)	0.624	
Total trefoil	0.450 (0.267-0.910)	0.620 (0.420-1.025)	1.190 (0.665-2.160)	3.095 (1.960-5.562)	<0.001	1<4, 2<4
Total tetrafoil	0.395 (0.127-0.697)	0.520 (0.325-1.020)	0.990 (0.310-1.720)	2.155 (1.010-3.177)	<0.001	1<4, 2<4
Total spherical	-0.660 (-0.877 to -0.537)	-0.790 (-1.030 to -0.580)	-0.690 (-1.005 to 0.125)	-0.765 (-1.295 to -0.340)	0.493	
High order astigmatism	0.205 (0.157-0.350)	0.320 (0.125-0.530)	0.430 (0.330-0.825)	0.735 (0.580-1.320)	<0.001	1<3, 1<4, 2<4
Point spread function	0.088 (0.065-0.100)	0.081 (0.060-0.094)	0.058 (0.032-0.073)	0.044 (0.038-0.053)	0.001	4<1, 4<2

Comparisons between groups were carried out with Kruskal-Wallis test. Dunn's test was used for multiple comparisons. The groups were numbered as control group=1, small group=2, medium group=3, and large group=4 for multiple comparison analysis. IQR: Interquartile range.

Table 5 Specular microscopy findings of pterygium, control and subgroups median (IQR)

Parameters	Control group (*n*=34)	Total pterygium group (*n*=34)	Small pterygium (*n*=17)	Medium pterygium (*n*=9)	Large pterygium (*n*=8)	P^a, P^b
CCT (μm)	512.50 (488.75-526.00)	510.50 (492.00-536.25)	510.00 (490.50-521.50)	511.00 (499.50-547.50)	523.50 (470.75-544.50)	0.570, 0.732
ECD	2554.00 (2252.50-2890.00)	2448.50 (2176.00-2750.25)	2428.00 (2116.00-2727.50)	2477.00 (2277.00-2969.50)	2322.00 (2141.50-2754.25)	0.289, 0.517
CV (%)	32.00 (29.75-34.00)	32.00 (30.00-36.00)	32.00 (31.00-36.00)	32.00 (29.00-34.50)	31.00 (29.25-36.00)	0.666, 0.671
Hexagonality (%)	54.00 (50.75-59.00)	54.00 (47.75-58.00)	52.00 (47.00-56.00)	54.00 (47.50-61.00)	56.00 (47.75-61.00)	0.497, 0.574
No. of cells	204.50 (162.50-231.75)	151.00 (108.75-208.50)	142.00 (113.00-209.00)	200.00 (122.00-259.50)	124.00 (53.50-193.75)	0.007, 0.010
CAmin (μm^2)	160.00 (143.25-186.25)	182.00 (157.50-197.00)	171.00 (148.00-197.00)	172.00 (149.50-196.50)	191.50 (164.25-197.75)	0.068, 0.224
CAmax (μm^2)	823.50 (726.75-913.25)	843.50 (738.25-1016.75)	853.00 (781.00-1023.50)	720.00 (653.50-1003.00)	869.50 (771.75-1074.50)	0.477, 0.323
AVG (μm^2)	380.00 (335.0-426.25)	408.50 (363.50-459.50)	412.00 (366.50-473.00)	404.00 (338.50-440.00)	431.50 (364.00-467.25)	0.046, 0.157
SD	121.50 (106.75-134.75)	135.50 (113.50-147.25)	137.00 (124.50-156.00)	114.00 (93.00-159.00)	139.00 (116.00-147.50)	0.032, 0.039

IQR: Interquartile range; CCT: Central corneal thickness; ECD: Endothelial cell density; CV: Coefficient of variation (SD/AVG)×100%; CAmin: Minimum cell area; CAmax: Maximum cell area; AVG: Average cell area; SD: Standard deviation of the cell area. [a]Comparison between the total pterygium group and control group using Mann-Whitney *U* test; [b]Comparison between controls and all subgroups using Kruskal-Wallis test.

topographic indices and ocular aberrations without directly affecting the visual axis[3-4,14-15]. It has been reported that these parameters return after excision with distortions due to the aberrations tending to improve[5,14,16]. Moreover, pterygium distorts central topography, causing focal corneal flattening and astigmatism[1,3,17]. In the present study, pterygium caused a flattening of simK1 values and an increase in topographic corneal astigmatism, resulting in decreased UCVA and similar BCVA values. We interpret this as pterygium causing correctable refractive errors, as reported by Gumus *et al*[6]. Furthermore, these authors reported that pterygium, especially of larger size, correlated with increased ocular aberrations. All aberrations, except spherical aberration, correlated with both horizontal and vertical pterygium size[4]. Pesudovs and Figueiredo[14] reported a relationship between ocular wavefront aberrations and pterygium, especially with trefoil. Although our results show increased wavefront aberrations in pterygium eyes compared to control eyes, we believe they may reflect early disease stages, as our subgroups contained a relatively higher proportion of small pterygium. Furthermore, supporting this hypothesis, in multiple comparison analyses of the subgroups, the most significant changes occurred in the large pterygium group. We suggest that aberrational changes in the pterygium begin with trefoil, tetrafoil, and high-order astigmatism. These changes deteriorate visual quality and cause a significant decrease in PSF values. When examining the large pterygium subgroup, it was found that as the pterygium progresses on the corneal surface, the effect on aberrational changes increases significantly. Our findings demonstrated that changes in corneal curvature are primarily influenced by the horizontal movement of the pterygium, followed by its advance along the vertical axis. Due to the biomechanical structure of the cornea, superficial advance of pterygium exerts a greater impact on corneal curvature than deep penetration. The horizontal movement of the pterygium disturbs the natural curvature of the cornea to a greater extent, leading to more pronounced abberational changes. In contrast, vertical axis movement has a lesser effect on corneal curvature. Furthermore, superficial pterygium advance may apply direct pressure on the corneal surface, leading to greater distortion of corneal curvature. In contrast, deep penetration affects the deeper layers of the cornea but does not significantly alter the surface curvature unless it progresses extensively.

Specular microscopy allows for easy, non-contact, and rapid imaging of corneal endothelial cells, increasing its use in studying corneal diseases. Large-scale studies are being conducted to gather normative data for different populations. Data from studies in India (2525±337 cells/mm^2), China

(2932±363 cell/mm^2), and Türkiye (2671±356 cell/mm^2) have been published[18-20]. In addition, differences in the number of endothelial cells in pterygium have been reported in various studies with differing results. Some studies have reported morphological changes without affecting ECD[7,21-22]. A Chinese population study showed a significant association between ECD loss and pterygium in retrospective measurements, but no significant association in prospective measurements between the two variables. The authors attributed this contradictory finding to variability in ECD measurements[23]. In the present study, ECD was 2554.00 (2252.50-2890.00) in healthy eyes and 2448.50 (2176.00-2750.25) in pterygium eyes, with the difference being non-significant. We did not detect any significant changes in ECD in the subgroup analyses, which categorized pterygium as small, medium, or large. There was no correlation between HL and VL, pterygium depth, and ECD. However, an inverse relationship was detected between depth and hexagonality, with endothelial cell hexagonality decreasing as depth increased. These results suggest that the effect at the endothelial level may be related to the invasion of pterygium into deeper layers, rather than its surface progression. One possible explanation is that deeper pterygium invasion may lead to prolonged exposure of the deeper corneal layers to chronic inflammation, oxidative stress, and angiogenic or fibrotic mediators. Unlike superficial extension, which primarily distorts the anterior surface, deeper penetration could indirectly affect the endothelium by disrupting stromal homeostasis and inducing subtle microenvironmental changes at the posterior cornea. Furthermore, mechanical stress resulting from fibrovascular proliferation at deeper layers may contribute to endothelial cell morphology changes, such as reduced hexagonality. These mechanisms may help explain why depth appears to be a more effective variable than horizontal or vertical dimensions in predicting early endothelial alterations. Therefore, studies focusing on superficial pterygium progression may not show an effect at the endothelial level. Since the subgroups were based on HL and VL and did not affect the correlation analysis, it appears that changes in endothelial parameters may be more closely related to the depth of the pterygium rather than its surface distribution. In recent years, there has been increasing interest in the use of artificial intelligence for the diagnosis of pterygium, with most studies using anterior segment photographs[24-25]. Unlike conventional definitions, our study highlighted the importance of considering the depth of the lesion as a significant diagnostic parameter. As studies like ours highlight the role of depth in the assessment of pterygium, we believe its clinical relevance is likely to become more widely recognized. Incorporating the depth parameter into updated classifications may improve our understanding of these relationships. To test this hypothesis, larger studies using depth as the main variable are needed.

A significant negative correlation was found between pterygium depth and CCT in our cohort. Although the exact mechanism underlying this relationship remains unclear, one possible explanation is that deeper pterygium may be associated with chronic inflammation and progressive fibrovascular proliferation. These changes may induce structural remodeling in the corneal stroma, potentially leading to central corneal thinning. However, since this hypothesis is not yet supported by histopathological or longitudinal data, the clinical relevance of this finding should be interpreted with caution. Further studies are needed to confirm this association and clarify its pathophysiological basis.

Based on our findings, we suggest that treatment decisions should consider not only the horizontal and vertical dimensions of the pterygium but also its depth of penetration. While horizontal extension appears to have the greatest impact on corneal curvature and visual distortion, depth may indicate subclinical endothelial or stromal involvement. We therefore propose a preliminary three-dimensional classification model that includes: HL, VL, and depth, as evaluated through AS-OCT or similar imaging modalities. This model may guide clinicians in identifying patients at risk of permanent visual or structural corneal changes and selecting appropriate timing for surgical intervention. However, further large-scale studies will be necessary to validate this proposed classification system and its utility in routine clinical practice.

The limitations of our study include the small sample size, particularly in the pterygium subgroups, and the fact that most of the grading was based on the HL and VL of the pterygium. Larger studies with more patients in pterygium subgroups are needed. Endothelial examination using a new classification based on pterygium depth would provide data to validate or negate our hypothesis. The present study highlighted the significant role of both the horizontal and vertical pterygium movement in introducion corneal aberrations, with horizontal movement having the most pronounced effect. Superficial advance of the pterygium exerteds a greater influence on corneal curvature compared to deep penetration, as it may apply direct pressure to the corneal surface, causing more significant distortion. While deep penetration may affect the deeper layers of the cornea, it does not substantially alter surface curvature unless it progresses extensively. These findings provide valuable insights into the visual consequences of pterygium and offer a foundation for optimizing treatment and follow-up strategies, particularly in cases with significant corneal curvature distortion, by considering both the horizontal and vertical advances, as well as their depth. These findings highlight the potential role of lesion depth in endothelial

health. We suggest that depth-based assessments could help identify early subclinical changes that surface dimensions may overlook. Integrating a depth-based parameter into pterygium classification may enhance clinical decision-making, enabling earlier intervention in patients with significant stromal or endothelial involvement, regardless of surface size.

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