· Clinical Research ·

Evaluating corneal topographic patterns in keratoconic eyes and their association with keratoconus changes over time

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Abstract
● **AIM:** To evaluate various corneal topographic patterns in keratoconus (KCN) and their association with disease progression.

● **METHODS:** A retrospective cohort study was conducted on 636 eyes of 335 KCN patients (396 males, 240 females) with a mean age of 30.95±7.95y. Participants underwent two ocular examinations, including corneal tomography using the Pentacam-HR. Topographic patterns were classified based on axial curvature, and KCN progression was defined as a change of ≥1.00 D in maximum keratometry (Kmax). Accordingly, evaluated eyes were categorized into progressive, regressive, and stable groups.

● **RESULTS:** The most common topographic pattern was asymmetric bowtie with inferior steepening (AB-IS, 27.4%) in both males (26.8%) and females (28.3%). In the regressive group, asymmetric bowtie with skewed radial axes (21.3%) was most frequent, while AB-IS (31.3%) and inferior steepening (IS, 25.9%) dominated the stable and progressive groups, respectively. Significant differences were observed in corneal parameters across patterns: the oval pattern exhibited the most negative spherical equivalent and the lowest corrected visual acuity, whereas the irregular pattern showed the highest Kmax values in the first examination (*P*<0.05). The asymmetric bowtie with superior steepening (AB-SS) pattern also exhibited the least curvature. In terms of changes in topographic parameters over time, variations were observed in certain parameters across different patterns. Notably, the irregular pattern exhibited the most significant changes in Kmax between the two examinations. Although the AB-SS tended to regressed, the AB-IS and IS patterns showed a tendency toward progression (*P*<0.05). Changes in most components of the KCN screening indices also varied significantly across patterns (*P*<0.05).

● **CONCLUSION:** Corneal topographic patterns in KCN exhibit distinct characteristics and progression rates. Understanding these patterns can aid in predicting disease progression and tailoring treatment strategies.

● **KEYWORDS:** keratoconus; axial topography; topographic pattern; progression; regression

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INTRODUCTION

Keratoconus (KCN) is a frequently bilateral and partially inflammatory corneal disease, often exhibiting a greater degree of progression in one eye relative to the other[1]. This condition leads to thinning of the cornea, changes in its curvature, surface irregularities, an elevation in higher-order aberrations (HOAs), progressive irregular astigmatism, and, ultimately, a deterioration in visual acuity[2]. The exact etiology of KCN remains unclear; nonetheless, several risk factors have been identified, including familial history of the condition, parental consanguinity, habitual eye rubbing, and the presence of allergies, asthma, eczema, elevated low-density lipoprotein (LDL) levels (≥110 mg/dL), and Down syndrome[3-6]. A review conducted in 2020 indicated a global prevalence of KCN at 1.38 cases per thousand individuals[5]. In contrast, prevalence rates in Iran exhibit significant variability, ranging from below 1%[6] to as high as 4%[7]. A recent study has also shown that

5.36% of Iranians over the age of 60 are affected by KCN[8]. Additionally, certain studies have documented even greater prevalence rates, reaching up to 5% in the Middle Eastern region[9].

The shape of the cornea plays a crucial role in determining its optical power, which can be measured by analyzing several factors, including the curvature in both central and peripheral regions, asphericity, and specific parameters that describe the corneal surface[10]. A considerable number of corneal attributes can be examined through the patterns observed in corneal topography. Numerous studies have investigated the prevalence of these topographic patterns in both healthy individuals and those with KCN. Nevertheless, there has been a scarcity of comparative studies focusing on the corneal characteristics associated with various topographic patterns. Hashemi *et al*[11] demonstrated that various topographic patterns are associated with differing values of corneal curvature. Mirzajani *et al*[12] found a direct correlation between corneal topographic patterns and HOAs. In their study conducted in Tehran, Alipour *et al*[13] proposed a possible connection between corneal topographic patterns and the refractive status of the eye.

Alterations in corneal curvature and asphericity represent common observations in corneas affected by KCN[14]. Corneal topographic patterns can be interpreted as a comprehensive representation of the overall changes occurring in the cornea as a result of KCN. Consequently, it is plausible that the characteristics of KCN and its progression over time may vary across different topographic patterns. This proposition was investigated in a study conducted by Yang *et al*[15], which focused on KCN changes in relation to corneal topography. Nonetheless, the participants in this research were KCN individuals who utilized rigid contact lenses. The small sample size, the limited variety of topographic patterns, and the potential influence of rigid contact lens usage on the outcomes pose challenges in extrapolating the findings to the broader KCN population. An examination of the existing literature reveals that there has been no comprehensive investigation into the corneal characteristics associated with different topographic patterns of keratoconic corneas and their relationship to the alterations observed in KCN. This research was undertaken with this foundational assumption.

PARTICIPANTS AND METHODS

Ethical Approval Given the retrospective design of this research, it was not feasible to secure written consent from participants. The study adhered to the principles outlined in the Helsinki Declaration, and it received approval from the Ethics Committee of Iran University of Medical Sciences (IR.IUMS.REC.1403.685).

Participants This retrospective cohort study was conducted in 2024 at Noor Eye Hospital in Tehran, Iran. The research included all patients diagnosed with KCN who had undergone examinations at the hospital on a minimum of two occasions over the last 15y. The inclusion criteria included no history of ocular surgeries before the second examination, no history of systemic diseases such as diabetes or connective tissue disorders, no use of soft contact lenses within one week prior to each assessment, and no use of rigid or scleral contact lenses within two weeks before each examination. The exclusion criteria included the absence of ophthalmic examination documentation and the lack of corneal imaging data or imaging performed with devices other than the Pentacam-HR.

Examinations At each examination stage, preliminary ophthalmologic assessments were conducted to evaluate ocular structures utilizing a slit-lamp biomicroscope (Haag-Streit Corp., Switzerland) in conjunction with a Volk +90 diopter (D) lens. Following a minimum waiting period of 10min, optometric evaluations commenced, beginning with the measurement of uncorrected distance visual acuity. This was followed by objective refraction, which was carried out using an autorefractometer/keratometer (Topcon KR 8800, Topcon Corp., Tokyo, Japan). The best-corrected distance visual acuity (BCVA) was then recorded based on subjective refraction using the decimal criterion at a distance of 4 m, employing the bracketing technique[16]; this technique relied on patient cooperation and the correlation between uncorrected visual acuity and objective refraction data. Subsequently, corneal tomography was executed using the Pentacam-HR device (Oculus; Wetzlar, Germany). The second round of examinations for all participants took place after an interval of at least six months. To ensure consistency and minimize inter-observer variability, all assessments were conducted following a standardized protocol. Although multiple examiners participated in the data collection, they were trained to follow uniform procedures throughout the study; Besides, regular calibration and maintenance of Pentacam-HR devices were carried out in line with the manufacturer's guidelines to minimize data variability due to equipment aging or technical issues. This approach was maintained across all participants during both examination phases. The Pentacam-HR's refractive 4-map report, which highlighted the axial topography with a 0.50 D increment, was recorded for each individual. Corneal tomography data were collected for each eye separately; Both eyes were included in the analysis if they met the inclusion criteria and had valid Pentacam-HR imaging along with clinical record examinations from both visits.

Interpretation of Tomographic Data The diagnosis of KCN was established according to the criteria outlined in the research conducted by Rafati *et al*[17]; This includes identifying a localized steep region—commonly referred to as a "hot point"—on the corneal topographic map, where the

Table 1 Frequency and percentage of corneal topography patterns in the gender and keratoconus changes groups *n* (%)

Corneal topography patterns	Total	Male	Female	Regressive	Stable	Progressive
Round	62 (9.7)	36 (9.1)	26 (10.8)	9 (14.8)	35 (8)	18 (13.3)
Oval	31 (4.9)	19 (4.8)	12 (5)	6 (9.8)	20 (4.5)	5 (3.7)
Inferior steepening	119 (18.7)	78 (19.7)	41 (17.1)	8 (13.1)	76 (17.3)	35 (25.9)
Irregular	6 (0.9)	6 (1.5)	0	2 (3.3)	1 (0.2)	3 (2.2)
Symmetric bowtie with skewed radial axis	18 (2.8)	8 (2)	10 (4.2)	4 (6.6)	12 (2.7)	2 (1.5)
Asymmetric bowtie with inferior steepening	174 (27.4)	106 (26.8)	68 (28.3)	11 (18)	137 (31.3)	26 (19.3)
Asymmetric bowtie with superior steepening	18 (2.8)	12 (3)	6 (2.5)	3 (4.9)	15 (3.4)	0
Asymmetric bowtie with skewed radial axis	91 (14.3)	54 (13.6)	37 (15.4)	13 (21.3)	63 (14.3)	15 (11.1)
Symmetric bowtie	24 (3.8)	12 (3)	12 (5)	1 (1.6)	16 (3.6)	7 (5.2)
Kissing birds	93 (14.6)	65 (16.4)	28 (11.7)	4 (6.6)	65 (14.8)	24 (17.8)
Total	636 (100)	396 (100)	240 (100)	61 (100)	440 (100)	135 (100)

The percentages of each corneal topography pattern were presented across gender and keratoconus changes groups.

keratometry readings surpass 45.00 D. Additional indicators involve a central keratometry measurement exceeding 47.20 D, an asymmetry greater than 1.40 D between the inferior and superior corneal power, and a slope surpassing 21 degrees along the asymmetric astigmatic axes. Furthermore, the corneal thickness at the cone's apex is observed to be approximately 30 μm thinner than the measurement taken above the pupil center. KCN severity was classified according to the Amsler-Krumeich classification. Based on mean anterior keratometry, individuals were categorized into four stages: stage 1 (mean keratometry <48.00 D), stage 2 (48.00–53.00 D), stage 3 (53.00–55.00 D), and stage 4 (>55.00 D)[18].

The Rabinowitz classification system was employed in this study to categorize various topographic patterns[19]. These patterns included inferior steepening (IS), superior steepening (SS), asymmetric bowtie (AB) accompanied by SS, AB associated with IS, AB featuring a skewed radial axis (SRAX), symmetric bowtie (SB), SB with SRAX, as well as oval (O), irregular (IR), and round (R) shapes. The classification was further enhanced by including the kissing bird (KB) pattern[20].

The assessment of KCN alterations was based on variations in maximum keratometry observed between the two examinations[21]. Consequently, individuals were classified into three distinct groups: progressive (an increase of 1.00 D or more in maximum keratometry), regressive (a decrease of 1.00 D or more in maximum keratometry), and stable (variations of less than 1.00 D in maximum keratometry). The evaluated participants were also categorized into three groups based on the examination period: 0–12mo, 13–60mo, and more than 60mo.

Statistical Analysis The distribution of various patterns across the entire sample, categorized by sex and within each KCN change group, was detailed. The normality of the data distribution was assessed using the Kolmogorov-Smirnov test and drawing a Q-Q plot. Mean±standard deviations (SD) or medians with interquartile ranges (IQR) were reported for each evaluated parameter based on the normality of the distributions. Independent *t*-tests and one-way analysis of variance (ANOVA), or their nonparametric equivalents, including the Chi-square and Kruskal-Wallis tests, were used to examine differences in cases with two or multiple groupings, respectively. The frequencies of KCN progression, regression, and stability were analyzed within each topographic pattern, considering variations in sample size and morphological characteristics. Progression and regression rates were determined as the percentage of eyes within each pattern exhibiting a change of ≥1.00 D in maximum keratometry (Kmax) between examinations. All statistical evaluations were conducted using SPSS software version 26. The threshold for statistical significance was established at 0.05.

RESULTS

This study evaluated 636 eyes of 335 keratoconus (KCN) patients, with a mean age of 30.95±7.95y, including 396 males and 240 females. The average ages for males and females at the first examination were 30.35±7.70 and 30.90±8.24y, respectively, with no statistically significant difference observed (*P*=0.462). The mean interval between the two examinations was 71.04±42.02mo. Based on changes in Kmax, 69.2% of eyes were classified as stable, 21.2% as progressive, and 9.6% as regressive. The mean age of participants in the regressive, stable, and progressive groups was 32.01±8.30, 31.10±7.80, and 29.92±7.95y, respectively (*P*=0.173).

Table 1 represents the prevalence of various topographic patterns across the entire sample, categorized by sex and KCN change groups. The most prevalent topographic pattern was AB-IS at 27.4%, followed by IS at 18.7% and KB at 14.6%. The AB-IS pattern was dominant in both males (26.8%) and females (28.3%). In the regressive group, the most common patterns were AB-SRAX (21.3%), AB-IS (18.0%), and R (14.8%). In the stable group, AB-IS (31.3%), IS (17.3%), and

Table 2 Frequency and percentage of corneal topography patterns in each keratoconus stage *n* (%)

Corneal topography patterns	Stage 1	Stage 2	Stage 3	Stage 4
Round	24 (5)	24 (20)	2 (14.4)	12 (48)
Oval	16 (3.3)	8 (6.7)	3 (23.1)	4 (16)
Inferior steepening	103 (21.5)	13 (10.8)	2 (15.4)	1 (4)
Irregular	4 (0.8)	2 (1.7)	0	0
Symmetric bowtie with skewed radial axis	16 (3.3)	2 (1.7)	0	0
Asymmetric bowtie with inferior steepening	143 (29.9)	24 (20)	4 (30.80)	3 (12)
Asymmetric bowtie with superior steepening	17 (3.60)	0	0	1 (4)
Asymmetric bowtie with skewed radial axis	62 (13)	25 (20.8)	2 (15.4)	2 (8)
Symmetric bowtie	19 (4)	5 (4.20)	0	0
Kissing birds	74 (15.5)	17 (14.2)	0	2 (8)
Total	478 (100)	120 (100)	13 (100)	25 (100)

The percentages of each corneal topography pattern were presented across the different stages of keratoconus.

Table 3 Progression and regression rates in each corneal topography pattern

Corneal topography pattern	Total population		0-12mo follow-ups		13-60mo follow-ups		>60mo follow-ups	
	Regression rate	Progression rate	Regression rate	Progression rate	Regression rate	Progression rate	Regression rate	Progression rate
Round	14.50%	29.00%	0	0	9.70%	6.50%	4.90%	22.50%
Oval	19.40%	16.10%	0	0	3.30%	6.60%	16.13%	9.70%
Inferior steepening	6.70%	29.40%	0	1.70%	0.90%	1.01%	5.90%	17.70%
Irregular	33.30%	50.00%	0	0	33.40%	50.00%	0	0
Symmetric bowtie with skewed radial axis	22.20%	11.10%	0	0	11.20%	11.20%	11.20%	0
Asymmetric bowtie with inferior steepening	6.30%	14.90%	0.60%	0	2.90%	5.20%	2.90%	9.80%
Asymmetric bowtie with superior steepening	16.70%	0	5.60%	0	0	0	11.20%	0
Asymmetric bowtie with skewed radial axis	14.30%	16.50%	0	0	4.30%	6.60%	9.90%	9.90%
Symmetric bowtie	4.20%	29.20%	0	0	0	12.50%	4.20%	16.70%
Kissing birds	4.30%	25.80%	0	0	3.30%	8.70%	1.10%	17.30%
Total	9.60%	21.20%	0.30%	0.30%	3.80%	7.80%	5.60%	13.30%

KB (14.8%) were the most frequent, while in the progressive group, IS (25.9%), AB-IS (19.3%), KB (17.8%), and R (13.3%) were predominant.

Table 2 illustrates the distribution of topographic patterns across different stages of KCN, revealing distinct variations in prevalence. AB-IS was the most frequently observed pattern in early stages, while R and O patterns became more prominent in advanced keratoconus.

Table 3 presents the regression and progression rates across different follow-up periods for various topographic patterns. IR and R patterns demonstrate the highest progression rates, particularly in the total population and long-term follow-ups. Meanwhile, regression rates remain relatively low across most patterns, with notable exceptions in O and SB-SRAX groups.

Table 4 illustrates the mean/median values of the assessed parameters during the initial examination for the overall sample as well as for each specific pattern. Significant differences are observed across patterns, particularly in age distribution, refractive error, and keratometric values. The O pattern exhibited the most negative spherical equivalent (SE) and the lowest BCVA values, while the AB-SS pattern showed the least curvature. Additionally, index of surface variance (ISV) and index of vertical asymmetry (IVA) values show notable differences among the groups. The IR pattern exhibited the most adverse KCN screening indices, whereas the SB and SB-SRAX patterns demonstrated significantly better outcomes in these parameters.

Table 5 presents the alterations in each parameter between the two assessments for the overall sample, categorized by specific topographic patterns. Notable variations are observed in Kmax, anterior flat keratometry (K1F), and anterior steep keratometry (K2F) differences, with certain patterns exhibiting more pronounced shifts than others. The IR pattern showed the most significant increase in Kmax [1.35 (4.70) D], whereas the AB-SS pattern demonstrated a slight decrease in this parameter [-0.15 (0.60) D]. Additionally, significant differences in ISV, IVA, and IHD values highlight distinct variations among topographic groups.

DISCUSSION

This study represents one of the few comprehensive investigations that not only describe but also compare the characteristics of various corneal topographic patterns in KCN eyes and their association with disease behavior over time. Our findings highlight significant differences among these patterns in terms of refractive status, visual acuity, corneal shape indices, and progression trends, underscoring the importance of integrating

Table 4 The evaluated parameters in the first examination in each corneal topography patterns mean±SD or median (IQR)

Parameters	Total	R	O	IS	IR	SB-SRAX	AB-IS	AB-SS	AB-SRAX	SB	KB	*P*
Age, y	30.95±7.95	30.35±8.19	33.19±9.78	32.55±7.2	32.33±10.6	30.61±7.01	30.21±7.27	23.22±9.64	29.73±7.09	28.63±5.86	33.17±8.83	<0.001
SE	-2.25 (3.37)	-3.69 (5.50)	-4.00 (4.63)	-1.50 (2.00)	-2.12 (2.75)	-2.44 (2.13)	-2.31 (3.38)	-2.25 (3.00)	-2.37 (3.38)	-2.50 (4.68)	-2.00 (2.75)	<0.001
BCVA	0.80 (0.50)	0.60 (0.60)	0.50 (0.40)	0.80 (0.45)	0.55 (0.10)	1.00 (0.20)	0.90 (0.40)	0.80 (0.20)	0.80 (0.50)	0.80 (0.35)	0.80 (0.50)	0.001
K1F	44.50 (3.55)	47.70 (6.20)	47.40 (6.20)	44.00 (3.10)	42.95 (7.80)	43.70 (3.50)	43.90 (3.10)	42.35 (2.10)	44.90 (3.41)	44.25 (2.60)	44.60 (3.00)	<0.001
K2F	47.05 (4.90)	50.25 (8.40)	49.80 (9.60)	46.10 (3.30)	51.85 (6.80)	46.70 (3.50)	46.40 (4.30)	45.75 (1.80)	48.50 (5.70)	46.85 (3.70)	47.50 (5.00)	<0.001
Kmax F	50.30 (8.05)	56.75 (11.30)	55.00 (11.90)	50.40 (5.80)	57.20 (7.40)	48.10 (6.00)	49.00 (7.10)	47.05 (2.90)	51.60 (8.00)	48.15 (5.85)	51.60 (7.30)	<0.001
QF	-0.50 (0.52)	-1.06 (1.08)	-0.79 (0.79)	-0.31 (0.43)	-0.91 (0.56)	-0.45 (0.28)	-0.49 (0.43)	-0.44 (0.22)	-0.58 (0.48)	-0.47 (0.43)	-0.44 (0.60)	<0.001
Rperi F	7.91 (0.37)	7.81(0.41)	7.94 (0.31)	7.91 (0.29)	7.95 (0.36)	8.06 (0.51)	7.95 (0.35)	8.05 (0.23)	7.87 (0.39)	7.84 (0.51)	7.91 (0.33)	0.065
K1B	-6.40 (0.80)	-7.00 (1.20)	-6.90 (1.30)	-6.40 (0.80)	-6.05 (1.20)	-6.20 (0.60)	-6.30 (0.70)	-6.10 (0.50)	-6.50 (0.80)	-6.30 (1.10)	-6.50 (0.80)	<0.001
K2B	-6.90 (1.00)	-7.70 (1.50)	-7.60 (1.90)	-6.70 (0.70)	-7.65 (1.60)	-6.80 (0.80)	-6.90 (0.90)	-6.65 (0.60)	-7.10 (1.40)	-6.95 (0.80)	-6.70 (1.10)	<0.001
QB	-0.51 (0.83)	-1.21 (1.18)	-1.13 (1.07)	-0.37 (0.57)	-1.02 (0.82)	-0.31 (0.64)	-0.48 (0.69)	-0.35 (0.26)	-0.55 (0.83)	-0.57 (0.92)	-0.48 (0.71)	<0.001
Rper B	6.71 (0.36)	6.67 (0.45)	6.71 (0.25)	6.75 (0.35)	6.87 (0.15)	6.78 (0.44)	6.73 (0.34)	6.66 (0.40)	6.68 (0.36)	6.61 (0.38)	6.70 (0.37)	0.479
Pupil thick	490.00 (59.50)	478.00 (72.00)	478.00 (63.00)	495.00 (52.00)	497.00 (114.00)	507.50 (33.00)	492.50 (57.00)	545.00 (32.00)	478.00 (54.00)	478.50 (77.00)	496.00 (59.00)	<0.001
Thinnest	472.00 (65.00)	445.50 (78.00)	460.00 (39.00)	471.00 (61.00)	481.00 (122.00)	496.00 (39.00)	480.00 (62.00)	541.50 (26.00)	466.00 (51.00)	473.00 (73.00)	474.00 (68.00)	<0.001
ISV	52.00 (54.00)	93.50 (93.00)	75.00 (73.00)	61.00 (56.00)	104.50 (70.00)	36.00 (31.00)	45.00 (43.00)	34.00 (7.00)	54.00 (47.00)	36.00 (29.50)	66.50 (56.00)	<0.001
IVA	0.55 (0.63)	0.82 (0.94)	0.57 (0.72)	0.72 (0.69)	0.93 (0.24)	0.26 (0.29)	0.45 (0.45)	0.22 (0.07)	0.53 (0.50)	0.19 (0.24)	0.74 (0.66)	<0.001
KI	1.13 (0.16)	1.23 (0.29)	1.14 (0.20)	1.16 (0.17)	1.20 (0.33)	1.06 (0.09)	1.11 (0.11)	1.00 (0.04)	1.13 (0.13)	1.05 (0.08)	1.15 (0.14)	<0.001
CKI	1.02 (0.04)	1.08 (0.10)	1.06 (0.07)	1.01 (0.03)	1.03 (0.08)	1.02 (0.02)	1.02 (0.04)	1.01 (0.00)	1.03 (0.04)	1.02 (0.05)	1.02 (0.04)	<0.001
IHA	19.10 (25.80)	20.40 (28.30)	20.40 (26.10)	17.30 (24.70)	4.25 (24.30)	10.00 (10.20)	20.90 (28.20)	16.15 (8.80)	23.90 (25.30)	7.95 (14.6)	16.05 (21.50)	<0.001
IHD	0.06 (0.07)	0.09 (0.14)	0.07 (0.11)	0.07 (0.08)	0.12 (0.03)	0.03 (0.03)	0.04 (0.06)	0.02 (0.01)	0.07 (0.07)	0.02 (0.03)	0.07 (0.08)	<0.001
Rmin	6.71 (1.05)	5.92 (1.32)	6.14 (1.53)	6.71 (0.78)	5.90 (0.83)	7.02 (0.86)	6.89 (0.97)	7.18 (0.45)	6.54 (1.01)	7.01 (0.83)	6.55 (0.98)	<0.001

SD: Standard deviation; IQR: Interquartile range; R: Round; O: Oval; IS: Inferior steepening; IR: Irregular; SB-SRAX: Symmetric bowtie with skewed radial axes; AB-IS: Asymmetric bowtie with inferior steepening; AB-SS: Asymmetric bowtie with superior steepening; AB-SRAX: Asymmetric bowtie with skewed radial axes; SB: Symmetric bowtie; KB: Kissing birds; SE: Spherical equivalent (D); BCVA: Best corrected visual acuity (decimal); K1F: Anterior flat keratometry (D); K2F: Anterior steep keratometry (D); Kmax F: Anterior maximum keratometry (D); QF: Anterior asphericity; Rperi F: Anterior peripheral curvature (mm); K1B: Posterior flat curvature (mm); K2B: Posterior steep curvature (mm); QB: Posterior asphericity; Rper B: Posterior peripheral curvature (mm); Pupil thick: Central pupil thickness (μm); Thinnest: Thinnest corneal thickness (μm); ISV: Index of surface variance; IVA: Index of vertical asymmetry; KI: Keratoconus index; CKI: Central keratoconus index; IHA: Index of height asymmetry; IHD: Index of height decentration; Rmin: Minimum curvature (mm). One-way analysis of variance for comparison of first examination between each corneal topography patterns, *P*<0.05 considered significant.

topographic pattern analysis into routine KCN management.

The findings of this study reveal that the most common topographic pattern is AB-IS, followed by IS and KB. Notably, approximately 45% of corneas affected by KCN exhibit steepening in the inferior regions. Most studies on ectatic eyes found that the AB-SRAX pattern is the most common, followed by the AB-IS pattern[22-24]; However, the SB pattern remains the predominant configuration within the normal population of Iran[11,13], suggesting the existence of regular astigmatism in the corneal structure. The manifestation of ectasia in the cornea results in progressive thinning and weakening of the corneal structure, leading to alterations in corneal topography[25]. These changes are often characterized by irregular steepening, asymmetry, and increased curvature, which can significantly affect visual acuity[1]. Over time, the cornea may develop a more conical shape, disrupting its normal refractive properties and potentially leading to complications such as increased astigmatism and reduced optical quality[26]. These findings align with previous studies showing a predilection for inferior corneal involvement in KCN patients, likely due to mechanical stress from eyelid forces[27] and habitual eye rubbing[28].

Research conducted by Solodkova *et al*[29] examined the biomechanical properties of the cornea in patients with KCN in Russia, revealing that central KCN was the predominant type observed (18 eyes), followed by inferior KCN (16 eyes) and bowtie configurations (12 eyes). Furthermore, Rafati *et al*[17] investigated the characteristics of KCN patients referred to Noor Eye Hospital in Tehran, finding that 52.1% of the evaluated eyes displayed the central type, 43.6% were categorized as paracentral, and 4.3% were classified as peripheral. The classification system employed in the previously mentioned research was based on the location of maximum keratometry, categorized as follows: 0 to 3 mm for the central region, 3 to 5 mm for the paracentral area, and measurements beyond 5 mm for the peripheral zone. It appears that an exclusive focus on the location of maximum keratometry does not adequately encompass the entire range of corneal changes; therefore, utilizing the topographic pattern proves to be a more effective approach for characterizing these alterations. The results indicate that in the Iranian population,

Table 5 Changes of the evaluated parameters between two examinations in each corneal topography patterns mean±SD or median (IQR)

Parameters	Total	R	O	IS	IR	SB-SRAX	AB-IS	AB-SS	AB-SRAX	SB	KB	*P*
Date diff (mo)	71.04±42.01	76.73±39.22	75.7±41.14	71.89±44.91	47.83±40.68	74.94±39.48	70.71±42.21	70.39±41.35	62.89±39.7	57.87±42.24	77.41±42.19	0.251
SE diff	-0.25 (1.25)	-0.37 (1.13)	0.00 (1.25)	-0.25 (1.00)	-0.75 (0.69)	-0.25 (0.75)	-0.25 (1.25)	0.00 (1.38)	-0.25 (1.25)	-0.25 (1.57)	-0.25 (1.12)	0.936
BCVA diff	0.00 (0.10)	0.00 (0.10)	0.00 (0.10)	0.00 (0.10)	-0.05 (0.15)	0.00 (0.00)	0.00 (0.10)	0.00 (0.10)	0.00 (0.10)	0.00 (0.20)	0.00 (0.10)	0.050
K1F diff	0.10 (0.50)	0.20 (1.00)	0.00 (0.80)	0.20 (0.80)	0.15 (2.00)	-0.05 (0.40)	0.00 (0.40)	-0.20 (0.20)	0.10 (0.50)	0.15 (0.55)	0.10 (0.70)	<0.001
K2F diff	0.10 (0.60)	0.20 (1.20)	0.10 (0.50)	0.20 (0.90)	1.25 (1.60)	0.10 (0.70)	0.10 (0.50)	-0.15 (0.60)	0.20 (0.60)	0.15 (0.65)	0.20 (0.85)	0.003
Kmax F diff	0.30 (0.90)	0.20 (1.60)	0.00 (1.30)	0.40 (1.40)	1.35 (4.70)	0.15 (0.70)	0.30 (0.80)	-0.15 (0.60)	0.10 (0.70)	0.30 (1.55)	0.40 (1.10)	<0.001
QF diff	-0.03 (0.18)	0.00 (0.24)	0.01 (0.23)	-0.08 (0.24)	-0.03 (0.34)	-0.02 (0.17)	-0.02 (0.15)	0.00 (0.13)	-0.01 (0.14)	-0.05 (0.15)	-0.05 (0.15)	0.002
Rperi F diff	0.00 (0.05)	-0.01 (0.07)	-0.02 (0.09)	0.00 (0.04)	-0.02 (0.14)	0.00 (0.04)	0.00 (0.03)	0.03 (0.03)	-0.01 (0.03)	0.00 (0.02)	0.00 (0.05)	0.008
K1B diff	0.00 (0.30)	-0.10 (0.20)	0.00 (0.20)	0.00 (0.30)	-0.20 (1.20)	0.00 (0.00)	0.00 (0.20)	0.00 (0.10)	0.00 (0.20)	0.00 (0.10)	0.00 (0.30)	0.146
K2B diff	0.00 (0.20)	-0.10 (0.30)	0.00 (0.20)	-0.10 (0.30)	-0.05 (1.40)	0.00 (0.20)	0.00 (0.10)	0.00 (0.10)	0.00 (0.20)	0.00 (0.20)	0.00 (0.30)	0.076
QB diff	-0.05 (0.26)	-0.02 (0.28)	0.00 (0.25)	-0.12 (0.42)	-0.32 (0.43)	0.05 (0.38)	-0.05 (0.21)	-0.03 (0.21)	-0.03 (0.24)	-0.08 (0.13)	-0.04 (0.23)	0.069
Rper B diff	0.01 (0.07)	0.00 (0.10)	0.01 (0.11)	0.00 (0.10)	-0.05 (0.09)	0.02 (0.05)	0.01 (0.07)	0.01 (0.14)	0.00 (0.07)	0.00 (0.06)	0.01 (0.10)	0.667
Pupil thick diff	-2.00 (14.00)	-2.50 (19.00)	-2.50 (13.00)	-2.00 (15.00)	-1.50 (11.00)	-1.50 (9.00)	-2.00 (13.00)	-6.00 (12.00)	-2.00 (14.00)	-2.50 (14.00)	-2.00 (13.00)	0.868
Thinnest diff	-2.00 (15.00)	-3.50 (17.00)	-3.00 (10.00)	-3.00 (17.00)	-5.00 (15.00)	-1.00 (11.00)	-1.00 (13.00)	-4.50 (12.00)	-1.00 (16.00)	-6.00 (15.00)	-3.00 (15.00)	0.466
ISV diff	1.00 (6.00)	-1.00 (8.00)	-1.00 (6.00)	2.00 (9.00)	3.00 (7.00)	0.00 (4.00)	1.00 (4.00)	1.00 (7.00)	0.00 (5.00)	1.50 (8.00)	3.00 (8.00)	0.001
IVA diff	0.00 (0.09)	-0.02 (0.17)	-0.02 (0.09)	0.01 (0.11)	-0.06 (0.23)	0.00 (0.07)	0.01 (0.07)	0.02 (0.08)	-0.01 (0.08)	0.01 (0.10)	0.02 (0.11)	<0.001
KI diff	0.00 (0.02)	0.00 (0.04)	0.00 (0.04)	0.00 (0.04)	0.03 (0.03)	0.00 (0.02)	0.00 (0.02)	0.00 (0.02)	0.00 (0.02)	0.00 (0.04)	0.00 (0.02)	0.022
CKI diff	0.00 (0.01)	0.00 (0.01)	0.00 (0.02)	0.00 (0.01)	0.01 (0.03)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.00 (0.01)	0.00 (0.02)	0.00 (0.01)	0.013
IHA diff	1.10 (16.60)	1.90 (29.85)	-0.10 (18.70)	1.10 (23.30)	-1.35 (12.30)	-0.20 (7.90)	3.40 (12.80)	0.50 (6.00)	-2.00 (20.00)	2.50 (8.90)	1.30 (17.15)	0.669
IHD diff	0.01 (0.03)	0.01 (0.03)	0.00 (0.01)	0.02 (0.05)	0.00 (0.03)	0.00 (0.02)	0.00 (0.02)	0.00 (0.01)	0.00 (0.01)	0.01 (0.03)	0.01 (0.05)	<0.001
Rmin diff	-0.03 (0.11)	-0.02 (0.15)	0.00 (0.14)	-0.05 (0.14)	-0.13 (0.47)	0.00 (0.10)	-0.03 (0.09)	0.03 (0.08)	-0.02 (0.10)	-0.04 (0.21)	-0.05 (0.13)	<0.001

SD: Standard deviation; IQR: Interquartile range; R: Round; O: Oval; IS: Inferior steepening; IR: Irregular; SB-SRAX: Symmetric bowtie with skewed radial axes; AB-IS: Asymmetric bowtie with inferior steepening; AB-SS: Asymmetric bowtie with superior steepening; AB-SRAX: Asymmetric bowtie with skewed radial axes; SB: Symmetric bowtie; KB: Kissing birds; Diff: Difference; SE: Spherical equivalent (D); BCVA: Best corrected visual acuity (decimal); K1F: Anterior flat keratometry (D); K2F: Anterior steep keratometry (D); Kmax F: Anterior maximum keratometry (D); QF: Anterior asphericity; Rperi F: Anterior peripheral curvature (mm); K1B: Posterior flat curvature (mm); K2B: Posterior steep curvature (mm); QB: Posterior asphericity; Rper B: Posterior peripheral curvature (mm); Pupil thick: Central pupil thickness (μm); Thinnest: Thinnest corneal thickness (μm); ISV: Index of surface variance; IVA: Index of vertical asymmetry; KI: Keratoconus index; CKI: Central keratoconus index; IHA: Index of height asymmetry; IHD: Index of height decentration; Rmin: Minimum curvature (mm). One-way analysis of variance for comparison of first examination between each corneal topography patterns, *P*<0.05 considered significant.

the most significant corneal changes associated with KCN predominantly occur along the vertical axis, while horizontal changes are relatively less significant, with a higher incidence of alterations noted in the inferior sections of the cornea.

The present study reveals that the AB-SS pattern exhibits the least curvature in its central region when compared to other patterns, while also demonstrating the highest corrected visual acuity. Although superior KCN is relatively rare, it has been the subject of several studies[30-31]. Typically, alterations in curvature in the upper cornea are attributed to factors such as eyelid positioning and the tear film status, which contribute to an increased steepness in that area[30,32]. An assessment of corneal thickness, asphericity, and KCN screening indices indicates that corneas characterized by superior steepening patterns generally do not present with adverse conditions. It appears that the changes noted in the AB-SS pattern are primarily topographical, suggesting that these corneas do not exhibit significant deviations from normal conditions. Additionally, the preservation of central curvature and acceptable corrected visual acuity in AB-SS cases may indicate that standard treatment protocols for KCN need to account for these variations in topographic presentation[33].

The present study shows that the presence of skewness alone does not lead to significant alterations in corneal status. The findings demonstrate that the corrected visual acuity for the SB-SRAX and AB-SRAX patterns was measured at 1.00 and 0.80, respectively, while the maximum corneal curvature for these patterns was recorded at 48.10 and 51.60 D, respectively. Existing literature suggests that a skewness exceeding 21 degrees is regarded as a potential risk factor for ectasia[34]. Skew ray error is identified as a specific error in Placido disk-based imaging systems, attributed to the absence of rotational symmetry of the cornea in relation to the topographer axis, which results in inaccuracies in the captured images[35]. This error likely contributes to unintended skewness in both the upper and lower sections of symmetric and asymmetric dumbbell shapes, and it appears that a similar error is also present in Scheimpflug-based imaging systems. In the present study, the precise measurement of skewness was not conducted; however, it appears that an increase in this angle, along with a topographic configuration resembling KB, correlates with a worsening of KCN and diminished visual acuity, particularly when considering the skewness and asymmetry of the lower segment in relation to the upper segment (approaching pellucid like KCN)[36]. The pattern of changes in the lower corneal region, particularly those associated with SRAX or progressing toward KB, plays a crucial role in selecting and customizing treatment options such as intracorneal ring segments[37]. As a point, annular intra-stromal rings are more effective for central KCN, while segmental rings offer greater advantages in cases of paracentral KCN[38].

Notably, a comparative analysis of KCN screening indices between the SB-SRAX and AB-SRAX patterns reveals significant disparities in these metrics, particularly in the ISV and IHA, which correspond with lower corrected visual acuity in the AB-SRAX pattern. This suggests that the increased asymmetry in the AB-SRAX pattern may contribute to greater optical aberrations, reduced corneal stability, and may even increase in progression risk. Studies have indicated that irregular corneal morphology, particularly in cases with higher skewness and asymmetry, is associated with a decline in visual acuity due to disruptions in the regular distribution of refractive power[39]. It is also important to recognize that skewness may serve as an indicator of substantial alterations in the KCN cornea[40]; however, other characteristics such as asymmetry and the presence of localized steepening will also play a critical role in determining the overall condition of the cornea. Increasing the SRAX value and corneal alterations toward pellucid marginal degeneration (PMD) status results in significant changes in refractive error. Eyes with PMD typically exhibit against-the-rule (ATR) astigmatism, which is a characteristic feature of this condition[41].

The findings of the present study indicate that the O pattern is associated with the lowest corrected visual acuity, followed by the IR and R patterns. These patterns demonstrated more negative SE values in comparison to other configurations, whereas the IS pattern exhibited the least negative SE among the various patterns analyzed. It appears that ectasia occurring in the central regions of the cornea correlates with a myopic shift, potentially attributable to an increase in anterior chamber depth[42]. Moreover, the R and O patterns displayed the highest keratometry measurements in the central area, which inherently elevates corneal power and, as a result, heightens the probability of developing greater myopia[43]. An important factor in the relationship between topographic patterns and SE is the degree of corneal astigmatism. A direct association exists between the absolute value of SE and corneal astigmatism, which may have influenced the observed relationships[44]. The irregularities on the corneal surface commonly led to a significant rise in HOAs, ultimately diminishing visual acuity[45]. Additionally, alterations in the biometric measurements of the eye, coupled with variations in HOAs, are anticipated[46]. Changes in biometric parameters, including anterior chamber depth, at various stages of KCN[42], will further contribute to diminished corrected visual acuity. The presence of highly irregularities in these patterns may indicate a greater need for specialized optical correction, such as scleral lenses or hybrid lenses, to mitigate the effects of HOAs[47]. Advanced wavefront-guided approaches may provide improved visual quality for patients exhibiting these irregular patterns[48].

KCN progression varies with age, showing signs of improvement, stability, or worsening[49]. Due to the lack of a universal criterion for defining change[21], different studies report varying observations. In this study, we assessed alterations between two examinations without considering a specific time frame, defining progression based on an increase or decrease of at least 1.00 D in anterior Kmax. Our primary focus was to compare changes related to topographic patterns, rather than the timing of examinations. A key aspect of corneal progression assessment is adapting the definition of progression to the specific KCN type within a population. Relying solely on central corneal metrics such as step keratometry, mean keratometry, and corneal astigmatism[50] may not accurately reflect changes in cases where paracentral or peripheral corneal regions are affected.

The findings of the present study suggest that KCN can exhibit progression, regression, and stability across various topographic patterns. Among the various corneal topographic patterns observed, significant differences were noted in terms of progression, regression, and stability. The IR and IS patterns showed the highest rates of progression, at 50% and 29.4%, respectively, suggesting a strong association with disease activity. In contrast, the AB-SS pattern demonstrated the lowest progression rate (0) indicating relative stability. The IR and SB-SRAX patterns exhibited relatively high regression rates (33.3% and 22.2%, respectively), potentially reflecting post-stabilization changes.

Notably, the IR pattern, although rare (n=6), was the most unstable, showing both high progression and regression rates, likely due to underlying biomechanical instability or active inflammation. The presence of active pathologies, such as hydrops[51], in the keratoconic cornea likely contributes to the IR pattern, leading to an unstable KCN condition. Furthermore, the analysis of the assessed parameters reveals that significant alterations occurred in the cornea characterized by the IR between the two evaluations, with the mean changes in maximum keratometry for eyes exhibiting the IR pattern being the most pronounced among all patterns. These findings highlight the necessity for aggressive monitoring and individualized management in patients with IR patterns. The instability observed suggests that early intervention, such as corneal cross-linking, may be crucial in halting further progression[52].

The existing literature suggests that the correlation between topographic patterns and changes in KCN has been primarily investigated in the research conducted by Yang *et al*[15]. This study found that keratoconic patients utilizing rigid contact lenses exhibited a corneal pattern characterized by a flat center and steep mid-periphery following lens removal. The findings indicated that the application of rigid contact lenses was linked to a decrease in central corneal curvature for the majority of subjects studied, and the resultant pattern and alterations were associated with this phenomenon. Given that the observed pattern was undoubtedly affected by using contact lenses, the topographic and tomographic changes noted in the two assessments cannot be directly attributed to the identified pattern.

The current study's findings further reveal that IS and AB-IS patterns were the most prevalent in the progressive group, while AB-SRAX and AB-IS patterns were the most common among regressive cases. This suggests a potential interplay between corneal structural integrity and the natural history of disease progression. Clinically, patients presenting with IS and AB-IS patterns may require closer monitoring, as these configurations might indicate a predisposition toward disease worsening. The regression observed in AB-SRAX and AB-IS patterns prompts further investigation into the potential role of biomechanical stabilization or even improvement mechanisms in specific keratoconic subtypes[53]. The stage of KCN is a key characteristic in assessing disease progression. Due to the limitation that a large proportion of individuals in Amsler-Krumeich classifications[18] in the stages of three and four had a history of corneal surgery, many patients in these advanced stages could not be evaluated in the present study. The results of this study reveal that AB-IS was the most commonly observed pattern in the initial stages, whereas R and O patterns became increasingly prevalent as KCN progressed to advanced stages. These findings suggest that KCN affecting the central regions of the cornea is linked to a higher likelihood of progression, an important factor to consider in clinical decision-making.

The extended interval between examinations was both a characteristic and a limitation of this study. Categorizing the examination periods into three groups—less than a year, one to five years, and more than five years—revealed that significant corneal changes may not occur over short durations, whereas longer follow-up periods allow for more noticeable variations; This issue has been examined from multiple perspectives thus far[21,54]. The findings of this study revealed that while most eyes remained stable over short intervals, changes in both progression and regression were observed over longer durations. The present study indicate that the IR and R patterns exhibit the highest progression rates, especially within the overall population and extended follow-up periods. In contrast, regression rates tend to remain low across most patterns, although the O and SB-SRAX groups display notable exceptions, showing a higher tendency for regression. These variations were accompanied by differences among topographic patterns, reflecting distinct trends in corneal changes based on the nature of KCN.

Eye rubbing is a critical risk factor influencing the development and alterations associated with KCN. This action can be performed using the fingertip, knuckle, or nail, with the knuckle exerting the most substantial mechanical pressure on the cornea[55]. It appears that more vigorous eye rubbing correlates with greater changes in the keratoconic cornea[56], and since varying degrees of KCN are linked to distinct topographic patterns, the nature and frequency of eye rubbing may also play a role in the emergence of these different topographic configurations. Furthermore, the prevalence of eye rubbing differs among various communities, influenced by varying levels of UV exposure[57]. This observation may indirectly validate the distinctions in topographic patterns observed across these communities. Such considerations could further elucidate how environmental factors contribute to the variations in corneal alterations associated with different patterns. Given the absence of a clear standard for assessing both the nature and frequency of eye rubbing, and the finding that many individuals with KCN are often unaware of the relationship between eye rubbing and the condition[58], it is advisable that this matter be addressed in forthcoming research.

This study faced several limitations that should be considered when interpreting the results. Certain topographic patterns, such as the IR pattern, were underrepresented in the sample, reducing the statistical power and limiting the generalizability of findings for these specific configurations. The retrospective nature of the study resulted in widely varying follow-up intervals, ranging from 6mo to over 15y, potentially influencing the interpretation of progression and regression trends. Additionally, a limited sample size in certain follow-ups, specific topographic patterns, and advanced keratoconus stages restricted the ability to fully generalize the findings to the broader KCN population.

Efforts were made to minimize inter-observer variability through a standardized data collection protocol; however, the involvement of multiple examiners may have introduced minor inconsistencies in measurements. Furthermore, the SS pattern was either extremely rare or entirely absent in this cohort, preventing meaningful analysis of its clinical significance. Another limitation was the lack of formal assessment of eye rubbing behavior, despite its well-documented role in KCN progression. Future prospective studies with larger, more balanced samples, standardized follow-up intervals, and structured behavioral assessments are necessary to validate these findings and further explore the clinical implications of rare topographic patterns.

In conclusion, corneal topographic patterns in KCN exhibit distinct morphological, refractive, and progression characteristics. Understanding these differences can significantly enhance clinical decision-making, enabling earlier detection of progressive cases and more effective tailoring of treatment strategies. This study demonstrates that patterns such as IS and AB-IS are associated with higher progression rates, while configurations like AB-SS tend to be more stable. The IR pattern, although rare, shows the greatest instability and visual compromise, highlighting the need for close monitoring and timely intervention. These findings emphasize the importance of integrating corneal pattern recognition into routine KCN management, not only for diagnosis but also for predicting disease behavior and optimizing therapeutic outcomes.

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