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ORIGINAL ARTICLE

Age-Related Changes in Refractive, Corneal, and Ocular Residual Astigmatism: A Power Vector Analysis

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Abstract

Introduction: Astigmatism results from the combined contribution of corneal and internal ocular components. Understanding the relationship between refractive astigmatism (RA), corneal astigmatism (CA), and ocular residual astigmatism (ORA) across different age groups is essential for optimizing outcomes in refractive surgery, toric intraocular lens implantation, and contact lens correction. **Materials and Methods:** This prospective cross-sectional study was conducted at a tertiary care hospital in South India from July 2023 to March 2024. A total of 150 eyes from 86 patients aged 10–59 years were included and categorized into five age groups. RA and CA were measured using automated refractometry and keratometry. ORA was calculated using power vector analysis as described by Thibos. Statistical analysis included descriptive statistics and Pearson correlation. **Results:** Refractive astigmatism was predominantly with-the-rule (WTR) in younger age groups (81% in 10–19 years) and shifted progressively to against-the-rule (ATR) in older age groups (76.9% in 50–59 years). Corneal astigmatism showed a similar age-related trend, with decreasing WTR and increasing ATR patterns. In contrast, ORA remained predominantly ATR (66%) across all age groups without significant age-related variation. ORA was found to compensate for corneal astigmatism in younger individuals and accentuate it in older individuals. **Conclusion:** Refractive astigmatism shows a significant age-related shift influenced primarily by corneal changes and modulated by ocular residual astigmatism. Accurate assessment of ORA is crucial for individualized refractive correction and improving surgical outcomes.

Keywords: Refractive astigmatism, Corneal astigmatism, Ocular residual astigmatism, Power vector analysis, Age-related changes, Toric intraocular lens

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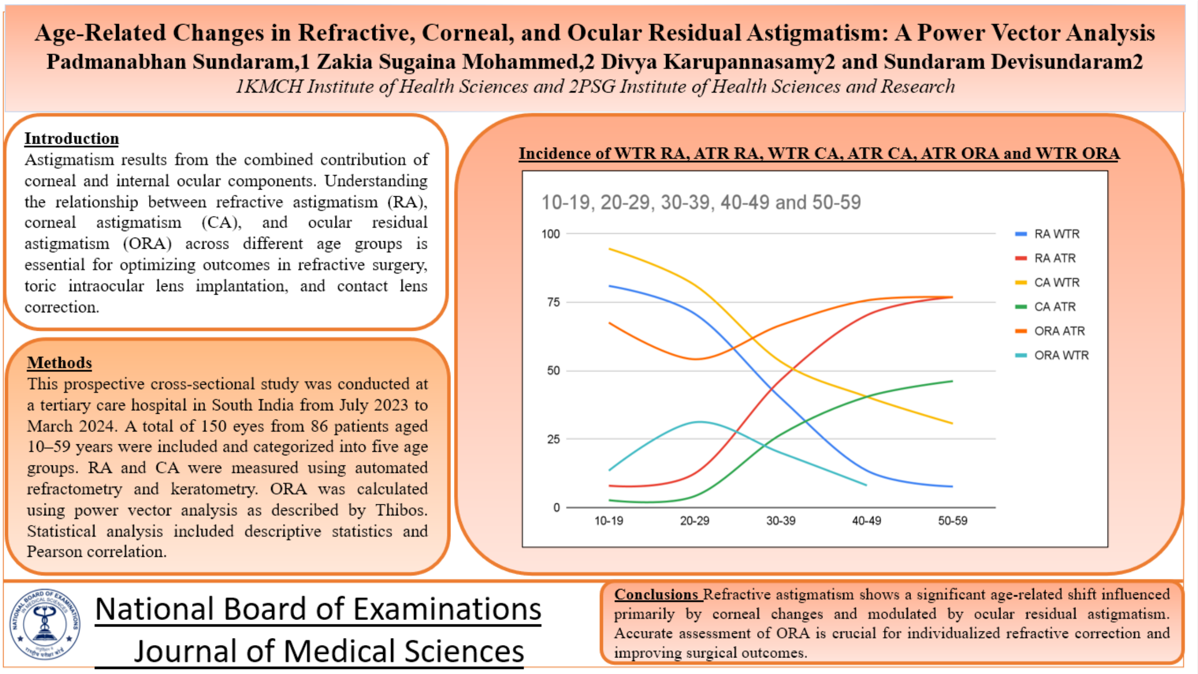
Graphical Abstract



Introduction

Astigmatism is one of the most common refractive errors globally, affecting both children and adults [1]. It arises due to meridional asymmetry of the cornea or lens, lens tilt or decentration, variations in refractive index within the crystalline lens [2], or posterior segment asymmetry [3], leading to unequal refraction of light along different meridians.

Astigmatism is classified based on axis orientation into regular (with-the-rule [WTR], against-the-rule [ATR], and oblique) and irregular types. Regular astigmatism occurs when principal meridians are perpendicular, while irregular astigmatism involves multiple meridians. Based on contributing components, refractive astigmatism (RA) represents total ocular astigmatism and is the sum of corneal astigmatism (CA) and ocular residual astigmatism (ORA). ORA, a term introduced by Alpins [4], accounts for internal ocular contributions including posterior corneal astigmatism, lenticular, and retinal factors. While RA and CA can be directly measured, ORA is derived mathematically using power vector analysis as described by Thibos [5].

Although internal astigmatism was recognized early [6], detailed evaluation of its relationship with RA and CA has expanded after the introduction of power vector analysis. ORA has been shown to significantly influence outcomes in refractive procedures such as LASIK [7,8], LASEK [9], SMILE [10], orthokeratology [11], and RGP lens fitting [12]. It also plays a compensatory role in early life, particularly in offsetting WTR astigmatism [11,13,14], while studies in elderly populations highlight age-related changes in astigmatism patterns [15].

Several studies have explored age-related variations in astigmatism components. Attebo et al. [16] reported increasing ATR astigmatism with age, while Remon et al. [17], Leung et al. [18], Harvey et al. [19], Schuster et al. [20], Naeser et al. [21], and Rozema et al. [22] demonstrated shifts in astigmatism patterns across different age groups. However, Indian studies utilizing power vector analysis remain limited. Senthil et al. [23] demonstrated its application in evaluating surgically induced astigmatism.

Given the limited Indian data and the clinical importance of understanding astigmatism components, this study was undertaken to analyze RA, CA, and ORA using power vector analysis across different age groups (10–59 years). Patients above 60 years were excluded due to potential confounding effects of cataract-induced astigmatism [24,15].

Materials and Methods

A prospective cross-sectional study was conducted among patients attending the Ophthalmology outpatient department of a multidisciplinary tertiary care hospital in South India between July 2023 and March 2024. The study protocol was approved by the Institutional Ethics Committee (Approval No: PSG/IHEC/2023Appr/Exp/101), and the study adhered to the tenets of the Declaration of Helsinki. Written informed consent was obtained from all participants, and assent with parental/guardian consent was obtained for minors.

The sample size was calculated based on a reported prevalence of astigmatism of 13% as stated by Schuster et al. [20], using the formula $n = 4pq/d^2$, with an absolute precision (d) of 6% and an anticipated non-response rate of 25%, yielding a required sample size of 150 eyes.

A total of 150 eyes from 86 patients aged 10–59 years, irrespective of gender, with a minimum refractive astigmatism of 0.5 diopters were included in the study. Participants were recruited using consecutive sampling. Patients with ocular surface disorders, squint, intraocular diseases such as uveitis, cataract, or glaucoma, history of contact lens use, or prior extraocular or intraocular surgery were excluded.

Participants were categorized into five age groups: 10–19, 20–29, 30–39, 40–49, and 50–59 years. All subjects underwent a comprehensive ophthalmic evaluation including visual acuity assessment, retinoscopy, automated refractometry and keratometry, subjective refraction, non-contact tonometry, and slit-lamp examination. Refractive astigmatism (RA) and corneal astigmatism (CA) were measured using an automated refractometer and keratometer (TOPCON KR-800). All measurements were performed by the same examiner to minimize inter-observer variability.

Ocular residual astigmatism (ORA) was calculated using power vector analysis as described by Thibos et al. [5]. Refractive and corneal cylinder values were converted into their vector components J0 and J45 using the following equations:

$$J0 = -C/2 \times \cos(2\beta)$$
$$J45 = -C/2 \times \sin(2\beta)$$

where C represents cylinder power and β represents the positive cylinder axis. J0 corresponds to the Jackson cross-cylinder power at 0° and 90°, and J45 corresponds to the Jackson cross-cylinder power at 45° and 135°. Both RA and CA were converted to positive cylinder format prior to analysis.

ORA was determined as the vectorial difference between refractive and corneal astigmatism:

$$J0\ (ORA) = J0\ (RA) - J0\ (ACA)$$
$$J45\ (ORA) = J45\ (RA) - J45\ (ACA)$$

The magnitude and axis of ORA were calculated as:

ORA magnitude = $2\sqrt{(J0^2 + J45^2)}$
Axis of ORA = $\frac{1}{2} \tan^{-1} [J45 / J0] + 90°$

Descriptive statistics were expressed as frequencies and percentages. Pearson correlation coefficient was used to assess the strength and direction of association between continuous variables. A p-value of <0.05 was considered statistically significant. All data were entered in Microsoft Excel and analyzed using SPSS software (version 28).

Results

The overall distribution of astigmatism showed that refractive astigmatism (RA) was predominantly with-the-rule (WTR) (50.7%), followed by against-the-rule (ATR) (34.7%) and oblique astigmatism (14.6%). Corneal astigmatism (CA) demonstrated a stronger predominance of WTR (67.3%), with lower proportions of ATR (18.7%) and oblique (13.3%). In contrast, ocular residual astigmatism (ORA) exhibited a markedly different pattern, being predominantly ATR (66%), while WTR (17.3%) and oblique (16.7%) were comparatively less frequent. This indicates that although corneal astigmatism largely determines the WTR nature of refractive astigmatism, the predominantly ATR nature of ORA plays a significant modifying role in the overall refractive outcome (Table 1).

Analysis across different age groups revealed a clear age-related shift in the pattern of astigmatism. In younger individuals (10–19 years), both refractive and corneal astigmatism were predominantly WTR (81% and 94.6%, respectively), while ORA was mainly ATR (67.6%), suggesting a compensatory role. With increasing age, the proportion of WTR astigmatism progressively decreased, while ATR astigmatism increased in both RA and CA, becoming predominant in older age groups (76.9% in 50–59 years). ORA consistently remained predominantly ATR across all age groups (ranging from 52.1% to 76.9%) without a significant age-dependent trend. These findings indicate that ORA compensates for corneal WTR astigmatism in younger individuals and accentuates ATR astigmatism in older individuals, thereby influencing the overall refractive astigmatism pattern with age (Table 2).

Table 1. Overall astigmatism (n=150)

Type of astigmatism	WTR	ATR	OBLIQUE
RA	76(50.7%)	52(34.7%)	22(14.6%)
CA	101(67.3%)	28(18.7%)	20(13.3%)
ORA	26 (17.3%)	99(66%)	25(16.7%)

Table 2. Proportion of WTR, ATR and oblique astigmatism in RA, CA and ORA in different age groups (in numbers and by percentage)

Age group (number of eyes)	Type of astigmatism	Component of astigmatism		
		CA n (%)	ORA n (%)	RA n (%)
10-19(n=37)	WTR	35(94.6)	5(13.5)	30(81)
	ATR	1(2.7)	25(67.6)	3(8)
	OBLIQUE	1(2.7)	7(18.9)	4(11)
20-29(n=48)	WTR	39(81.3)	15(31.2)	34(70.8)
	ATR	2(4.2)	26(54.2)	6(12.5)
	OBLIQUE	6(12.5)	7(14.6)	8(16.7)
30-39(n=15)	WTR	8(53.3)	3(20)	6(40)
	ATR	4(26.7)	10(66.7)	7(46.7)
	OBLIQUE	3(20)	2(12.3)	2(13.3)
40-49(n=37)	WTR	15(40.5)	3(8.1)	5(13.5)
	ATR	15(40.5)	28(75.7)	26(70.3)
	OBLIQUE	7(18.9)	6(16.2)	6(16.2)
50-59(n=13)	WTR	4(30.7)	0	1(7.7)
	ATR	6(46.2)	10(76.9)	10(76.9)
	OBLIQUE	3(23.1)	3(23.1)	

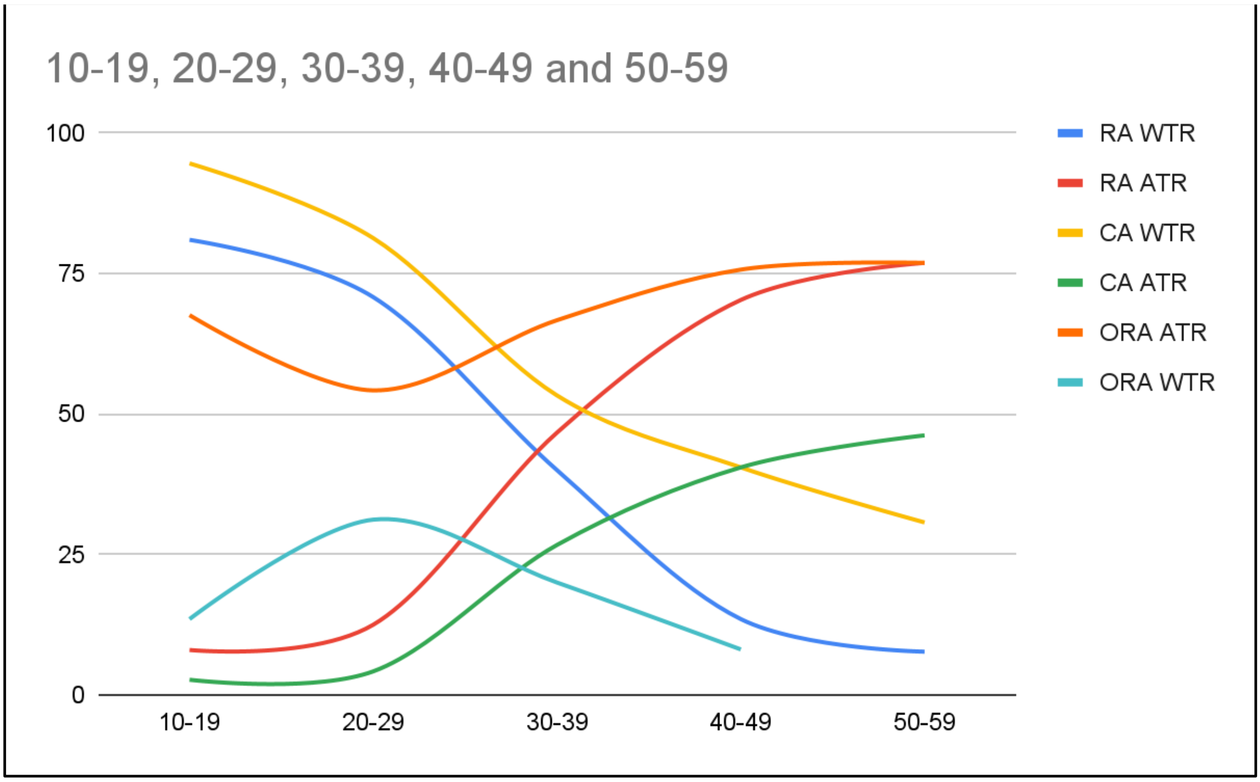


Figure 1. Showing course of incidence of WTR RA, ATR RA, WTR CA, ATR CA, ATR ORA and WTR ORA (in percentage) with increasing age

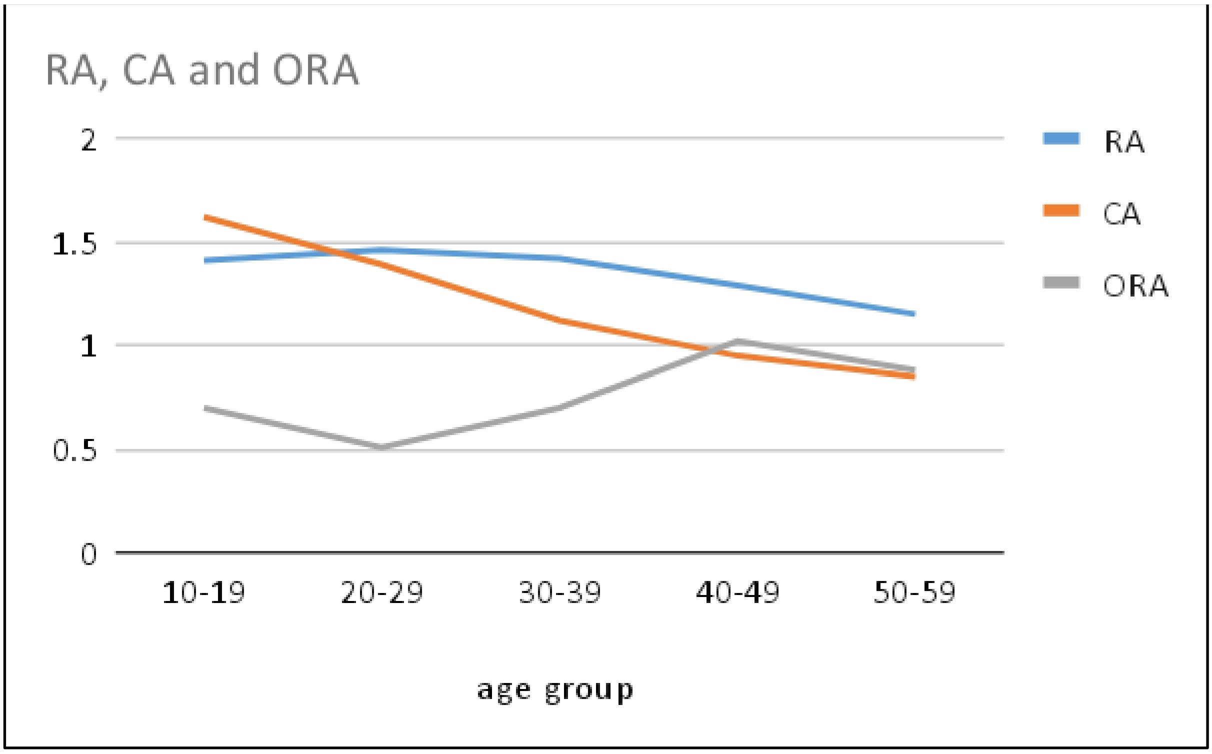


Figure 2. Showing course of magnitude of RA, CA and ORA with increasing age.

Vertical axis: Magnitude of astigmatism in diopters, horizontal axis shows increasing age groups

Discussion

A total of 150 eyes from 86 subjects were included in this study, distributed across five age groups (10–19, 20–29, 30–39, 40–49, and 50–59 years). The magnitude of refractive astigmatism ranged from 0.5 to 5.75 D with a mean of 1.375 ± 1.03 D. Unlike many previous studies that predominantly focused on myopic astigmatism [9,11,25], the present study included a broader spectrum of refractive errors such as compound hypermetropic astigmatism [15], simple myopic astigmatism [10], mixed astigmatism [19], and compound myopic astigmatism [18], thereby providing a more comprehensive representation. Refractive astigmatism was predominantly with-the-rule (WTR) (54.7%), followed by against-the-rule (ATR) (34.7%) and oblique astigmatism (14.6%), while corneal astigmatism was mainly WTR (67.3%) and ocular residual astigmatism (ORA) was predominantly ATR (66%).

The pattern of corneal astigmatism demonstrated a clear age-related transition. The mean corneal astigmatism was 1.26 ± 0.94 D, ranging from 0 to 5 D. In younger individuals (10–19 years), corneal astigmatism was almost entirely WTR (94.6%) with minimal ATR (2.7%). With increasing age, the proportion of WTR progressively declined to 30.7% in the 50–59 age group, while ATR increased to 46.2%. Notably, in the 40–49 age group, WTR and ATR were equal (40.5% each), indicating a transitional phase. This shift from WTR to ATR with advancing age is consistent with earlier observations by Baldwin and Mills [26] and Leung et al. [18]. The underlying mechanism is attributed to age-related biomechanical changes in the cornea, including reduction in eyelid pressure effects and progressive flattening of the vertical meridian, resulting in relative steepening of the horizontal meridian. Additionally, the proportion of oblique astigmatism increased with age, from 2.7% in the youngest group to 23.1% in the oldest group, consistent with findings by Ho et al. [27].

Refractive astigmatism followed a pattern closely paralleling corneal astigmatism. It was predominantly WTR in younger individuals (81% in 10–19 years) and shifted progressively towards ATR dominance with age (76.9% in 50–59 years). This observation is in agreement with the meta-analysis by Zhang et al. [28], which reported WTR predominance in individuals below 40 years and increasing ATR and oblique astigmatism with age. Similar trends have also been reported by Ho et al. [27] and Leung et al. [18]. Furthermore, Naeser et al. [21] observed a gradual increase in ATR astigmatism after 50 years of age. The strong positive correlation observed between refractive astigmatism and corneal astigmatism (WTR and ATR) suggests that corneal astigmatism is the primary determinant of refractive astigmatism patterns.

However, the role of ORA is crucial in modulating this relationship. In younger age groups, the proportion of WTR refractive astigmatism was lower than corneal astigmatism, while in older age groups, ATR refractive astigmatism exceeded corneal astigmatism. This is explained by the predominantly ATR nature of ORA across all age groups, which compensates for WTR corneal astigmatism in younger individuals and accentuates ATR corneal astigmatism in older individuals. Similar compensatory and augmenting effects of ORA have been reported by Rozema et al. [22] and Liu et al. [25], particularly in younger populations.

Correlation analysis further supported this relationship, showing strong positive correlations between refractive and corneal astigmatism, and contrasting associations with ORA, highlighting its modifying influence on overall refractive astigmatism.

The magnitude of refractive astigmatism also demonstrated a strong positive correlation with corneal astigmatism and a negative correlation with ORA, suggesting that while corneal factors contribute directly to the magnitude of astigmatism, ORA plays a modulatory role. Similar findings have been reported in earlier studies [18], emphasizing the interplay between corneal and internal components in determining refractive astigmatism.

Ocular residual astigmatism in this study had a mean value of 0.73 ± 0.59 D, ranging from 0.01 to 4.46 D, which is comparable to findings reported by Lin et al. [13], Tang et al. [29], and Mohammedpour et al. [30]. ORA was predominantly ATR (66%), with WTR and oblique components contributing 17.3% and 16.7%, respectively. This predominance of ATR ORA is consistent with previous studies, including those by Remon et al. [17] and Lin et al. [13]. Importantly, the proportion of ATR ORA remained relatively stable across all age groups (52.1%–76.9%), indicating that ORA does not exhibit significant age-dependent variation, unlike corneal and refractive astigmatism.

The consistent ATR nature of ORA explains its dual role: compensating for WTR corneal astigmatism in younger individuals and amplifying ATR corneal astigmatism in older individuals. In cases where ORA is WTR, it may further enhance WTR refractive astigmatism, particularly in younger age groups. These findings highlight the importance of individualized assessment of ORA, especially in refractive surgical planning. High ORA has been associated with suboptimal outcomes in LASIK [7], LASEK [9], and SMILE procedures [10], as well as in orthokeratology [11]. Additionally, accurate consideration of ORA is essential in toric intraocular lens calculations, where posterior corneal astigmatism also plays a significant role [31,32].

ORA includes contributions from posterior corneal astigmatism (PCA), which is typically ATR in nature, and lenticular astigmatism. Although keratometry accounts for total corneal power, it does not measure posterior corneal astigmatism directly, thereby including it within ORA. Advances in imaging techniques such as Scheimpflug imaging have enabled direct measurement of PCA, which has been reported to be approximately 0.25–0.3 D and predominantly ATR [21,32]. The remaining component of ORA is likely lenticular, which may vary in orientation and magnitude, explaining the presence of WTR and oblique ORA in some individuals. Further studies are required to isolate and quantify these components more precisely.

Unlike many previous studies that focused exclusively on myopic populations, the present study included all types of refractive errors, enhancing its generalizability. However, Hashemi et al. [33] reported that emmetropic individuals tend to have WTR ORA, a group that was not included in the present study. Additionally, oblique astigmatism was observed across all components (RA, CA, ORA) with proportions ranging from 2.7% to 23.1%, indicating its variable but significant presence.

The study has certain limitations. The sample size was relatively small and based on an OPD-based convenience sampling method, resulting in unequal distribution across age groups. Older age groups had fewer participants due to exclusion of individuals with cataract and other intraocular conditions. This uneven distribution may affect the precision of age-specific estimates. Nevertheless, the observed trends are consistent with findings from previous studies. Larger population-based studies in the Indian context, incorporating advanced imaging modalities for posterior corneal astigmatism and modern astigmatism calculators, are recommended to further enhance understanding of astigmatism components.

Conclusion

Refractive astigmatism demonstrates a clear age-related shift from predominantly with-the-rule in younger individuals to against-the-rule in older age groups, largely reflecting corresponding changes in corneal astigmatism. Ocular residual astigmatism, which remains predominantly against-the-rule across all age groups, plays a crucial modulatory role by compensating for corneal astigmatism in younger individuals and accentuating it in older individuals. This dynamic interaction between corneal and internal ocular components significantly influences the overall refractive astigmatism pattern. Therefore, accurate estimation of ocular residual astigmatism is essential for individualized planning in refractive surgery and toric intraocular lens implantation, as it contributes to variability in surgical outcomes and refractive correction.

Statements and Declarations

Conflicts of interest

The authors declare that they do not have conflict of interest.

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No funding was received for conducting this study.

Human and animal rights

This article does not contain any studies with human participants or animals performed by any of the authors.

Ethics approval

The study protocol was approved by the Institutional Ethics Committee (Approval No: PSG/IHEC/2023Appr/Exp/101),

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