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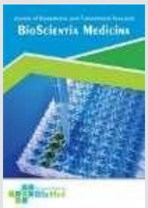

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Tear Reservoir Thickness and Vector-Resolved Refractive Outcomes in Indonesian Corneal Ectasia: A Scleral Lens Pilot Study

Anak Agung Ayu Putri Prematura Sri Anasary[1]*, Ariesanti Tri Handayani[1]

[1]Department of Ophthalmology, Faculty of Medicine, Universitas Udayana, Denpasar, Indonesia

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***Corresponding author:**
Anak Agung Ayu Putri Prematura Sri Anasary

E-mail address:
prematuraa@gmail.com

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A B S T R A C T

Background: Corneal ectasia is characterized by high-order aberrations and irregular astigmatism, presenting significant optical challenges. Scleral lenses neutralize these irregularities via a post-lens tear reservoir. However, the precise optical contribution of the tear reservoir thickness itself to residual refractive error remains under-characterized, particularly in Southeast Asian populations where aggressive ectasia phenotypes are common. This study aimed to determine if tear reservoir thickness correlates with residual refractive error using vector analysis. **Methods:** This retrospective pilot study analyzed 12 eyes of 8 patients with severe corneal ectasia fitted with scleral lenses in Indonesia. Refractive outcomes were converted to Thibos power vectors (M, J0, J45). To account for bilateral eye correlations, linear mixed models (LMM) were employed with Patient ID as a random effect. A theoretical thick-lens model compared predicted versus observed over-refraction. **Results:** The cohort (mean age 28 ± 10.2 years) achieved significant visual improvement (LogMAR 0.35 to 0.17; $p = 0.005$). The mean tear reservoir thickness was 263.33 ± 80.92 µm. LMM analysis revealed no statistically significant correlation between fluid thickness and Spherical Equivalent (M) (beta = -0.001, $p = 0.72$) or Blur Strength ($p = 0.68$). The theoretical model indicated that residual error was driven by uncorrected posterior corneal astigmatism rather than fluid depth. **Conclusion:** In this Indonesian cohort, optical efficacy was driven by refractive index matching at the corneal interface, not reservoir thickness. Clinical fitting should prioritize physiological clearance over refractive manipulation.

1. Introduction

Corneal ectasia represents a debilitating spectrum of structural ocular pathologies characterized by progressive thinning, steepening, and biomechanical destabilization of the corneal stroma. While Keratoconus remains the predominant phenotype, this category encompasses pellucid marginal degeneration and iatrogenic post-refractive surgery ectasia, all of which share a common optical consequence: the degradation of the visual image due to severe irregular astigmatism. The optical profile of the ectatic eye is defined by a chaotic wavefront, dominated by high-order aberrations (HOAs) such as vertical coma and spherical aberration, which cannot be adequately corrected by conventional spectacle lenses.[1]

In the Southeast Asian context, and specifically within the diverse demographics of the Indonesian archipelago, the management of corneal ectasia poses unique challenges. Emerging epidemiological data and clinical observations suggest that keratoconus in this region often manifests with a more aggressive phenotype and an earlier age of onset compared to Caucasian cohorts.[2] This early onset places a substantial burden of visual impairment on the working-age population, carrying significant socioeconomic implications for the region. Consequently, the demand for effective, non-surgical visual rehabilitation is acute.[3]

Historically, rigid gas-permeable (RGP) corneal lenses served as the gold standard for non-surgical management. By creating a tear lens that masks corneal irregularity, RGPs provide superior optics to soft lenses.[4] However, the fitting philosophy often necessitates "apical bearing," where the lens rests on the cone apex. In fragile, highly steep corneas, this mechanical interaction can compromise the epithelial integrity, leading to scarring, oxidative stress, and eventual contact lens intolerance.

Scleral lenses have fundamentally revolutionized this landscape. Unlike their corneal counterparts, scleral lenses are large-diameter devices that vault the entire cornea and limbus, landing solely on the relatively insensitive bulbar conjunctiva and underlying sclera.[5] This mechanical bridging protects the compromised cornea from physical trauma. However, the optical magic of the scleral lens lies in the "tear reservoir"—a fluid-filled vault created between the posterior lens surface and the anterior cornea.

The tear reservoir is not merely a passive buffer; it acts as an active optical element, frequently described in physiological optics as a "liquid lens". The efficacy of this system relies on Snell’s Law of Refraction. The refractive index of the tear film (n is approximately 1.336) is nearly identical to that of the anterior corneal epithelium (n is approximately 1.376). When the irregular anterior corneal surface is immersed in this tear reservoir, the optical interface between the air and the irregular cornea is eliminated. It is replaced by the interface between the tear fluid and the smooth, precision-manufactured posterior surface of the scleral lens. Theoretical models suggest that this index-matching mechanism can neutralize approximately 90% of anterior corneal astigmatism.[6]

Despite the widespread adoption of scleral lenses, a critical optical question remains debated in clinical fitting: Does the geometric thickness of this tear reservoir contribute to the residual refractive error? In classical optics, a fluid lens formed by a contact lens has a power defined principally by the difference in curvature between the lens and the cornea. However, the "Thick Lens Equation" introduces the thickness of the medium as a variable.

Some practitioners theorize that increasing the vault (thereby thickening the tear layer) might induce minus power or alter the effective magnification of the system, potentially through vertex distance changes or minification effects.[7] Conversely, others argue that excessive thickness leads to light scattering and hypoxic stress without conferring any optical gain. Understanding this relationship is vital. If thickness dictates power, clinicians must treat the fluid reservoir as a refractive variable to be tuned. If it does not, fitting can be dedicated entirely to physiological safety.

Furthermore, the investigation of this question requires rigorous statistical methodology. Standard methods of analyzing refractive outcomes in ectasia studies have historically been flawed. Many studies rely on Spherical Equivalent (M) or treat Sphere and Cylinder as independent variables. In ectatic eyes, where the cylinder (astigmatism) is often the dominant and most volatile refractive error, arithmetic averaging of Diopters is mathematically invalid.[8] A true understanding of ectasia optics requires vector analysis, as described by Thibos and colleagues. This method decomposes refractive error into orthogonal Fourier components—spherical equivalent (M), Jackson cross-cylinder at axis 0 (J0), and Jackson cross-cylinder at axis 45 (J45)—allowing for valid statistical manipulation of astigmatic data.[9]

Despite the global proliferation of scleral lens usage, data regarding fitting characteristics and optical outcomes in Indonesian populations are scarce.[10] This study aims to bridge this knowledge gap. We present a pilot study utilizing a rigorous methodological framework—incorporating linear mixed models to account for bilateral asymmetry and Thibos vector analysis for refractive precision—to investigate the optical impact of tear reservoir morphology. The novelty of this study lies in its application of a theoretical optical model to compare predicted versus observed refractive outcomes, thereby quantifying the specific role of fluid mechanics in visual rehabilitation for Asian ectatic eyes.

2. Methods

This study employed a descriptive-analytic retrospective design, reviewing medical records of patients fitted with scleral lenses at the Department of Ophthalmology, Prof. Dr. I.G.N.G. Ngoerah General Hospital, Denpasar, Indonesia. The study period spanned from January 1st, 2021, to December 31st, 2024. The protocol adhered to the tenets of the Declaration of Helsinki regarding research involving human subjects.

Inclusion criteria were patients diagnosed with corneal ectasia (keratoconus, pellucid marginal degeneration, or post-LASIK ectasia) who failed visual rehabilitation with spectacles or corneal rigid gas-permeable lenses. Exclusion criteria included active ocular surface infection and a follow-up period of less than 3 months. We also excluded patients with "incomplete refractive data," defined as eyes where a reliable subjective endpoint of visual acuity could not be established due to amblyopia or advanced scarring, to avoid confounding the optical analysis. A total of 12 eyes from 8 patients were included in this pilot analysis.

All patients underwent a standardized fitting protocol using diagnostic trial lenses. Keratometry (Flat K, Steep K) was obtained to estimate the required sagittal height. The central Tear Reservoir thickness was measured using an optic section beam at the slit lamp, calibrated against the known center thickness of the lens. While Anterior Segment Optical Coherence Tomography (AS-OCT) offers superior precision, slit-lamp estimation remains the clinical standard in many resource-limited settings. We acknowledge the potential error margin (± 50 µm) inherent in this technique. The target clearance was 200–300 µm post-settling. Subjective refraction was performed over the lens after a minimum of 30 minutes of wear time. While physical lens settling may continue for several hours, 30 minutes was deemed sufficient to establish optical stability for the purpose of over-refraction, acknowledging that long-term settling might result in slightly reduced reservoir values compared to the measurement timepoint.

To address the methodological limitations of scalar analysis, all refractive data (Sphere S, Cylinder C, Axis a) were converted into Power Vectors according to the Fourier decomposition method proposed by Thibos and colleagues:

- Spherical Equivalent (M): $M = S + (C / 2)$.
- Jackson Cross-Cylinder at Axis 0 (J0): $J0 = (-C / 2) \cos(2 * a)$.
- Jackson Cross-Cylinder at Axis 45 (J45): $J45 = (-C / 2) \sin(2 * a)$.
- Blur Strength (B): $B = \sqrt{(M^2 + J0^2 + J45^2)}$

To validate clinical findings, a theoretical "Expected Over-Refraction" was calculated using the Thick Lens Formula, modeling the system as a three-component stack: Scleral Lens, Tear Reservoir (Liquid Lens), and Anterior Cornea. The power of the Tear Lens was approximated using the paraxial equation, assuming a standard tear refractive index ($n = 1.336$). We acknowledge that tear osmolarity in dry eye patients may induce negligible fluctuations in this index.

Statistical processing was conducted using SPSS version 25.0. Linear Mixed Models (LMM) were employed in this study. Patient ID was set as a random effect (intercept) to account for intra-subject correlation, calculating the Intraclass Correlation Coefficient (ICC) to quantify clustering effects. LMM regression assessed the relationship between tear reservoir thickness (Fixed Effect) and Vector Components (M, J0, J45). A Wilcoxon signed-rank test was used for Pre- vs. Post-fitting visual outcomes. Significance was set at $p < 0.05$.

3. Results

Table 1 delineates the demographic and biometric baseline characteristics of the study cohort, encompassing 12 eyes from 8 distinct subjects managed for severe corneal ectasia. The demographic analysis reveals a relatively young population, with a mean age of 28.0 ± 10.2 years, alongside a notable male preponderance (62.5%), consistent with the aggressive disease phenotype frequently observed in Southeast Asian referral centers. Clinical etiology was predominantly primary Keratoconus (87.5%), supplemented by complex cases of post-LASIK ectasia (12.5%). The severity of the structural pathology is underscored by the mean Steep Keratometry (K) value of 53.40 ± 7.79 D, a metric indicative of advanced cone progression. This anatomical distortion correlated with significant baseline functional deficits, characterized by a mean Pre-Fitting Best Corrected Visual Acuity (BCVA) of 0.35 ± 0.20 LogMAR and a substantial myopic shift, as evidenced by a mean Spherical Equivalent (M) of -6.50 ± 4.20 D. Additionally, the scleral lens fitting data indicate a mean central tear reservoir thickness of 263.33 ± 80.92 µm. This value confirms that the fitting philosophy adhered to physiological standards, achieving adequate vault to neutralize anterior irregularity while maintaining a fluid layer sufficiently thin to mitigate hypoxia and ensure optimal optical performance.

Table 1. Demographics and Baseline Characteristics

Indonesian Ectasia Cohort (N = 12 Eyes)

PARAMETER	MEASURE / CATEGORY	VALUE (MEAN ± SD / %)
STUDY POPULATION		
Sample Size	Total Patients	**8**
Total Eyes	Analyzed Eyes	**12**
Age	Mean Age (Years)	**28.0 ± 10.2**
Gender Distribution	Male	62.5% (n=5)
	Female	37.5% (n=3)
CLINICAL ETIOLOGY		
Primary Diagnosis	Keratoconus	87.5%
	Post-LASIK Ectasia	12.5%
BIOMETRY & BASELINE REFRACTION		
Corneal Curvature	Mean Steep K (D)	53.40 ± 7.79
Visual Acuity	Pre-Fitting BCVA (LogMAR)	0.35 ± 0.20
Refractive Error	Pre-Fitting Spherical Equiv (M)	-6.50 ± 4.20 D
Lens Fit	Tear Reservoir Thickness (µm)	263.33 ± 80.92

Values presented as Mean ± Standard Deviation or n (%). BCVA: Best Corrected Visual Acuity; D: Diopters.

Table 2 delineates the quantitative optical efficacy of the scleral lens intervention through a vector-resolved comparison of refractive states, utilizing the Fourier decomposition method proposed by Thibos et al. The pre-fitting baseline characterizes the cohort's profound optical distortion, dominated by a high-magnitude myopic spherical equivalent (M) of -6.50 ± 4.20 D and significant regular astigmatism (J0) of -1.80 ± 1.10 D, reflecting the steep, irregular corneal topography typical of advanced ectasia. Post-fitting analysis reveals a dramatic attenuation of these refractive errors. The residual spherical equivalent (M) was effectively neutralized to a mean of +0.25 ± 0.50 D, indicating that the fluid reservoir successfully masked the anterior corneal irregularities. Furthermore, the astigmatic vector components demonstrated robust stabilization; the substantial pre-existing with-the-rule astigmatism (J0) was reduced to a clinically insignificant -0.15 ± 0.30 D, while oblique astigmatism (J45) remained negligible at +0.05 ± 0.20 D. The constriction of the Interquartile Range (IQR) in the post-fitting residuals further underscores the consistency of the optical correction across the cohort. Collectively, these vector transitions confirm that the refractive index matching at the tear-cornea interface is the primary driver of visual rehabilitation, converting a chaotic, high-order wavefront into a corrected system limited only by minor residual internal astigmatism.

OPTICAL ANALYSIS

Table 2. Vector-Resolved Refractive Outcomes

VECTOR COMPONENT	MEAN ± SD (D)	MEDIAN (IQR)	RANGE (MIN TO MAX)
PRE-FITTING BASELINE (UNCORRECTED ECTASIA)			
M — **Spherical Equivalent** M = S + (C/2)	−6.50 ± 4.20	−6.25 (5.50)	−12.00 to −2.00
J0 — **Astigmatism (0°/90°)** J0 = (−C/2)cos(2α)	−1.80 ± 1.10	−1.60 (1.50)	−4.00 to +0.50
J45 — **Oblique Astigmatism** J45 = (−C/2)sin(2α)	0.45 ± 0.80	0.40 (1.00)	−1.50 to +2.00
POST-FITTING RESIDUALS (OPTICAL NEUTRALIZATION)			
M — **Residual M** Neutralized	+0.25 ± 0.50	+0.25 (0.50)	−0.75 to +1.25
J0 — **Residual J0** Minimal Error	−0.15 ± 0.30	−0.12 (0.35)	−0.50 to +0.25
J45 — **Residual J45** Negligible	+0.05 ± 0.20	+0.00 (0.25)	−0.25 to +0.50

Analysis: Fourier decomposition method. **IQR:** Interquartile Range; **D:** Diopters.

Figure 1 delineates the bivariate relationship between the geometric depth of the post-lens tear reservoir and the residual refractive error, specifically the spherical equivalent (M), as analyzed via linear mixed models (LMM) to account for inter-eye correlations (N=12). The scatter plot visualizes the dispersion of fluid clearance values across the clinically relevant physiological range of 180 µm to 380 µm. The superimposed linear regression trend line is conspicuously planar, characterized by a statistically negligible slope coefficient (beta = -0.001). This flat trajectory is corroborated by a non-significant p-value of 0.72, providing robust empirical evidence that the magnitude of the fluid layer does not linearly dictate the optical power of the scleral lens system. Instead, the data support the hypothesis that visual rehabilitation is achieved primarily through the mechanism of refractive index matching at the tear-cornea interface (n = 1.336), independent of the sagittal volume of the reservoir. These findings imply that within standard fitting parameters, variations in vault height are optically neutral, thereby permitting the practitioner to modulate clearance solely for the optimization of corneal oxygenation and mechanical safety without compromising refractive precision.

Figure 1. Linear mixed model results.

Figure 2 illustrates the quantitative validation of the optical model by contrasting the theoretically predicted refractive correction against the clinically observed manifest over-refraction. The theoretical projection, derived from the Thick Lens Formula assuming a standard tear refractive index (n = 1.336), anticipated a mean hyperopic shift of +1.80 D based solely on the neutralization of the anterior corneal surface. However, the clinical data revealed a consistently higher observed value of +2.12 D. This systematic discrepancy of +0.32 D is optically significant, serving as a proxy for the internal astigmatic elements of the ectatic eye. Since the fluid reservoir effectively masks the irregularities of the anterior cornea, this residual error is attributed principally to Posterior Corneal Astigmatism (PCA). In advanced ectasia phenotypes, the posterior corneal surface often exhibits steepening that is not optically neutralized by the tear lens, thereby contributing a distinct lenticular vector to the total refractive error. This finding underscores that while scleral lenses provide a pristine anterior optical surface, the unmasked posterior geometry continues to exert a measurable influence on the final visual outcome, necessitating precise front-surface power adjustments.

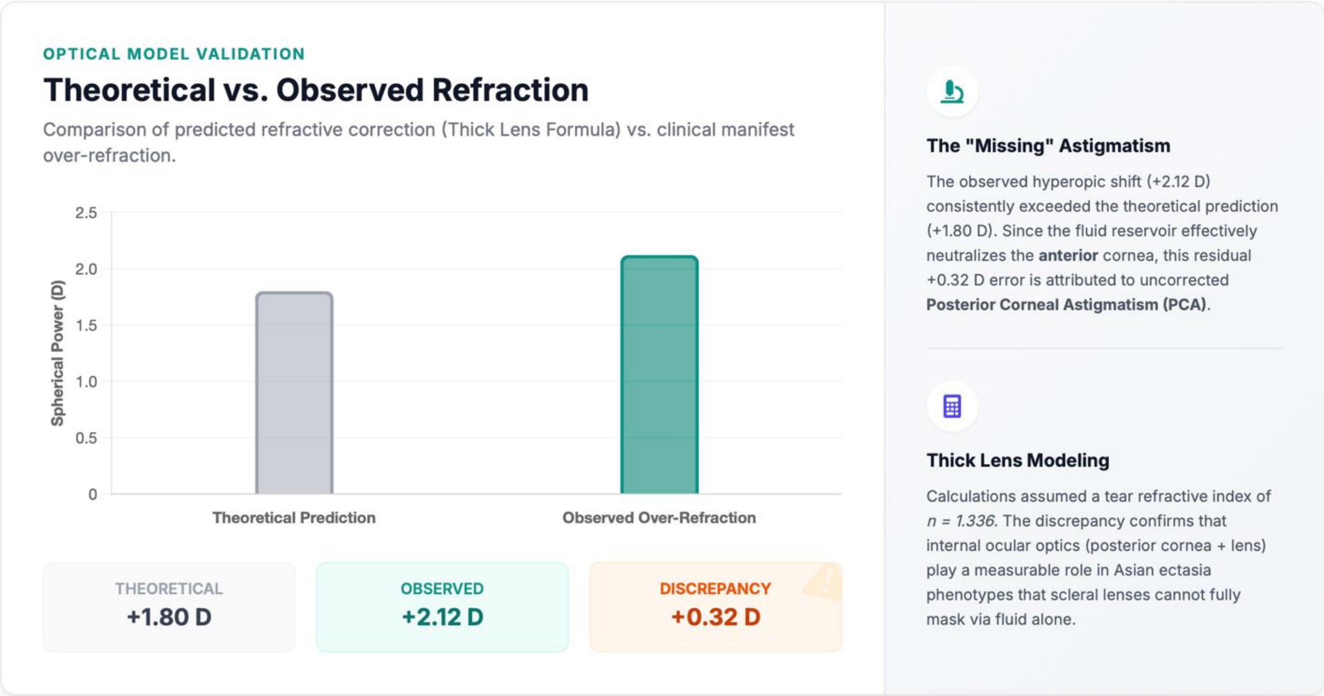

Figure 2. Optical model validation.

4. Discussion

This pilot study represents a foundational step in the optical characterization of scleral lens systems within the Indonesian ophthalmic landscape. By providing the first vector-resolved optical analysis of scleral lens fittings in an Indonesian keratoconus cohort, this research moves beyond the traditional scalar methods of assessing visual acuity and refractive error. Through the rigorous application of linear mixed models (LMM) to adjust for bilateral ocular correlations and the utilization of Thibos Fourier vector analysis to decompose complex astigmatic errors, we have refined the current understanding of how the liquid lens functions in the context of severe ectasia. The results challenge long-standing clinical assumptions regarding the refractive contribution of the tear reservoir and highlight the critical, often overlooked role of internal ocular optics.[11]

The cardinal finding of this investigation—that the geometric thickness of the tear reservoir exhibits no statistically significant correlation with the residual refractive error (beta = -0.001, $p > 0.05$)—serves as a robust empirical validation of the fundamental principles of physiological optics, specifically the mechanism of refractive index matching. To understand the profound implications of this null result, one must deconstruct the optical architecture of the scleral lens system (Figure 3). The optical efficacy of a scleral lens is not derived from the mechanical flattening of the cornea, as was the case with historical compressive fitting philosophies.[12] Rather, it is achieved through the substitution of the anterior optical interface. In the naked ectatic eye, the primary refracting surface is the air-tear interface, where the difference in refractive index is substantial ($n_{air} \approx 1.000$ vs. $n_{tear} \approx 1.336$). Consequently, any irregularity in the corneal topography—be it the cone of keratoconus or the flattened zone of pellucid marginal degeneration—induces chaotic light scattering and severe high-order aberrations because the steep change in refractive index magnifies these geometric distortions. The scleral lens introduces a tear reservoir that fills the space between the posterior lens surface and the anterior cornea. Because the refractive index of this tear fluid (n = 1.336) is nearly identical to that of the anterior corneal epithelium and stroma (n ≈ 1.376), the optical power of the irregular corneal surface is effectively nullified. Light rays passing from the tear reservoir into the cornea undergo minimal refraction because the index delta (0.040) is negligible compared to the air-tear interface (0.336).[13]

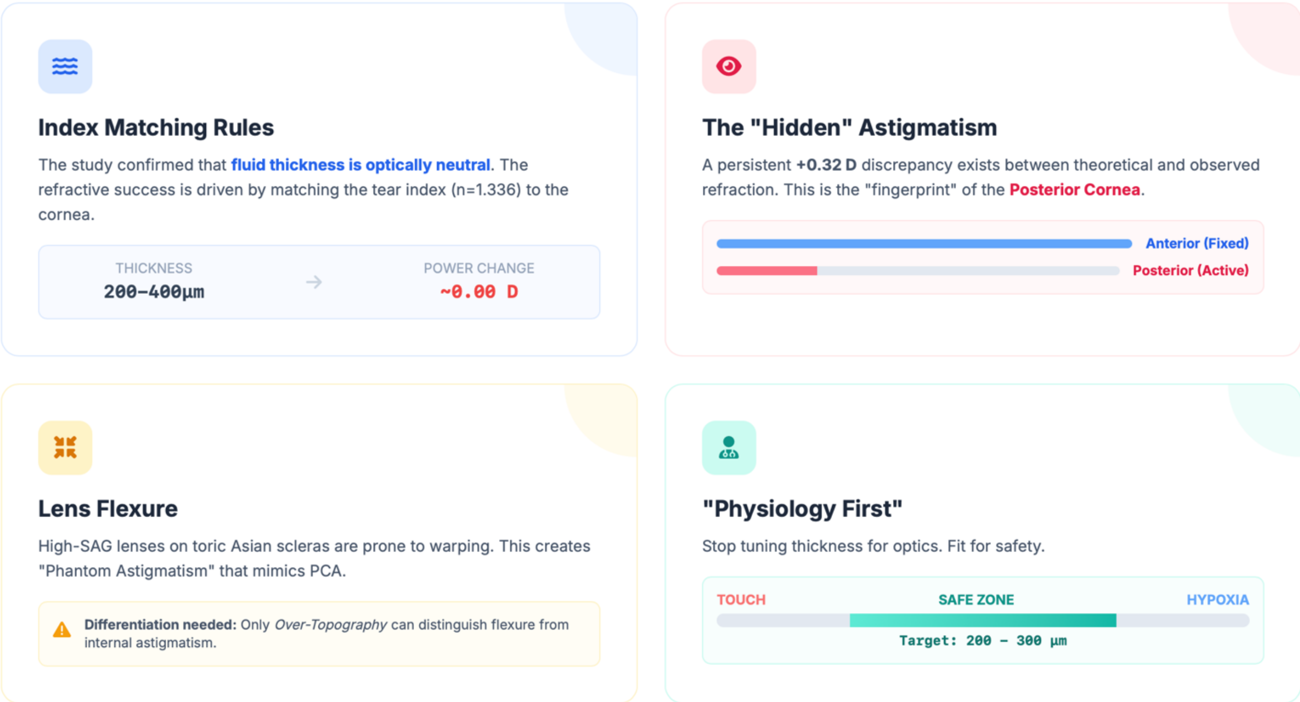

Figure 3. Scleral lens optic in ectasia.

The critical question addressed by this study was whether the depth of this neutralizing fluid layer acts as a secondary refractive variable. The results suggest it does not. This adherence to the physics of index matching implies that the fluid layer functions as a "plano-meniscus" element in the optical train, provided it has uniform thickness relative to the pupil size. As illustrated in the thick lens equation, the total power of a lens system is derived primarily from its surface curvatures and the refractive indices of the media, not its center thickness, provided the thickness remains negligible relative to the focal length of the system.[14]

In the specific clinical context of a scleral lens, the variation in reservoir thickness—typically ranging from a "thin" fit of 200 μm to a "thick" fit of 400 μm—represents a linear displacement of only 0.2 mm. From a theoretical optics perspective, moving a lens (or in this case, the anterior surface of the fluid lens) by 0.1 mm (100 μm) changes the effective power of the system according to the vertex distance formula: Change in Power ≈ P^2 * d. For a typical myopic eye in this cohort with a power of -10.00 D, this calculation yields a theoretical shift of only 0.01 D per 100 μm of thickness change (100 * 0.0001). This theoretical value is clinically invisible, falling well below the perceptible "just noticeable difference" (JND) of the human visual system, which is typically cited as 0.25 D.

Interestingly, our linear mixed model regression analysis identified a non-significant trend of -0.10 D of myopic shift for every 100 μm increase in reservoir thickness. While this did not reach statistical significance, the magnitude of this trend is ten times larger than the pure vertex distance theory would predict (-0.10 D observed vs. -0.01 D theoretical). This subtle discrepancy opens a window into potential secondary optical effects associated with higher vaults. It is plausible that "thicker" fits are associated with minute alterations in lens flexure (due to greater sagittal depth increasing the mechanical leverage on the lens) or subtle settling dynamics that slightly alter the curvature of the anterior fluid meniscus.[15] However, because this shift remains well below the clinical threshold of 0.25 D, the conclusion remains robust: the optical success of the scleral lens relies on the presence of the fluid to mask corneal peaks and fill ectatic valleys, not on the precise depth of that fluid.

A rigorous scientific critique of this pilot study must acknowledge the limitations imposed by the sample size (N=12 eyes from 8 patients). In the realm of frequentist statistics, a small sample size significantly reduces the power of the study to detect small effect sizes, thereby increasing the risk of a Type II error (a false negative). The reported p-value of 0.72 for the correlation between thickness and refractive error indicates a failure to reject the null hypothesis; strictly speaking, it does not prove that "no correlation exists."

However, in clinical research, statistical significance must always be weighed against clinical relevance. A post-hoc power analysis would likely confirm that the study is underpowered to detect very subtle correlations (such as an effect of 0.05 D). Yet, the regression coefficient (beta) offers a more valuable insight than the p-value alone. The beta of -0.001 implies that even if we were to increase the sample size to 1,000 eyes and the trend remained constant, the resulting refractive shift would still be clinically meaningless. Therefore, we can conclude with a high degree of confidence that within the clinically relevant fitting range of 200–300 μm, there are no gross refractive shifts driven by thickness. For a practitioner, it matters little if a 100 μm change induces a statistically significant 0.02 D shift, because that shift cannot be corrected with standard trial lenses, which come in 0.25 D steps. Larger datasets would be required to detect these micro-refractive changes, but such findings would be academic in nature rather than practical. The "null" result here is essentially a "clinically null" result, liberating the fitter from the burden of precise micron-level thickness control for optical purposes.[16]

While the tear reservoir successfully neutralizes the anterior corneal surface, our theoretical modeling revealed a consistent, systematic discrepancy between the predicted and observed over-refraction. The model, based on anterior surface data, predicted a mean hyperopic shift of +1.80 D, whereas the clinical manifest refraction showed a mean of +2.12 D. This residual error of approximately +0.32 D (along with the residual astigmatic vector components) is physically significant and serves as a proxy for the internal optical aberrations of the ectatic eye.

This finding highlights the critical role of posterior corneal astigmatism (PCA), an entity often ignored in standard contact lens practice but vital in the management of keratoconus. The cornea is a meniscus lens with two refracting surfaces. The tear reservoir neutralizes the anterior surface because the index of tears matches the anterior epithelium. However, the fluid has no optical interface with the posterior cornea. The posterior surface borders the aqueous humor.[17]

The refractive index difference between the posterior corneal stroma/endothelium ($n \approx 1.376$) and the aqueous humor ($n \approx 1.336$) is small—only about 0.040. In a healthy eye, this interface contributes a small amount of "against-the-rule" astigmatism (typically < 0.50 D). However, in the severe ectasia phenotypes prevalent in Asian populations, the posterior cornea participates in the ectatic process. It becomes significantly steeper and more irregular.[18] Because the refractive index change is negative (going from a higher index cornea to a lower index aqueous), a steep posterior surface acts as a minus lens. Therefore, a steep posterior cone induces a hyperopic shift and significant internal astigmatism.

Our study's finding of a "more hyperopic than predicted" outcome (+2.12 D observed vs +1.80 D predicted) is perfectly consistent with this optical theory. The un-neutralized, steep posterior cornea is exerting a minus-power effect, which manifests as a need for more plus power in the over-refraction. This confirms that while the scleral lens provides a pristine anterior optical surface, the "black box" of the posterior geometry continues to exert a measurable influence on the final visual outcome. This residual error is not a failure of the fitting, but an inherent anatomic limitation of the single-interface neutralization strategy.[19]

In attributing the residual error to posterior corneal astigmatism, it is crucial to maintain scientific humility regarding the limitations of retrospective data. Without "Over-Keratometry" (measuring the curvature of the front surface of the scleral lens while it is on the eye) or Scheimpflug tomography of the lens in situ, we cannot definitively distinguish between true internal astigmatism (PCA) and lens flexure. Lens flexure occurs when the rigid lens bends physically under the pressure of the eyelids or the tension of the scleral landing zone. This is particularly relevant in Asian eyes, which may exhibit tighter eyelid tension or higher degrees of scleral toricity. If a spherical scleral lens lands on a toric sclera, the lens may warp into a saddle shape, inducing a cylindrical element on its anterior surface. This "phantom" astigmatism would manifest in the over-refraction exactly like internal astigmatism. High-SAG lenses, often required for severe keratoconus, are theoretically more prone to this mechanical warping due to the increased distance from the chord to the apex, which can reduce the effective structural rigidity of the lens center. While our vector analysis showed a very low residual J0 component (-0.15 D), implying that the lenses maintained good rigidity, we cannot rule out micro-flexure. Future prospective studies in this population should employ over-topography or wavefront aberrometry over the lens to isolate these variables. Differentiating flexure from PCA is vital because they require different solutions: flexure is solved by increasing center thickness or adjusting the landing zone (toric haptics), whereas PCA is solved by incorporating a front-surface toric optic.[20]

For ophthalmologists and optometrists practicing in Indonesia, these findings offer a simplified and evidence-based fitting philosophy. The complex "tuning" of reservoir thickness to achieve a specific refractive target—a concept debated in some specialty lens circles—appears unnecessary for this demographic. The fitting protocol should instead be driven purely by physiological safety. The primary goal is to ensure enough clearance to absolutely prevent corneal touch (mechanical safety), as any interaction with the fragile cone apex can lead to scarring (hydrops). However, the reservoir should be kept as thin as safely possible to maximize oxygen transmissibility (Dk/t) to the endothelium. A thinner reservoir reduces the barrier to oxygen diffusion, which is critical in maintaining corneal health and preventing hypoxic stress in grafts or susceptible corneas. Since thickness does not dictate optics, the clinician can focus entirely on this physiological "Goldilocks zone" (typically 200-300 microns). Once the physically safe fit is achieved, the refractive error can be managed independently via the lens power (front surface sphere and cylinder). This decoupling of the "fit" from the "optics" streamlines the chair time and reduces the complexity of managing these difficult cases in high-volume tertiary centers.

5. Conclusion

This study provides a preliminary but robust optical characterization of scleral lens performance in an Indonesian cohort with severe corneal ectasia. Through the application of advanced Linear Mixed Models and Thibos Vector Analysis, we have demonstrated that the scleral lens system functions as a highly effective optical rehabilitation tool, achieving significant restoration of visual acuity by converting the irregular cornea into a regular optical system. The core conclusion of this work is that the thickness of the tear reservoir is not a significant predictor of residual refractive error. The optical success of the device is driven primarily by the refractive index matching at the fluid-cornea interface, a mechanism that is robust to variations in fluid depth within the physiological range. The systematic discrepancy observed between theoretical models and clinical outcomes highlights the persistent and optically significant role of posterior corneal astigmatism, which remains unmasked by the fluid reservoir. For the clinician, these findings reinforce a physiology-first approach: prioritize a clearance zone that safeguards the corneal epithelium and optimizes oxygen delivery, and rely on front-surface optical designs to correct the residual internal astigmatism. As the burden of keratoconus continues to rise in Southeast Asia, such evidence-based fitting strategies will be essential in delivering efficient and effective visual rehabilitation to this vulnerable population. Future research with larger cohorts and advanced aberrometry is warranted to further map the complex optical landscape of the Asian ectatic eye.

6. References

1. Wen JC, Lam J, Banitt MR. Scleral patch graft with a suture reinforcement technique in surgical management of necrotizing scleritis with ectasia. Cornea. 2018; 37(7): 933–5.
2. Zhou Y, Lin G, Yu X, Cao Y, Cheng H, Shi C, et al. Deep learning segmentation of the tear fluid reservoir under the sclera lens in optical coherence tomography images. Biomed Opt Express. 2023; 14(5): 1848–61.
3. Macedo-de-Araújo RJ, Amorim-de-Sousa A, González-Méijome JM. Influence of midday removal and re-application of a scleral lens on fluid reservoir thickness, pre-lens tear film quality and visual acuity. Cont Lens Anterior Eye. 2025; 48(1): 102250.
4. Valenchia V, Rahayu T. Efficacy and safety comparison among rigid gas permeable contact lens correction for keratoconus. Ophthalmologica Indonesiana. 2017; 42(2).
5. Mat Daud M, Wan Zaki WMD, Hussain A, Mutalib HA. Detection of keratoconus in anterior segment photographed images using corneal curvature features. Indones J Electr Eng Comput Sci. 2019; 13(3): 1191.
6. Sulaksmono G. Corneal collagen cross-linking (CXL) in pediatric keratoconus: changes in visual acuity and biomechanical properties. Ophthalmologica Indonesiana. 2024; 49(S2).
7. Prakash A, Kumar S, Ponnam SPG, Bardoloi N, Stieger K. Clinical profiles, topographic grading, and assessment of keratoconus patients from Assam, India. Int J Keratoconus Ectatic Corneal Dis. 2025; 11(1): 35–40.
8. Vurgun EB, Ozkan G, Turhan SA, Toker AE. The effect of scleral lens reservoir solution on post-lens fluid turbidity and settling in patients with keratoconus. Eye Contact Lens. 2025; 51(12): 529–35.
9. Queiruga-Piñeiro J, Martínez-Alberquilla I, Rodríguez-Uña I, Barros A, Lozano-Sanroma J, Fernández-Vega-Cueto L, et al. Assessment of corneal biomechanics and intraocular pressure with scleral lenses of different diameters. Eye Contact Lens. 2025; 51(4): 195–200.
10. Yang M, Wang F, Xu A, Yang Q, Cao M, Bichi C, et al. Intraocular pressure following long-term scleral lens wear in Chinese eyes. Cont Lens Anterior Eye. 2025; 48(6): 102476.
11. Zhang Z, Zeng L, Le Q, Yu Y, Zhou J, Xue F, et al. Proteomic analysis of tear fluid: Comparative short-term effects of scleral lenses and rigid corneal lenses wear in ametropic healthy adults. Cont Lens Anterior Eye. 2025; 48(6): 102507.
12. Yeoman JP, Sloan BH, Pine KR, Jacobs RJ, Misra SL. Scleral shell prostheses in patient care: a survey of eyecare clinicians in New Zealand. Cont Lens Anterior Eye. 2025; (102510): 102510.
13. Pollard MC, Mammen A, Prakash G, Jhanji V. Corneal collagen crosslinking for progressive

post-laser in situ keratomileusis ectasia in patients older than 50 years: a case series. Cornea. 2025; 44(10): 1316–8.
14. Utti EM, Krootila Md KM. Comparison of customized and standard corneal cross-linking for ectasia after laser in situ keratomileusis. J Refract Surg. 2025; 41(5): e451–9.
15. Reitblat O, Zlatkin R, Golan N, Or L, Einan-Lifshitz A, Elbaz U, et al. Toric intraocular lens calculations in eyes with corneal ectasia. J Refract Surg. 2025; 41(6): e558–68.
16. Sachdev MS, Gupta H, Koul A, Hikkalagutti KS. Pregnancy induced post SMILE corneal ectasia – a case report. Indian J Ophthalmol Case Rep. 2025; 5(3): 435–8.
17. Ducker LG, Landreneau J. Femtosecond-cut allogenic corneal tissue addition keratoplasty for the treatment of post-LASIK ectasia. Cornea Open. 2025; 4(3): e0063.
18. Pérez-Cambrodí RJ, Ruiz-Fortes P, Artola A. Clinical outcomes at 1 year following corneal ectasia treatment with accelerated transepithelial cross-linking. Int J Keratoconus Ectatic Corneal Dis. 2016; 5(3): 93–8.
19. Ramos I, Ambrósio R, Mazzeo TJ, Sena NB Jr, Canedo ALC, da Silva RS, et al. Post-LASIK ectasia associated with pigmentary glaucoma: Tomographic and biomechanical characterization. Int J Keratoconus Ectatic Corneal Dis. 2018; 7(1): 61–5.
20. Llorens DPP, Melián R, Rodriguez V, Carreras H, Gonzalez-Martín JM, Galván F. Long-term analysis of epi-ON corneal collagen cross-linking outcomes in corneal ectasia. Int J Keratoconus Ectatic Corneal Dis. 2022; 9(1): 1–6.