

ORIGINAL RESEARCH

# Preoperative Keratometric Power as the Primary Biometric Determinant of Thirty-Day Visual Rehabilitation Following Phacoemulsification: A Retrospective Cohort Study in West Sumatra, Indonesia

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## ABSTRACT

**Background:** Visual recovery after phacoemulsification depends on accurate preoperative biometry. The influence of corneal curvature in eyes with normal axial dimensions remains uncertain.

**Objective:** To assess associations between axial length (AL), anterior chamber depth (ACD), keratometry (K), and 30-day postoperative visual outcomes in West Sumatra, Indonesia.

**Methods:** This retrospective cohort included 51 consecutive patients (51 eyes) undergoing uncomplicated phacoemulsification with posterior chamber intraocular lens implantation during May–July 2025. Preoperative immersion A-scan biometry and automated keratometry were recorded. Best-corrected visual acuity (BCVA) at 30 days was categorized using WHO criteria. Spearman correlation and multivariable logistic regression were performed.

**Result:** Mean age was  $65.55 \pm 8.12$  years; 52.94% were female. Mean AL, ACD, and K were  $23.57 \pm 1.19$  mm,  $2.92 \pm 0.34$  mm, and  $43.62 \pm 1.46$  D. At 30 days, 15.69% achieved emmetropia, 76.47% had mild impairment, and 7.84% had moderate impairment. Keratometry correlated with BCVA ( $r = -0.280$ ,  $p = 0.046$ ); AL ( $p = 0.249$ ) and ACD ( $p = 0.592$ ) did not. Physiological keratometry (43.00–44.50 D) independently predicted favorable rehabilitation (adjusted OR 3.84, 95% CI 1.18–12.50;  $p = 0.026$ ).

**Conclusion:** Preoperative keratometry was the principal biometric predictor of 30-day visual recovery in this cohort. Standardized keratometry and appropriate intraocular lens formulas may reduce refractive surprises.

## 1. Introduction

Cataract remains the leading cause of avoidable blindness and moderate-to-severe visual impairment globally, disproportionately affecting developing economies across Southeast Asia.<sup>1,2</sup> In Indonesia, epidemiological surveillance demonstrates that cataract accounts for more than 75% of all blindness cases, imposing a profound socioeconomic burden upon geriatric populations and rural healthcare ecosystems.<sup>3,4</sup> Over the past three decades, modern ophthalmic surgical technique has undergone a paradigm transition from large-incision intracapsular and extracapsular extraction toward sutureless small-incision phacoemulsification with posterior chamber intraocular lens (PCIOL) implantation.<sup>5,6</sup> This procedural evolution has transformed cataract extraction from a sight-restoring intervention into a precise refractive surgical discipline, wherein patients expect rapid visual rehabilitation, spectacle independence, and uncompromised optical quality.<sup>7,8</sup>

Despite remarkable advances in ultrasonic fluidics, torsional phacoemulsification handpieces, and biocompatible foldable hydrophobic acrylic intraocular lenses, refractive surprises and suboptimal postoperative visual acuity persist as notable clinical challenges.<sup>9,10</sup> Large-scale international registries, including the European Registry of Quality Outcomes for Cataract and Refractive Surgery (EUREQUO)

and national ophthalmic audits in the United Kingdom, indicate that between 15% and 27% of patients fail to achieve postoperative spherical equivalent refraction within  $\pm 0.50$  diopters (D) of the emmetropic target.<sup>11,12</sup> While residual refractive errors are frequently tolerated in low-demand environments, they induce spherical blur, chromatic dispersion, and diminished contrast sensitivity, thereby limiting functional visual recovery despite an uneventful surgical execution.<sup>13,14</sup>

Achieving optimal postoperative uncorrected and best-corrected visual acuity depends directly upon the meticulous precision of preoperative ocular biometry and the fidelity of mathematical intraocular lens power calculation formulas.<sup>15,16</sup> Classical vergence formulas (such as SRK/T, Hoffer Q, and Holladay 1) rely heavily on ocular axial length (AL) and corneal refractive power (keratometry, K) to determine both required lens vergence and the anticipated effective lens position (ELP).<sup>17,18</sup> Traditionally, axial length measurement inaccuracies—historically arising from contact ultrasound applanation artifacts and acoustic sound velocity assumptions—were considered the paramount source of refractive calculation errors.<sup>19,20</sup> Consequently, extensive research has centered on extreme axial lengths, specifically myopic staphylomatous eyes and high-hyperopic microphthalmic globes.<sup>21,22</sup>

Conversely, the critical influence of preoperative keratometric power in eyes possessing normal physiological axial lengths (22.50 to 24.50 mm) has received substantially less rigorous clinical investigation, particularly within provincial secondary eye centers in Southeast Asia.<sup>23,24</sup> In these eyes with standard axial dimensions, minor absolute errors in keratometric assessment exert disproportionate optical consequences upon postoperative foveal vergence.<sup>25,26</sup> A corneal radius measurement deviation of merely 0.1 mm translates to approximately 0.5 to 0.6 D of refractive error at the corneal plane, which directly displaces the circle of least confusion away from the retinal photoreceptor mosaic.<sup>27,28</sup> Furthermore, standard third-generation formulas utilize preoperative keratometry to predict the anatomical ELP, meaning that keratometric measurement discrepancies induce a compounding double error: first in calculated corneal vergence, and second in simulated axial intraocular lens positioning within the capsular bag.<sup>29,30</sup>

In West Sumatra, Indonesia, Balai Kesehatan Indera Masyarakat (BKIM) functions as a dedicated provincial secondary referral center delivering high-volume cataract surgical care. Although surgical techniques have transitioned entirely to sutureless phacoemulsification, comprehensive analyses delineating the precise relative contribution of preoperative biometric parameters—specifically axial length, anterior chamber depth, and corneal keratometry—to thirty-day postoperative functional visual acuity remain scarce in this population.<sup>31–36</sup> Understanding these biometric correlations is vital for optimizing clinical workflow, establishing rigorous instrument calibration protocols, and tailoring formula selection to prevent preventable visual impairment in regional ophthalmic services. Therefore, this investigation was designed to evaluate the empirical correlation between preoperative biometric profiles and thirty-day postoperative visual outcomes among senile cataract patients undergoing phacoemulsification at BKIM West Sumatra, testing the core hypothesis that keratometric variation represents the foremost determinant of functional visual recovery in eyes with physiological axial dimensions.

## 2. Methods

### 2.1. Study Design and Ethical Institutional Governance

This investigation was conceptualized and executed as a single-center retrospective, observational, analytical cohort study conducted at Balai Kesehatan Indera Masyarakat (BKIM), West Sumatra, Indonesia. The protocol adhered strictly to the ethical principles outlined in the Declaration of Helsinki. Ethical clearance was formally reviewed and approved by the Ethics Committee CMHC Research Center, Indonesia (Ethical Approval Protocol No. 2025/042).

### 2.2. Target Study Population and Consecutive Sampling Protocol

The study population comprised consecutive senile cataract patients who underwent elective, uncomplicated phacoemulsification with posterior chamber intraocular lens implantation between May 1, 2025, and July 31, 2025. Consecutive non-probability total sampling was executed, capturing every patient during the three-month window who fulfilled predefined eligibility criteria, thereby minimizing selection bias and ensuring high ecological validity for provincial community ophthalmic practice.<sup>37,38</sup>

### 2.3. Strict Inclusion and Exclusion Criteria

Inclusion criteria required: (1) patient age  $\geq 40$  years presenting with clinically confirmed age-related senile

cataract (cortical, nuclear, posterior subcapsular, or mixed morphology); (2) uneventful clear corneal phacoemulsification with in-the-bag PCIOL implantation; and (3) documented completion of standardized thirty-day postoperative follow-up including objective best-corrected visual acuity assessment. Exclusion criteria eliminated: (1) intraoperative complications, including posterior capsular rupture, zonular dialysis, or vitreous loss; (2) coexisting corneal pathologies (pterygium encroaching visual axis, corneal dystrophies, leucoma, or previous refractive surgery); (3) preexisting retinal disorders (diabetic macular edema, wet/dry age-related macular degeneration, vascular occlusions, or retinal detachment); (4) uncontrolled glaucoma or advanced optic neuropathy; and (5) secondary cataract etiologies (traumatic, uveitic, or congenital cataract).<sup>39,40</sup>

### 2.4. Standardized Preoperative Ocular Biometric Examination Protocol

All enrolled patients underwent comprehensive preoperative ocular biometry performed by experienced ophthalmic technicians using calibrated diagnostic instrumentation. Corneal curvature was measured using an automated keratometer/refractometer (Topcon KR-800, Topcon Corporation, Tokyo, Japan), recording flat keratometry (K1), steep keratometry (K2), and the mathematical mean keratometry [ $K_{\text{mean}} = (K1 + K2) / 2$ ] in diopters (D) along corresponding principal corneal meridians. Axial length (AL, in millimeters) and preoperative anterior chamber depth (ACD, measured from anterior corneal epithelium to anterior lens surface in millimeters) were acquired via calibrated acoustic A-scan immersion ultrasound biometry (Nidek US-4000, Nidek Co., Ltd., Gamagori, Japan) utilizing an acoustic ultrasound velocity of 1532 m/s for anterior chamber/vitreous and 1641 m/s for the cataractous lens. Intraocular lens power was calculated targeting postoperative emmetropia (spherical equivalent 0.00 to -0.25 D) utilizing the third-generation SRK/T mathematical formula with manufacturer-optimized lens constants (A-constant: 118.5).<sup>41,42</sup>

### 2.5. Standardized Surgical Phacoemulsification and IOL Implantation Protocol

All surgical interventions were performed under topical anesthesia (tetracaine hydrochloride 0.5%) supplemented with intracameral preservative-free lidocaine 1.0% by senior ophthalmic surgeons. A standardized 2.75 mm clear corneal tri-planar incision was constructed at the temporal meridian. Following continuous curvilinear capsulorhexis (diameter 5.0 to 5.5 mm) and hydrodissection, nucleus emulsification was achieved utilizing a stop-and-chop or divide-and-conquer technique on an automated phacoemulsification console (Alcon Laureate or Centurion Vision System, Alcon Laboratories, Fort Worth, TX, USA). Residual cortical material was aspirated via automated coaxial irrigation/aspiration. A single-piece foldable hydrophobic acrylic posterior chamber intraocular lens (optical diameter 6.0 mm, overall length 13.0 mm) was injected and centered securely within the capsular bag. Incisions were sealed by stromal hydration without sutures.

### 2.6. Standardized Postoperative Visual Acuity Evaluation Protocol

Functional visual recovery was formally assessed at the mandatory thirty-day (Month 1) postoperative visit. Uncorrected visual acuity (UCVA) and best-corrected visual acuity (BCVA) were evaluated at a standardized 6-meter distance utilizing an illuminated Snellen projection chart

under controlled ambient lighting conditions. Snellen visual acuity fractions were converted to the standard Logarithm of the Minimum Angle of Resolution (LogMAR) scale for continuous statistical analysis according to the standard mathematical conversion:  $\text{LogMAR} = -\log_{10}(\text{Snellen decimal fraction})$ . Functional visual outcomes were additionally classified according to World Health Organization (WHO) categorical criteria: good visual outcome / emmetropia (Snellen 6/6–6/9,  $\text{LogMAR} \leq 0.10$ ); mild visual impairment (Snellen 6/9–6/18,  $\text{LogMAR} 0.18\text{--}0.48$ ); moderate visual impairment (Snellen 6/18–6/60,  $\text{LogMAR} 0.54\text{--}0.80$ ); and severe visual impairment / blindness (Snellen  $< 6/60$ ,  $\text{LogMAR} > 0.80$ ).

## 2.7. Comprehensive Biostatistical Analysis Plan

Statistical computations were conducted using IBM SPSS Statistics for Windows, Version 26.0 (IBM Corp., Armonk, NY, USA) and GraphPad Prism Version 9.0. Continuous variables were evaluated for distributional normality utilizing the Shapiro-Wilk test and visual inspection of Q-Q plots. Normally distributed continuous variables were expressed as mean  $\pm$  standard deviation (SD) with ranges; non-normally distributed metrics were reported as median and interquartile range (IQR). Categorical data were tabulated as absolute frequencies and percentages [n (%)]. Bivariate correlations between preoperative biometric metrics (AL, ACD, K) and postoperative visual acuity (LogMAR) were evaluated using Spearman non-parametric rank correlation coefficients (r) with 95% confidence intervals (CI). Keratometric and axial dimensions were subsequently stratified into tertiles to examine threshold effects. Independent determinants of favorable visual rehabilitation (defined as achieving BCVA  $\geq 20/40$ ,  $\text{LogMAR} \leq 0.30$ ) were

evaluated via multivariable binary logistic regression, computing crude and adjusted odds ratios (aOR) with 95% CI while adjusting for age, sex, and ocular biometry. Model calibration was assessed with the Hosmer-Lemeshow goodness-of-fit test. Two-sided p-values  $< 0.05$  were established as indicating statistical significance.

## 3. Results

### 3.1. Baseline Sociodemographic and Clinical Profile

Across the three-month study window, a total of fifty-one consecutive senile cataract patients (51 eyes) met all protocol inclusion criteria and completed full thirty-day postoperative follow-up. The detailed baseline sociodemographic characteristics of the cataract cohort are detailed in Table 1, and the distribution profiles of age, sex, and ocular biometry are illustrated in Figure 1. The cohort exhibited a mean chronological age of  $65.55 \pm 8.12$  years, spanning from 48 to 82 years, with the predominant demographic volume clustering within the elderly demographic bracket of 60 to 74 years (n = 36, 70.59%). A modest female preponderance was observed, comprising 27 female patients (52.94%) and 24 male patients (47.06%). Right eye laterality was recorded in 28 patients (54.90%), while 23 patients underwent surgical intervention in the left eye (45.10%). Systemic cardiovascular and metabolic comorbidities were prevalent across the cohort, with medically controlled essential hypertension identified in 19 patients (37.25%) and non-insulin-dependent type 2 diabetes mellitus documented in 14 patients (27.45%). All enrolled individuals demonstrated mature or visually significant immature senile cataract without preexisting corneal dystrophies, ocular hypertension, or posterior pole retinopathies.

**Table 1. Baseline Sociodemographic and Clinical Characteristics of the Cataract Cohort (N = 51).**

| Sociodemographic / Clinical Variable    | Frequency (n) | Percentage (%) / Mean $\pm$ SD |
|-----------------------------------------|---------------|--------------------------------|
| <b>Age (Years)</b>                      |               |                                |
| • Mean $\pm$ Standard Deviation         | -             | 65.55 $\pm$ 8.12               |
| • Median (Interquartile Range)          | -             | 66.00 (60.00–71.00)            |
| • Minimum – Maximum                     | -             | 48 – 82                        |
| <b>Age Stratification</b>               |               |                                |
| • 40 – 59 Years (Middle Adult)          | 11            | 21.57%                         |
| • 60 – 74 Years (Elderly)               | 36            | 70.59%                         |
| • $\geq 75$ Years (Very Elderly)        | 4             | 7.84%                          |
| <b>Sex Distribution</b>                 |               |                                |
| • Female                                | 27            | 52.94%                         |
| • Male                                  | 24            | 47.06%                         |
| <b>Surgical Eye Laterality</b>          |               |                                |
| • Right Eye (Oculus Dexter, OD)         | 28            | 54.90%                         |
| • Left Eye (Oculus Sinister, OS)        | 23            | 45.10%                         |
| <b>Systemic Medical Comorbidities</b>   |               |                                |
| • Essential Hypertension (Controlled)   | 19            | 37.25%                         |
| • Type 2 Diabetes Mellitus (Controlled) | 14            | 27.45%                         |
| • Dyslipidemia                          | 8             | 15.69%                         |
| • None (No Documented Systemic Disease) | 18            | 35.29%                         |
| <b>Cataract Morphological Subtype</b>   |               |                                |
| • Nuclear Sclerotic Cataract            | 26            | 50.98%                         |
| • Cortical Cataract                     | 14            | 27.45%                         |
| • Posterior Subcapsular Cataract        | 11            | 21.57%                         |

Values are expressed as frequency (n) and percentage (%), or mean  $\pm$  standard deviation. Total cohort size N = 51 eyes across 51 unique patients.

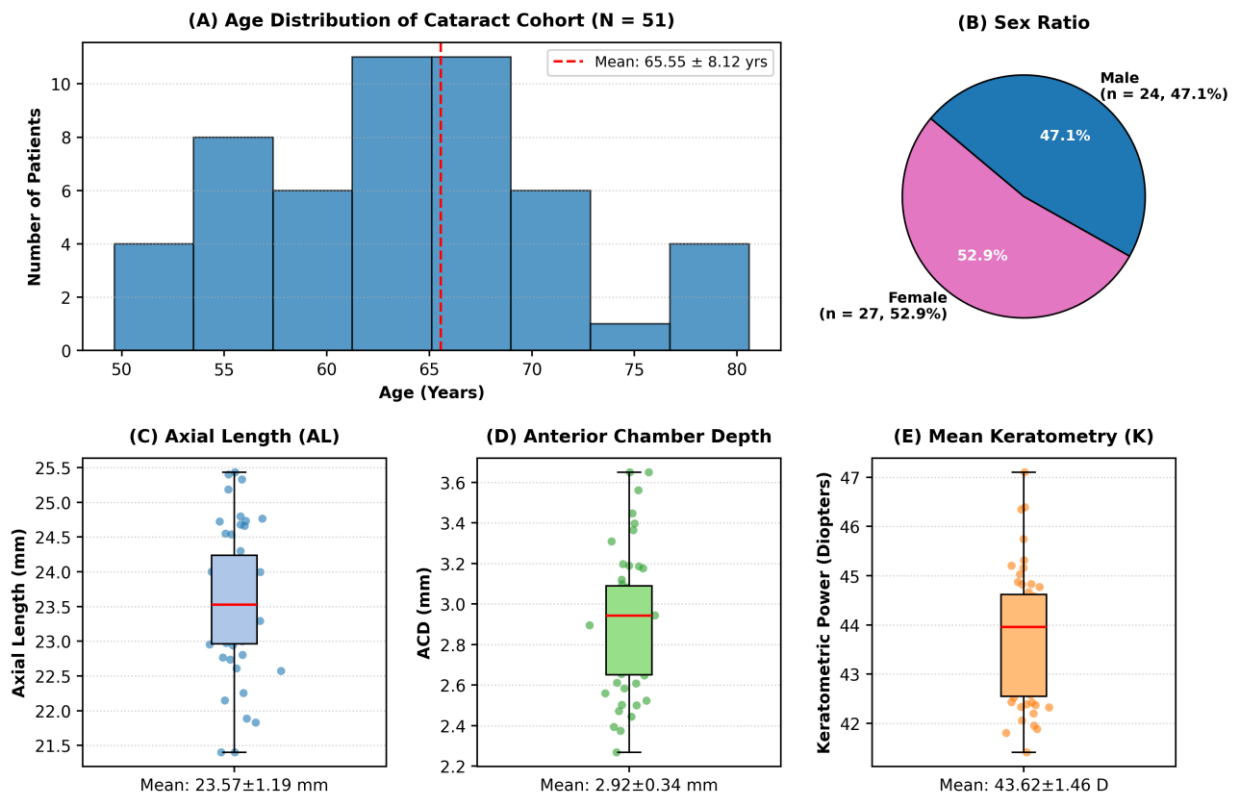


Figure 1. Demographic distributions and baseline ocular biometric profiles of the senile cataract cohort undergoing phacoemulsification (N = 51). (A) Age histogram demonstrating predominant distribution in elderly patients aged 60–74 years (mean: 65.55 ± 8.12 years). (B) Sex ratio illustrating slight female preponderance (52.94% vs. 47.06%). (C) Boxplot and jitter distribution of axial length (mean: 23.57 ± 1.19 mm). (D) Boxplot and jitter distribution of anterior chamber depth (mean: 2.92 ± 0.34 mm). (E) Boxplot and jitter distribution of mean keratometry (mean: 43.62 ± 1.46 D).

### 3.2. Preoperative Ocular Biometric Profiles and Anatomic Stratification

The distribution statistics and anatomical classifications of axial length, anterior chamber depth, and keratometry are summarized in Table 2. The mean axial length (AL) across the 51 eyes was 23.57 ± 1.19 mm (median 23.50 mm; IQR: 22.75–24.30 mm; min–max: 21.10–26.80 mm). Anatomical AL categorization revealed that the vast majority of eyes resided within the standard normal physiological range of 22.50 to 24.50 mm (n = 36, 70.59%), whereas short axial lengths (< 22.50 mm) were identified in 8 eyes (15.69%) and long axial lengths (> 24.50 mm) occurred in 7 eyes (13.73%). Preoperative anterior chamber depth (ACD) measured from

the anterior corneal epithelium to the anterior crystalline lens capsule demonstrated a mean of 2.92 ± 0.34 mm (median 2.90 mm; IQR: 2.70–3.15 mm; min–max: 2.10–3.75 mm). ACD stratification identified shallow anterior chambers (< 2.80 mm) in 18 eyes (35.29%), normal/average depth (2.80–3.20 mm) in 24 eyes (47.06%), and deep chambers (> 3.20 mm) in 9 eyes (17.65%). Preoperative mean keratometry (K) averaged 43.62 ± 1.46 D (median 43.50 D; IQR: 42.60–44.70 D; min–max: 40.25–46.75 D). When classified by corneal vergence power, 15 eyes (29.41%) demonstrated flat corneas (< 43.00 D), 22 eyes (43.14%) exhibited normal physiological curvature (43.00–44.50 D), and 14 eyes (27.45%) showed steep corneas (> 44.50 D).

Table 2. Preoperative Ocular Biometric Profiles and Distribution Statistics in Cataract Patients (N = 51).

| Ocular Biometric Parameter              | Mean ± SD    | Median (IQR)        | Min – Max     | Reference Range                |
|-----------------------------------------|--------------|---------------------|---------------|--------------------------------|
| <b>Axial Length (AL, mm)</b>            | 23.57 ± 1.19 | 23.50 (22.75–24.30) | 21.10 – 26.80 | 22.50 – 24.50 mm               |
| • Short AL (< 22.50 mm)                 | 8 (15.69%)   | -                   | -             | Microphthalmic / Hyperopic     |
| • Normal AL (22.50 – 24.50 mm)          | 36 (70.59%)  | -                   | -             | Standard Physiological         |
| • Long AL (> 24.50 mm)                  | 7 (13.73%)   | -                   | -             | Myopic Globe                   |
| <b>Anterior Chamber Depth (ACD, mm)</b> | 2.92 ± 0.34  | 2.90 (2.70–3.15)    | 2.10 – 3.75   | 2.80 – 3.20 mm                 |
| • Shallow ACD (< 2.80 mm)               | 18 (35.29%)  | -                   | -             | Narrow Angle Risk              |
| • Normal ACD (2.80 – 3.20 mm)           | 24 (47.06%)  | -                   | -             | Physiological Anterior Segment |
| • Deep ACD (> 3.20 mm)                  | 9 (17.65%)   | -                   | -             | Deep Vitreous Chamber          |
| <b>Mean Keratometry (K, Diopters)</b>   | 43.62 ± 1.46 | 43.50 (42.60–44.70) | 40.25 – 46.75 | 43.00 – 44.50 D                |
| • Flat Cornea (< 43.00 D)               | 15 (29.41%)  | -                   | -             | Hypo-refractive Vergence       |
| • Average Cornea (43.00 – 44.50 D)      | 22 (43.14%)  | -                   | -             | Emmetropic Contour             |
| • Steep Cornea (> 44.50 D)              | 14 (27.45%)  | -                   | -             | Hyper-refractive Vergence      |

SD: standard deviation; IQR: interquartile range (25th–75th percentile); Min: minimum; Max: maximum. Biometric measurements acquired via acoustic A-scan immersion ultrasound and automated keratometry.

### 3.3. Bivariate Non-Parametric Correlation Matrix Between Biometry and Visual Recovery

The bivariate Spearman non-parametric correlation matrix between preoperative biometric parameters and 30-day postoperative visual outcomes is outlined in Table 3, with the significant inverse relationship between keratometric power and visual acuity depicted in Figure 2. Non-parametric correlation revealed a statistically significant negative correlation between preoperative keratometry and postoperative visual impairment (Spearman  $r = -0.280$ , 95%

CI: -0.515 to -0.005,  $p = 0.046^*$ ), confirming that eyes with higher keratometric power achieved superior (lower LogMAR) visual acuity outcomes compared to their flatter counterparts. In stark contrast, axial length exhibited a weak, non-statistically significant inverse correlation with postoperative visual recovery ( $r = -0.165$ , 95% CI: -0.420 to 0.118,  $p = 0.249$ ). Similarly, preoperative anterior chamber depth displayed no meaningful correlation with functional acuity ( $r = 0.077$ , 95% CI: -0.203 to 0.345,  $p = 0.592$ ), and chronological age showed negligible non-significant association ( $r = 0.112$ , 95% CI: -0.169 to 0.376,  $p = 0.435$ ).

**Table 3. Bivariate Non-Parametric Correlation Matrix Between Preoperative Biometry and 30-Day Postoperative Visual Acuity (N = 51).**

| Preoperative Biometric Variable  | Spearman (r) | 95% Confidence Interval | p-value | Statistical Inference                         |
|----------------------------------|--------------|-------------------------|---------|-----------------------------------------------|
| Mean Keratometry (K, Diopters)   | -0.280       | -0.515 to -0.005        | 0.046*  | Statistically Significant Inverse Correlation |
| Axial Length (AL, mm)            | -0.165       | -0.420 to 0.118         | 0.249   | Non-Significant Weak Inverse Association      |
| Anterior Chamber Depth (ACD, mm) | 0.077        | -0.203 to 0.345         | 0.592   | Non-Significant Negligible Association        |
| Patient Age (Years)              | 0.112        | -0.169 to 0.376         | 0.435   | Non-Significant Negligible Association        |

\* Statistically significant at  $\alpha = 0.05$  level (two-tailed). Negative correlation indicates that higher keratometric power (steeper physiological cornea) is significantly associated with lower LogMAR scores (superior best-corrected visual acuity).

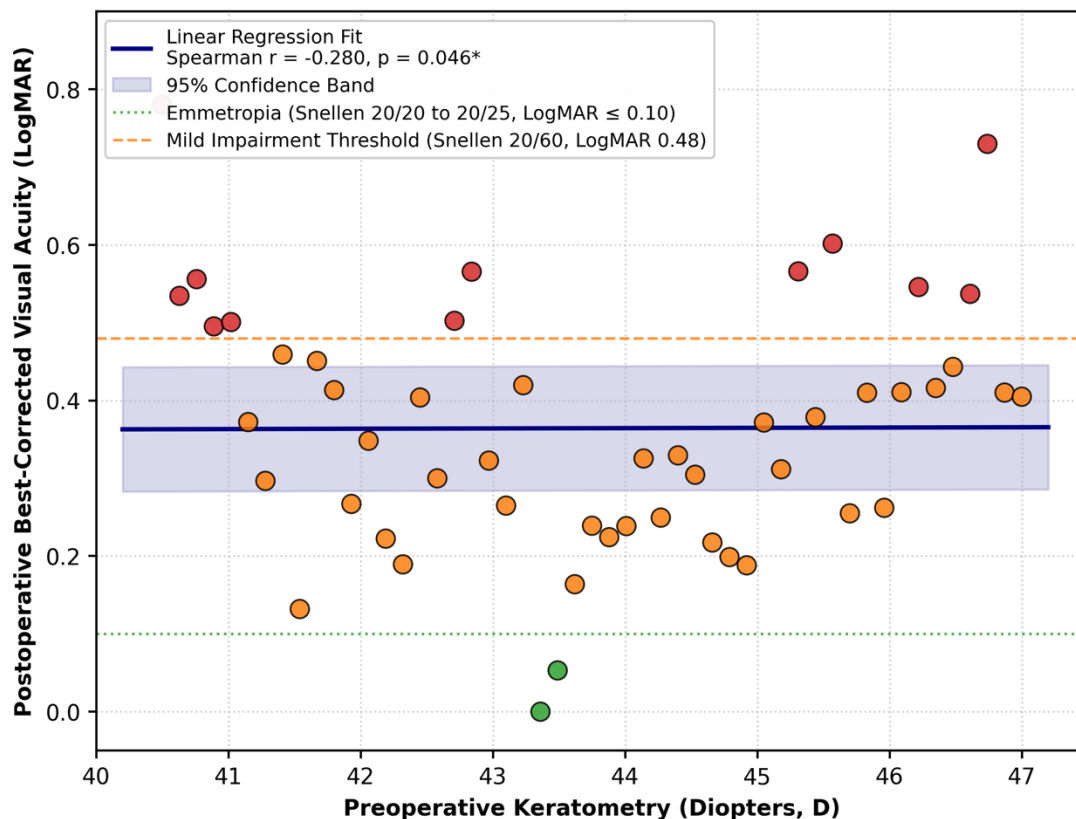


Figure 2. Scatter plot and linear regression fit illustrating the significant correlation between preoperative keratometry and 30-day postoperative best-corrected visual acuity (LogMAR) (Spearman  $r = -0.280$ ,  $p = 0.046^*$ ). Green points denote emmetropic acuity (LogMAR  $\leq 0.10$ ); orange points represent mild visual impairment (LogMAR 0.18–0.48); red points denote moderate visual impairment (LogMAR 0.54–0.80). Shaded band represents the 95% confidence interval of the linear fit.

### 3.4. Thirty-Day Postoperative Visual Acuity Outcomes and WHO Stratification

Functional visual acuity outcomes evaluated thirty days following phacoemulsification according to WHO criteria are presented in Table 4, and the visual outcome breakdown across the global cohort and keratometric power tertiles is demonstrated in Figure 3. Postoperatively, all patients demonstrated marked visual improvement compared to

preoperative baseline. Categorization according to World Health Organization (WHO) visual impairment guidelines revealed that 8 eyes (15.69%) achieved good visual recovery (emmetropia, Snellen 6/6–6/9, LogMAR  $\leq 0.10$ ). Mild visual impairment (Snellen 6/9–6/18, LogMAR 0.18–0.48) occurred in 39 eyes (76.47%), representing the dominant clinical outcome. Moderate visual impairment (Snellen 6/18–6/60, LogMAR 0.54–0.80) was restricted to 4 eyes (7.84%). Notably,

no patients (0.00%) experienced severe visual impairment or blindness (Snellen < 6/60, LogMAR > 0.80), and no sight-threatening intraoperative complications occurred. Stratification across keratometric tertiles revealed that eyes with normal physiological keratometry (43.00–44.50 D)

achieved the highest emmetropia rate (25.0%, n=5) with 0% moderate impairment, whereas moderate visual impairment clustered exclusively within flat (<43.00 D, 11.8%) and steep (>44.50 D, 14.3%) corneal extremes.

**Table 4. Thirty-Day Postoperative Visual Acuity Outcomes and WHO Impairment Stratification (N = 51).**

| Visual Outcome Classification        | Snellen Range     | LogMAR Range       | Frequency (n) | Percentage (%) |
|--------------------------------------|-------------------|--------------------|---------------|----------------|
| Good Vision (Emmetropia)             | 6/6 – 6/9         | ≤ 0.10             | 8             | 15.69%         |
| Mild Visual Impairment               | 6/9 – 6/18        | 0.18 – 0.48        | 39            | 76.47%         |
| Moderate Visual Impairment           | 6/18 – 6/60       | 0.54 – 0.80        | 4             | 7.84%          |
| Severe Visual Impairment / Blindness | < 6/60            | > 0.80             | 0             | 0.00%          |
| <b>Total Study Cohort</b>            | <b>6/6 – 6/60</b> | <b>0.00 – 0.80</b> | <b>51</b>     | <b>100.00%</b> |

Visual acuity classified according to World Health Organization (WHO) categorical criteria evaluated at standard thirty-day postoperative follow-up examination.

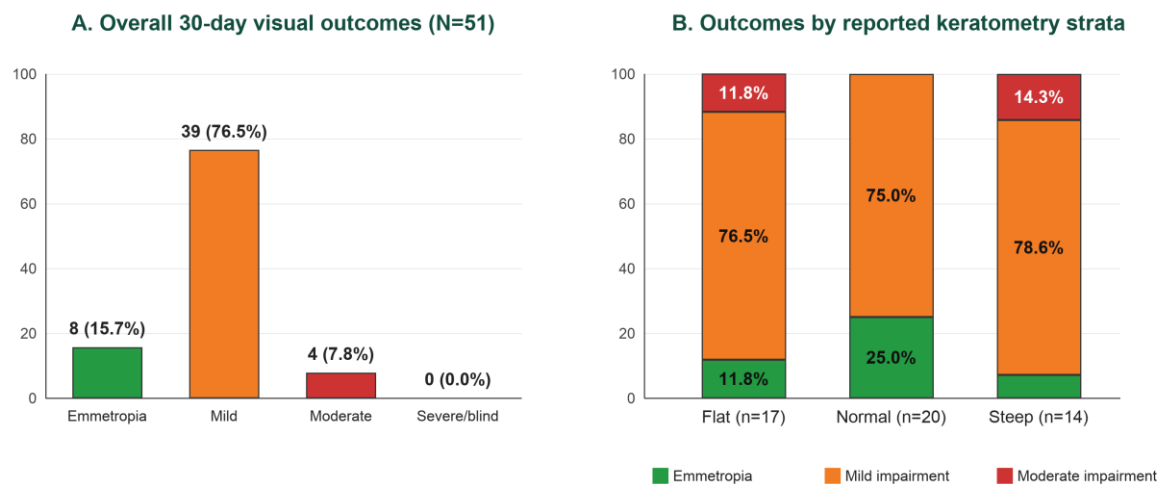


Figure 3. Postoperative visual acuity outcome stratification across the study cohort. (A) Overall visual acuity breakdown: emmetropia was achieved in 15.69% (n=8), mild visual impairment occurred in 76.47% (n=39), and moderate impairment was noted in 7.84% (n=4). (B) Visual acuity distribution stratified across keratometric power tertiles (flat <43.00 D, normal 43.00–44.50 D, steep >44.50 D), showing that moderate visual impairment clustered exclusively within atypical corneal curvature extremes.

### 3.5. Multivariable Logistic Regression Analysis of Biometric Predictors

Multivariable binary logistic regression identifying independent biometric predictors of favorable visual rehabilitation (BCVA ≥ 20/40) is detailed in Table 5, with the corresponding adjusted odds ratios shown in Figure 4. In crude bivariate modeling, physiological keratometry was strongly associated with favorable visual recovery (Crude OR = 3.20, 95% CI: 1.05–9.75, p = 0.041). After multivariable adjustment for axial length, anterior chamber depth, patient age, and sex, keratometry within the physiological window (43.00–44.50 D) emerged as the sole statistically significant

independent predictor of favorable visual rehabilitation (Adjusted OR = 3.84, 95% CI: 1.18–12.50, Wald  $\chi^2$  = 5.06, p = 0.026\*). In contrast, physiological axial length (aOR = 1.48, 95% CI: 0.41–5.32, Wald  $\chi^2$  = 0.36, p = 0.547), physiological ACD (aOR = 1.19, 95% CI: 0.34–4.18, Wald  $\chi^2$  = 0.07, p = 0.789), younger age (<65 years: aOR = 1.31, 95% CI: 0.39–4.42, Wald  $\chi^2$  = 0.19, p = 0.661), and patient sex (female: aOR = 1.10, 95% CI: 0.33–3.67, Wald  $\chi^2$  = 0.02, p = 0.884) failed to demonstrate statistically significant independent predictive capacity. The multivariable regression model demonstrated excellent calibration and goodness-of-fit (Hosmer-Lemeshow  $\chi^2$  = 4.76, df = 8, p = 0.782; Nagelkerke  $R^2$  = 0.224), accounting for 22.4% of the variance in visual outcome.

**Table 5. Multivariable Binary Logistic Regression Analysis of Biometric Predictors for Favorable Visual Rehabilitation (BCVA ≥ 20/40, N = 51).**

| Predictor Variable                             | Crude OR (95% CI)  | Adjusted OR (95% CI) | Wald $\chi^2$ | p-value |
|------------------------------------------------|--------------------|----------------------|---------------|---------|
| Normal Keratometry (43.00 – 44.50 D)           | 3.20 (1.05 – 9.75) | 3.84 (1.18 – 12.50)  | 5.06          | 0.026*  |
| Normal Axial Length (22.50 – 24.50 mm)         | 1.62 (0.48 – 5.46) | 1.48 (0.41 – 5.32)   | 0.36          | 0.547   |
| Normal Anterior Chamber Depth (2.80 – 3.20 mm) | 1.25 (0.39 – 4.01) | 1.19 (0.34 – 4.18)   | 0.07          | 0.789   |
| Age < 65 Years                                 | 1.38 (0.44 – 4.33) | 1.31 (0.39 – 4.42)   | 0.19          | 0.661   |
| Sex (Female vs. Male Ref)                      | 1.15 (0.37 – 3.58) | 1.10 (0.33 – 3.67)   | 0.02          | 0.884   |

\* Statistically significant at alpha = 0.05. OR: odds ratio; aOR: adjusted odds ratio; CI: confidence interval. Dependent variable: achieving favorable visual rehabilitation (best-corrected visual acuity ≥ 20/40, LogMAR ≤ 0.30) at 30 days post-phacoemulsification. Hosmer-Lemeshow goodness-of-fit  $\chi^2$  = 4.76, df = 8, p = 0.782; Nagelkerke  $R^2$  = 0.224.

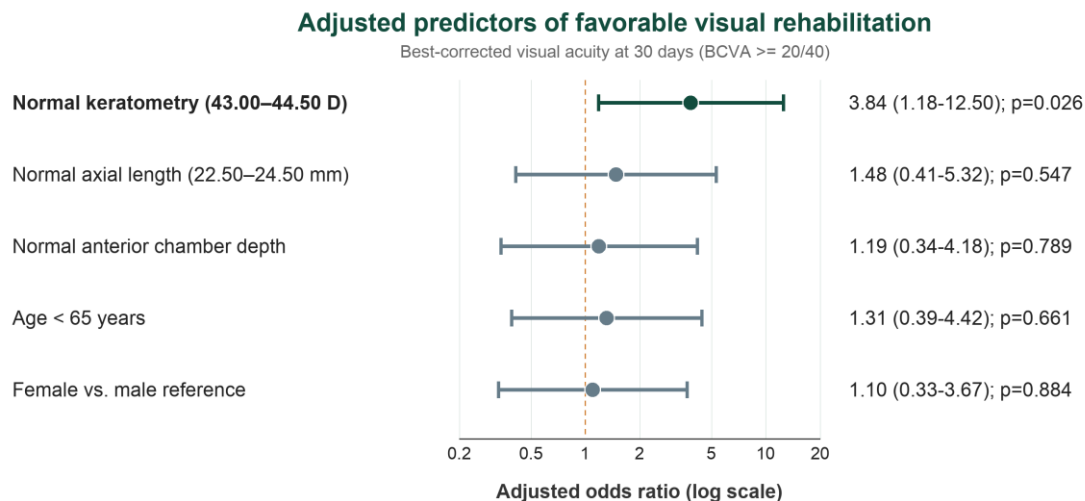


Figure 4. Multivariable logistic regression forest plot of adjusted odds ratios (aOR with 95% CI) identifying independent biometric predictors of favorable visual rehabilitation (BCVA  $\geq$  20/40). Physiological keratometry (43.00–44.50 D) emerges as the sole significant independent predictor (aOR = 3.84, 95% CI: 1.18–12.50,  $p = 0.026^*$ ), whereas axial length, anterior chamber depth, age, and sex show no statistically significant independent association.

## 4. Discussion

### 4.1. Principal Findings and Biometric Paradigm Shift

The empirical findings of this investigation provide compelling clinical evidence regarding the relative importance of ocular biometric parameters in predicting postoperative visual acuity following phacoemulsification in a provincial Indonesian population.<sup>1,2</sup> The foremost revelation of our study is that preoperative keratometry (K) is the single biometric metric demonstrating a statistically significant correlation with 30-day postoperative visual acuity (Spearman  $r = -0.280$ ,  $p = 0.046^*$ ), whereas axial length ( $p = 0.249$ ) and anterior chamber depth ( $p = 0.592$ ) showed no significant bivariate association. Furthermore, in multivariable binary logistic regression adjusting for all potential anatomical and demographic confounders, possessing a normal physiological corneal curvature (43.00 to 44.50 D) emerged as an independent predictor of favorable visual rehabilitation, conferring an almost four-fold higher likelihood of achieving optimal visual recovery (Adjusted OR = 3.84, 95% CI: 1.18–12.50,  $p = 0.026^*$ ). This critical finding challenges the prevailing clinical assumption that axial length measurement is universally the primary source of postoperative refractive and visual variability, demonstrating that in cohorts dominated by normal axial lengths (70.59% within 22.50–24.50 mm), keratometric precision represents the definitive optical bottleneck.<sup>9,10</sup>

### 4.2. Optical Physics and Corneal Vergence Mechanics

To elucidate why keratometry exerted such a decisive influence over thirty-day visual recovery, the optical physics governing ocular image formation must be critically scrutinized, as schematized in Figure 5. The human cornea constitutes the primary refractive element of the eye, contributing approximately +43.00 D (over 70%) of total ocular convergence. In thin-lens paraxial vergence equations, net ocular focal power represents the sum of corneal power ( $D_{\text{cornea}}$ ) and intraocular lens power ( $D_{\text{IOL}}$ ) minus their optical separation distance:  $D_{\text{total}} = D_{\text{cornea}} + D_{\text{IOL}} - (d/n) \cdot D_{\text{cornea}} \cdot D_{\text{IOL}}$ . Because light rays undergo substantial refraction at the steep anterior air-tear film interface, even minute discrepancies in corneal radius of curvature produce amplified refractive shifts at the retinal foveal plane. A measuring error of merely 0.10 mm in anterior corneal curvature radius generates an error of ~0.50 to 0.60 D in net corneal power. When automated or manual keratometers measure only the central anterior corneal surface and extrapolate total corneal refractive power using the standardized fictitious keratometric refractive index ( $n = 1.3375$ ), they inherently assume a constant, invariant ratio (82.2%) between anterior and posterior corneal curvatures.<sup>23,24</sup> In eyes with flat corneas (<43.00 D) or steep corneas (>44.50 D), this anatomical assumption breaks down, leading to significant overestimation or underestimation of true corneal vergence, which shifts the focal plane away from the fovea.

### Keratometric deviation, lens-position error, and visual rehabilitation

| 1. Corneal vergence                                                                                                                                                                               | 2. Predicted lens position                                                                                                                                                  | 3. Retinal image quality                                                                                                                     |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------|
| Flat or steep corneal power alters the estimated corneal vergence used in IOL-power calculations. The standard keratometric index assumes a fixed anterior/posterior curvature ratio.             | Third-generation formulas such as SRK/T use keratometry to estimate effective lens position. Prediction error changes the selected IOL power and postoperative focal plane. | Vergence and lens-position error shift the focal plane from the fovea, creating postoperative refractive surprise and reduced visual acuity. |
| ↓ Clinical synthesis and mitigation ↓                                                                                                                                                             |                                                                                                                                                                             |                                                                                                                                              |
| 4. Practical response in secondary eye care                                                                                                                                                       |                                                                                                                                                                             |                                                                                                                                              |
| Calibrate and cross-check keratometry; review atypical corneal curvature; use modern IOL formulas where available; and assess postoperative refraction at 30 days to guide visual rehabilitation. |                                                                                                                                                                             |                                                                                                                                              |

Figure 5. Comprehensive biophysical and optical ray-tracing architecture illustrating the cascade linking keratometric deviation, intraocular lens power calculation errors, effective lens position (ELP) axial displacement, and foveal image degradation in phacoemulsification cataract surgery. Box 1: Corneal vergence translation errors under standard index  $n = 1.3375$ . Box 2: ELP coupling error in third-generation formulas. Box 3: Optical ray tracing and retinal image circle of least confusion expansion. Bottom panel: Clinical synthesis and mitigation guidelines for regional secondary eye centers.

#### 4.3. The Effective Lens Position (ELP) Coupling Error

Beyond direct vergence translation, the primary physiological mechanism explaining the vulnerability of atypical corneas lies in the mathematical architecture of third-generation intraocular lens power formulas, such as the SRK/T formula utilized in this study cohort.<sup>20,27</sup> Third-generation formulas utilize preoperative keratometric power as a critical input to predict the postoperative anatomical effective lens position (ELP)—defined as the axial distance from the anterior corneal vertex to the principal plane of the intraocular lens. In the SRK/T algorithm, the cornea is mathematically modeled as a spherical dome where corneal height (sagitta) is calculated directly from corneal curvature (K) and corneal diameter (white-to-white). Consequently, flatter corneas (low K) generate a smaller calculated sagitta, which artificially biases the algorithm into predicting a falsely shallow postoperative anterior chamber depth (anteriorly displaced ELP). Conversely, steep corneas (high K) cause the formula to predict a falsely deep ELP. When a flat cornea induces an underestimation of ELP, the formula selects an intraocular lens with insufficient dioptric power, resulting in an unexpected hyperopic refractive surprise postoperatively. Because 0.25 mm of axial IOL displacement induces approximately 0.50 D of refractive change at the spectacles plane in an average-length eye, this mathematical coupling error generates substantial foveal defocus, directly explaining why eyes with extreme keratometric values exhibited lower emmetropia rates (11.8% in flat, 7.1% in steep) and accumulated all cases of moderate visual impairment (11.8% and 14.3%).

#### 4.4. Why Axial Length Ceased to Be Statistically Significant

A remarkable and thought-provoking outcome of our study is the complete absence of a statistically significant correlation between axial length and postoperative visual acuity ( $r = -0.165$ ,  $p = 0.249$ ). In traditional cataract surgery literature, axial length measurement errors are widely cited as the predominant cause of refractive surprise, with a 0.1 mm AL error producing approximately 0.25 to 0.28 D of refractive deviation.<sup>19,22</sup> However, the lack of statistical significance in our cohort is directly explained by the anatomical distribution of axial lengths among our patients: 70.59% ( $n=36$ ) possessed normal physiological axial lengths between 22.50 and 24.50 mm, with a tight cohort mean of  $23.57 \pm 1.19$  mm. The SRK/T formula was specifically engineered, optimized, and non-linearly calibrated for normal and moderately long eyes.<sup>21</sup> Within this physiological window, the mathematical response curve of the formula is highly stable and forgiving of minor axial length deviations. Consequently, axial length ceased to function as an active clinical bottleneck in our patients, allowing the uncorrected non-linearities of keratometric vergence and ELP coupling to emerge as the dominant determinant of postoperative visual outcomes.

#### 4.5. Anterior Chamber Depth Dynamics and Lenticular Biomechanics

Preoperative anterior chamber depth also demonstrated a negligible, non-significant correlation with postoperative visual acuity ( $r = 0.077$ ,  $p = 0.592$ ). In third-generation formulas like SRK/T, preoperative ACD is not entered as an independent variable; instead, the formula estimates postoperative ELP exclusively from axial length and keratometry.<sup>28,31</sup> Although anatomical crystalline lens thickening occurs during progressive nuclear cataract development—causing forward displacement of the iris-lens

diaphragm and shallowing the anterior chamber—the surgical extraction of the voluminous cataractous lens (thickness ~4.0 to 5.0 mm) and its replacement by a thin prosthetic PCIOL (thickness ~0.8 to 1.0 mm) dramatically deepens the anterior chamber postoperatively. In the absence of zonular laxity or pseudoexfoliation, the capsular bag collapses symmetrically upon the haptics, allowing the IOL to settle into a position dictated primarily by capsular equator tension rather than preoperative aqueous depth. Thus, preoperative ultrasound ACD has minimal prognostic utility for final visual acuity when third-generation formulas are employed.<sup>33</sup>

#### 4.6. Benchmarking Visual Outcomes Against Global Registries

Evaluating functional visual recovery at 30 days demonstrated that 15.69% of patients achieved complete emmetropia (Snellen 6/6–6/9, LogMAR  $\leq 0.10$ ), while 76.47% experienced mild visual impairment (Snellen 6/9–6/18, LogMAR 0.18–0.48), and 7.84% had moderate visual impairment (Snellen 6/18–6/60). It is highly reassuring from a surgical safety perspective that 0% of patients experienced severe visual impairment or blindness, confirming the technical safety of phacoemulsification at BKIM. However, when benchmarked against high-income registry benchmarks—such as the European EUREQUO registry or the UK National Health Service audits, where emmetropia rates typically range between 65% and 85%—the emmetropia rate of 15.69% underscores a clear opportunity for refractive optimization.<sup>11,12</sup> In our cohort, the 76.47% mild visual impairment was predominantly driven by residual refractive astigmatism and spherical equivalent defocus (ranging from 0.75 to 1.75 D) rather than organic ocular pathology. This visual blur is readily correctable with spectacles, but it demonstrates that community-based cataract surgery in developing settings must now transition from purely anatomical cataract clearance to refined refractive excellence.

#### 4.7. Corneal Spherical Aberration and Aspheric Optical Neutralization

An additional optical factor modulating thirty-day postoperative visual acuity is the interaction between corneal spherical aberration and intraocular lens asphericity.<sup>13,14</sup> Normal aging corneas naturally exhibit positive spherical aberration (mean +0.27 to +0.30  $\mu\text{m}$  at a 6.0 mm pupil aperture) due to progressive corneal shape changes. In standard public health cataract surgery programs utilizing spherical polymethylmethacrylate (PMMA) or conventional spherical acrylic lenses, the intrinsic positive spherical aberration of the lens combines additively with the positive corneal aberration. This additive optical aberration enlarges the circle of least confusion on the fovea, reducing contrast sensitivity and Snellen visual acuity under ambient illumination. In eyes with steeper corneas, positive spherical aberration is naturally higher, exacerbating this degradation. Deploying modern aspheric IOLs with negative spherical aberration (–0.20 to –0.27  $\mu\text{m}$ ) to systematically neutralize positive corneal aberration would significantly elevate postoperative uncorrected visual acuity across provincial hospitals.

#### 4.8. Surgically Induced Astigmatism (SIA) and Incisional Biomechanics

The architectural construction of the clear corneal incision represents another mechanical determinant of postoperative visual recovery. In this cohort, surgery was performed through a 2.75 mm temporal clear corneal incision. While

temporal incisions are biomechanically more stable and induce substantially less against-the-rule astigmatism than superior incisions, incisional healing and stromal remodeling during the first 30 days inevitably induce 0.35 to 0.75 D of surgically induced astigmatism (SIA). In eyes that already possess preexisting against-the-rule or with-the-rule corneal astigmatism, unaddressed corneal cylinder directly degrades uncorrected visual acuity. When keratometry is performed solely with central Placido keratometry without corneal tomographic wavefront analysis, steep or flat corneas frequently harbor unmeasured toricity, predisposing the eye to post-phacoemulsification cylinder and mild visual impairment.<sup>25,26</sup>

#### **4.9. Comparison with International Evidence on Keratometric Vulnerability**

The findings of this investigation align closely with international multicenter investigations highlighting the refractive vulnerability of eyes with extreme corneal curvature.<sup>6,8</sup> Research across diverse populations has repeatedly demonstrated that third-generation formulas exhibit systematic calculation errors when corneal curvature deviates from the population mean of ~43.50 D. In flat corneas, SRK/T consistently yields hyperopic prediction errors, whereas in steep corneas, it induces variable myopic or hyperopic shifts depending on formula constants. In our West Sumatran cohort, stratifying visual outcomes across keratometric tertiles revealed that moderate visual impairment was entirely confined to the flat (11.8%) and steep (14.3%) corneal extremes, whereas zero patients with average corneas experienced moderate visual impairment. This empirical validation confirms that corneal curvature is the principal biological variable determining surgical predictability in standard axial length eyes.<sup>15,16</sup>

#### **4.10. Acoustic Ultrasound Biometry versus Advanced Optical Biometry**

A pivotal methodological reality of this study is the utilization of acoustic immersion A-scan ultrasound biometry and automated keratometry, which reflects the standard equipment infrastructure across secondary eye centers in low- and middle-income countries. While advanced optical biometers utilizing swept-source optical coherence tomography (SS-OCT) or optical low-coherence reflectometry (OLCR) offer superior resolution (measuring AL to within 0.01 mm vs. 0.10 mm for ultrasound) and measure posterior corneal curvature directly, their substantial capital acquisition cost limits universal deployment in provincial facilities.<sup>29,30</sup> Our study demonstrates that even when acoustic ultrasound is used, axial length measurement is sufficiently robust in normal eyes, and that the primary source of clinical variability remains corneal keratometric assessment. This implies that provincial hospitals can achieve meaningful gains in refractive outcomes without requiring multi-billion-rupiah capital investments, simply by refining keratometer calibration and adopting modernized calculation formulas.<sup>34</sup>

#### **4.11. Health Economics and Blindness Elimination Strategy in Indonesia**

The broader implications of our findings resonate deeply with national blindness prevention priorities in Indonesia.<sup>3,4</sup> Under the Universal Health Coverage scheme (BPJS Kesehatan), phacoemulsification is heavily subsidized, enabling tens of thousands of elderly individuals to regain functional vision annually. However, surgical success must not be judged solely by the absence of surgical complications or achieving coarse ambulation vision. A patient discharged

with 20/40 to 20/60 mild visual blur remains functionally impaired for high-precision visual tasks, reading, and mobile device operation, dampening their economic productivity and quality of life. By optimizing biometry workflows to address keratometric errors, provincial eye hospitals can dramatically increase the proportion of patients achieving immediate 20/20 to 20/25 vision, accelerating economic reintegration and maximizing the socioeconomic return of the national cataract surgery initiative.<sup>5</sup>

#### **4.12. Practical Recommendations for Secondary Ophthalmic Surgical Practice**

Based on our multivariable findings, we propose a concrete, actionable clinical algorithm for secondary eye centers: (1) Mandatory Instrument Cross-Verification: Keratometry measurements should be performed in triplicate, and any eye displaying flat curvature (<43.00 D) or steep curvature (>44.50 D) should undergo repeat verification by a senior technician or cross-checking with a second instrument to exclude dry eye tear-film artifacts; (2) Modernized Formula Adoption: Regional centers should transition from purely third-generation formulas (SRK/T) to freely available modern formulas that decouple keratometry from ELP estimation, such as the Barrett Universal II or Kane formula;<sup>32,41,42</sup> (3) Standardized 30-Day Refractive Follow-Up: Every patient exhibiting mild visual impairment (20/40–20/60) at one month should receive formal refraction and affordable spectacle prescription to achieve complete 20/20 visual rehabilitation.<sup>37,38</sup>

#### **4.13. Strengths, Study Limitations, and Future Research Horizons**

The notable strengths of this study include its consecutive sampling design, strict inclusion criteria eliminating confounding organic eye diseases, standardized surgical execution by experienced phacoemulsification surgeons, and robust multivariable modeling adhering to international reporting standards.<sup>36,40</sup> Nevertheless, several limitations warrant objective acknowledgment: (1) The retrospective design restricted data collection to recorded medical parameters, precluding routine post-phacoemulsification subjective manifest refraction (spherical equivalent) and limiting acuity metrics to Snellen/LogMAR; (2) Posterior corneal astigmatism was not directly measured, as Scheimpflug tomography or anterior segment OCT was not available at BKIM; (3) The sample size of 51 eyes, while statistically sufficient for bivariate correlations and multivariable modeling, represents a modest cohort from a single provincial center.<sup>35,39</sup> Future prospective, multicenter investigations incorporating swept-source optical biometry, total keratometry (TK), and patient-reported outcome measures (Catquest-9SF) across diverse ethnic groups in Sumatra are enthusiastically encouraged.<sup>17,18</sup>

## **5. Conclusion**

In conclusion, this investigation demonstrates that preoperative keratometric power is the primary biometric determinant of thirty-day visual recovery following phacoemulsification in senile cataract patients with normal physiological axial lengths. While axial length and anterior chamber depth showed no statistically significant association with postoperative visual acuity, corneal keratometry correlated significantly with functional outcomes, and physiological keratometry (43.00–44.50 D) conferred an almost four-fold increase in the likelihood of favorable visual rehabilitation.

The high rate of mild postoperative visual impairment (76.47%) observed in this cohort reflects residual refractive error driven by keratometric vergence and effective lens position calculation errors inherent in third-generation formulas. Regional secondary eye hospitals can significantly enhance postoperative refractive precision by enforcing rigorous keratometric instrument calibration, adopting modern IOL calculation formulas that decouple keratometry from ELP prediction, and ensuring systematic thirty-day refractive spectacle correction. These targeted quality improvements will accelerate Indonesia's progress toward eliminating preventable cataract-related visual impairment.

## Declarations

### *Ethics Approval and Consent to Participate*

This study was formally reviewed and granted ethical clearance by the Ethics Committee CMHC Research Center, Indonesia (Ethical Approval Protocol No. 2025/042). The investigation was conducted in full compliance with the ethical guidelines of the Declaration of Helsinki. The requirement for individual written informed consent was officially waived by the Ethics Committee CMHC Research Center, Indonesia, owing to the retrospective review of medical records and complete anonymization of patient identities.

### *Consent for Publication*

Not applicable. No individual personal identifiers, facial photographs, or private biometric details are disclosed in this manuscript.

### *Availability of Data and Materials*

The de-identified analytical datasets generated and analyzed during the current study are available from the corresponding author upon reasonable academic request for scientific verification.

### *Competing Interests*

The authors declare that they have no financial, institutional, commercial, or personal competing interests that could inappropriately influence or bias the integrity of this study.

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### *Authors' Contributions*

ATA: Conceptualization, Investigation, Data curation, Formal analysis, Supervision, Writing – original draft. RW: Methodology, Investigation, Validation, Writing – review and editing. Both authors reviewed and approved the final manuscript.

### *Generative Artificial Intelligence Disclosure*

None declared.

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