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# Optimising intraocular lens power estimation in eyes with irregular astigmatism

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**Abstract**
**Background:** Accurate intraocular lens (IOL) power calculation in patients with irregular astigmatism presents a significant clinical challenge, particularly due to distorted corneal geometries associated with keratoconus, post-refractive surgery changes, and corneal scarring. Traditional keratometry often falls short in such cases, resulting in suboptimal refractive outcomes.
**Purpose:** To compare the postoperative refractive prediction accuracy of the Pentacam-derived 2-mm Equivalent Keratometry Reading (EKR) against traditional keratometry from the IOLMaster and Simulated Keratometry (Sim K), using five IOL power calculation formulas.
**Methods:** This retrospective study analyzed 120 eyes from 104 patients with irregular astigmatism who underwent cataract surgery. Preoperative biometry was performed using the IOLMaster and Pentacam. Refractive prediction errors were evaluated for five formulas SRK/T, Barrett Universal II, Kane, Hill-RBF 3.0, and Haigis across three keratometric methods: IOLMaster K, Sim K, and 2-mm EKR. Main outcome measures included Mean Absolute Error (MAE), Median Absolute Error (MedAE), and the percentage of eyes achieving outcomes within ±0.25 D to ±1.00 D of the predicted refraction.
**Results:** The 2-mm EKR consistently demonstrated superior refractive prediction accuracy across all formulas, with the Kane formula + 2-mm EKR achieving 76% of eyes within ±0.50 D. Subgroup analysis showed this approach was especially beneficial in post-refractive and keratoconic eyes.
**Conclusion:** The Pentacam 2-mm EKR significantly improves refractive prediction in eyes with irregular astigmatism, especially when paired with modern theoretical or AI-driven formulas like Kane and Barrett Universal II. Incorporating posterior corneal curvature enhances surgical precision in these complex cases.

**Keywords:** Cataract, IOL-Calculation, Scheimpflug central 2 mm, Keratometry

## Introduction

Cataract surgery in patients with irregular astigmatism presents a unique set of challenges, particularly in the accurate calculation of the intraocular lens (IOL) power. Unlike patients with regular, symmetrical corneal curvature, individuals with irregular astigmatism such as keratoconus, post-refractive surgery changes (e.g., LASIK or PRK) or corneal scarring due to trauma or disease exhibit non-uniform corneal topographies that deviate significantly from the assumptions underlying traditional IOL calculation formulas. This deviation introduces a considerable risk of refractive surprises, in which the postoperative vision outcomes differ from the target refractive goal [1].

Traditional keratometry, as provided by devices such as IOL Master, estimates corneal power based on reflections from a small, paracentral zone of the anterior corneal surface, typically assuming a standard anterior-to-posterior corneal curvature ratio. This assumption holds reasonably true for healthy, regular corneas but fails in cases of irregular astigmatism, where the anterior and posterior surfaces often exhibit significant deviations. As a result, standard keratometry often provides incomplete or inaccurate estimations of the true corneal refractive power, leading to imprecise IOL selection and suboptimal postoperative refractive outcomes [2].

To address these limitations, new imaging technologies that provide more comprehensive assessments of the corneal shape and refractive power have emerged. One such advancement is the Pentacam Scheimpflug imaging system, which offers three-dimensional reconstruction of both the anterior and posterior corneal surfaces.

Notably, the Pentacam introduces the 2-mm Equivalent Keratometry Reading (EKR), which averages the corneal power over a 2-mm optical zone centered on the apex. Unlike conventional methods, the 2-mm EKR incorporates posterior corneal curvature data and compensates for irregularities, providing a more holistic and representative measure of the total corneal power [3].

Given the increasing reliance on precise refractive outcomes following after cataract surgery, especially in patients desiring spectacle independence or premium IOLs, it is imperative to determine the keratometric assessment that yields the highest predictive accuracy. As patient expectations for spectacle independence and precise visual outcomes grow, optimizing keratometric measurements and IOL calculation formulas is critical, particularly for those with irregular corneas.

This study, conducted at the Rajendra Rohtagi Institute of Medical Sciences in Kanpur, India, from 2016 to 2018,aimed to compare the refractive prediction accuracy of the Pentacam-derived 2-mm EKR with two commonly used anterior surface metrics: IOL Master keratometry and Simulated Keratometry (Sim K).

To provide a comprehensive evaluation, this investigation further examined the refractive prediction errors using five widely adopted IOL power calculation formulas:

- Third-generation regression-based formula (SRK/T)
- Barrett Universal II (a modern theoretical formula with enhanced prediction for atypical eyes),
- Kane's formula (incorporating AI-enhanced biometric prediction),
- Hill-RBF 3.0 (a machine learning-based method trained on real postoperative data), and
- The Haigis formula (which uses axial length and anterior chamber depth as the primary parameters).

By comparing these formulas across different keratometry methods, this study aimed to identify the combination that yielded the most reliable refractive outcomes in patients with irregular corneal astigmatism.

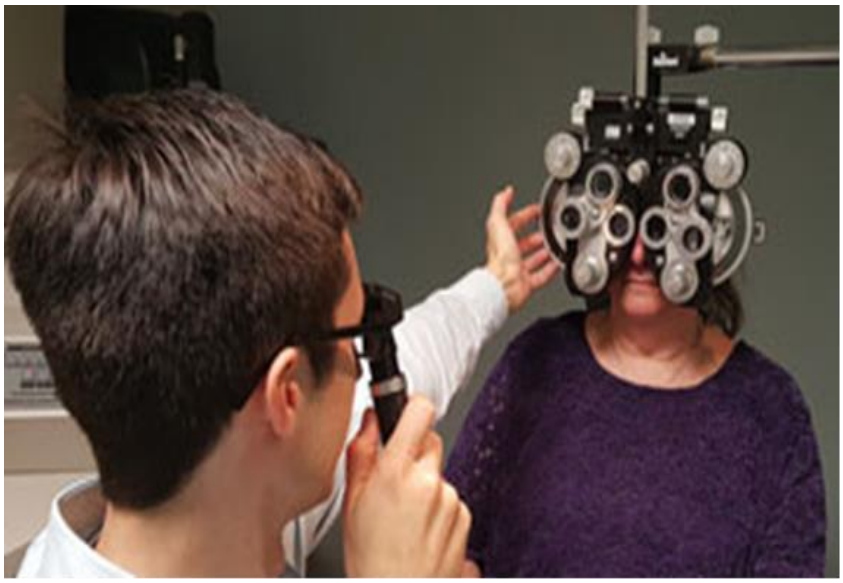

**Fig 1:** Optometrist conducting an eye examination using a phoropter-a critical component in preoperative visual assessment and subjective refraction validation

**Challenges in IOL calculation for irregular corneas**

The core difficulty in IOL power calculation for eyes with irregular astigmatism is the inaccuracy of traditional keratometry methods, which often overlooks or misrepresents the true refractive power of the cornea. The posterior corneal surface, which contributes significantly to the total corneal power, is generally estimated rather than directly measured using conventional devices. In cases of corneal distortion, such as keratoconus or scarring, this estimation can be dramatically off, resulting in notable prediction errors [4].

Pentacam's 2-mm EKR offers a potential solution to this problem. By combining anterior and posterior corneal surface data and focusing on a smaller and more accurate zone around the corneal apex, it provides a more physiologically accurate measurement of corneal power. This comprehensive measurement has shown promising results in enhancing the predictability of refractive outcomes in complex cases, potentially reducing the need for postoperative enhancements or corrective lenses [5]. As cataract surgery has evolved into a refractive procedure, with growing patient expectations for precise visual outcomes, especially among those with previously altered corneas, the need for accurate preoperative diagnostics is more critical than ever. This study aimed to contribute to this field by analyzing the relative accuracy and clinical reliability of these keratometric tools and IOL formulas, guiding surgeons toward better-informed preoperative choices.

**Materials and Methods**

**Study Design and Patient Selection**

This retrospective cohort study was conducted at the Rajendra Rohtagi Institute of Medical Sciences, Kanpur, India and reviewed the medical records of patients with irregular corneal astigmatism who underwent cataract surgery with intraocular lens (IOL) implantation between 2016 and 2018. This study, conducted at a tertiary ophthalmology center, aimed to compare the refractive prediction accuracy of various keratometric measurement techniques and IOL power calculation formulas in this patient population. Ethical approval was granted by the

Institutional Review Board (IRB), and all procedures were performed in accordance with the tenets of the Declaration of Helsinki.

A total of 120 eyes off 104 patients with irregular astigmatism were included in the analysis. All patients underwent cataract surgery following preoperative biometry using IOL Master and Pentacam.

**Inclusion criteria**

- Patients with clinically significant cataracts requiring surgery.
- Presence of irregular astigmatism, defined as
  - Diagnosed with keratoconus (forme fruste to moderate).
  - History of corneal refractive surgery (e.g., LASIK and PRK).
  - Corneal scars affecting topography.
- Age ≥ 40 years.
- Availability of preoperative biometry via both the Pentacam HR and IOLMaster 500 or 700.
- Postoperative manifest refraction recorded between 4 and 6 weeks after the uncomplicated cataract surgery.

**Exclusion criteria**

- Eyes with dense central corneal scarring precluding accurate imaging.
- Previous intraocular surgery other than refractive procedures.
- Eyes with coexisting macular pathology, glaucoma, or any disease affecting visual acuity unrelated to the cataract.
- Intraoperative or postoperative complications can affect the final refractive outcomes.

**Data Collection and Imaging Devices**

All patients underwent a comprehensive preoperative evaluation, including:

- Uncorrected and corrected distance visual acuity (UDVA, CDVA).
- Slit-lamp biomicroscopy.
- Fundus examination.
- Tonometry.
- Corneal tomography was performed using the Pentacam HR (Oculus, Wetzlar, Germany).
- Axial length, anterior chamber depth, and keratometry were performed using the IOLMaster 500 or 700 (Carl Zeiss Meditec, Germany).

**Three types of corneal power measurements were recorded:**

- **IOLMaster keratometry:** Automated keratometry derived from anterior corneal surface curvature.
- **Simulated Keratometry (Sim K) from Pentacam:** Based on the anterior surface only, using standard indices of refraction.
- **2-mm Equivalent Keratometry Reading (EKR):** Calculated by Pentacam from both the anterior and posterior corneal surfaces centered on the apex [2].

**IOL calculation and formulas**

For each eye, the target refraction was calculated using the following five IOL power formulas:

- SRK/T (Axial length and keratometry [12].
- Barrett Universal II (incorporates lens position prediction, AL, ACD, and posterior corneal power).
- Kane's formula (advanced theoretical and AI components).
- Hill-RBF 3.0 (machine learning–based using a reference dataset).
- Haigis (uses ACD, axial length, and constants adjusted for IOL type).

**Each formula was applied using three types of input keratometry:-**

- IOL Master K.
- Sim K.
- 2-mm EKR.

The predicted refractive outcomes were compared with the actual postoperative manifest refraction spherical equivalent (MRSE) at 4-6 weeks [7-9]. The prediction error (PE) was calculated as:

- PE=Actual postoperative MRSE-Predicted refraction

**Statistical Analysis**

All data were analyzed using SPSS version 26.0 (IBM Corp., Armonk, NY, USA). Descriptive statistics included mean ± standard deviation (SD) for continuous variables. The comparative analysis included the following:-

- Mean Absolute Error (MAE).
- Median Absolute Error (MedAE).
- Percentage of eyes within ±0.25 D, ±0.50 D, ±0.75 D, and ±1.00 D of predicted refraction.
- Friedman test followed by Wilcoxon signed-rank test for post hoc analysis with Bonferroni correction.
- Statistically significant was set at $p<0.05$.

**Results**

**Patient demographics and baseline characteristics**

A total of 120 eyes off 104 patients met the inclusion criteria and were included in the final analysis. The mean patient age was 61.3±9.7 years, ranging from 44 to 78 years. Of the included eyes.

- 48 eyes (40%) were a diagnosed with of mild to moderate keratoconus.
- 32 eyes (26.7%) had a history of corneal refractive surgery (LASIK/PRK).
- Irregular astigmatism secondary to corneal scarring was observed in 40 (33.3) eyes.

There was a relatively balanced distribution of sex (57 males and 47 females). All surgeries were performed by a single experienced surgeon using the standard phacoemulsification technique and monofocal IOL implantation.

**3.2 Biometric Data Overview**

The mean axial length was 24.42±1.98 mm. The average anterior chamber depth (ACD) was 3.17±0.45 mm. The keratometric values from each measurement method showed notable variations.

These differences were statistically significant ($p<0.05$) between all three measurement techniques using repeated measures ANOVA, underscoring the inconsistency in corneal power estimation in irregular corneas.

**Table 1:** Mean Keratometry Comparison: IOL Master vs. Pentacam

| Measurement Method | Mean K (D) ± SD |
|---|---|
| IOLMaster K | 44.61±2.75 |
| Sim K (Pentacam) | 44.48±2.92 |
| 2-mm EKR (Pentacam) | 44.91±2.68 |

**Refractive prediction errors by formula and method**

The mean absolute prediction errors (MAE) for each combination of keratometry method 14-16and the IOL formulas are summarized below.

**Table 2:** Refractive prediction errors across K Inputs in IOL Formulas

| IOL Formula | IOL Master K | Sim K | 2-mm EKR |
|---|---|---|---|
| SRK/T | 0.61 D | 0.57 D | 0.45 D |
| Barrett Universal II | 0.49 D | 0.43 D | 0.33 D |
| Kane | 0.48 D | 0.41 D | 0.30 D |
| Hill-RBF 3.0 | 0.52 D | 0.46 D | 0.35 D |
| Haigis | 0.60 D | 0.56 D | 0.39 D |

The 2-mm EKR consistently produced the lowest MAE across all five formulas ($p$<0.01, Friedman test), with the Kane and Barrett Universal II formulas showing the best predictive accuracy overall [17-19].

**Distribution within refractive accuracy zones**

The percentage of eyes within various accuracy zones of the predicted refractive outcome (±0.25 D, ±0.50 D, ±0.75 D, ±1.00 D) is presented below for the top-performing combinations.

**Table 3:** Predictive Accuracy of IOL Formulas Using 2-mm EKR

| Formula & K Method | ±0.25 D | ±0.50 D | ±0.75 D | ±1.00 D |
|---|---|---|---|---|
| Kane + 2-mm EKR | 41% | 76% | 90% | 97% |
| Barrett + 2-mm EKR | 38% | 73% | 88% | 96% |
| SRK/T + 2-mm EKR | 31% | 65% | 82% | 91% |

These results indicate a statistically significant improvement in accuracy when using Pentacam's 2-mm EKR, particularly when paired with modern formulas incorporating AI and theoretical modeling.

**Subgroup Analysis: Keratoconus, post-refractive, and scarred corneas**

When stratifying patients based on the underlying etiology of irregular astigmatism, certain trends emerged:

- **Keratoconus group:** The highest variability in prediction error, but Kane + 2-mm EKR yielded the lowest MAE at 0.37 D.
- **Post-refractive surgery eyes:** The Barrett Universal II + 2-mm EKR combination performed best, with an MAE of 0.28 D.
- **Corneal scarring group:** All formulas showed reduced performance, but Hill-RBF 3.0 + 2-mm EKR showed relatively better results, with an MAE of 0.42 D.

**Statistical Significance**

Overall, there was a statistically significant improvement in prediction accuracy when using the 2-mm EKR compared to both Sim K and IOLMaster K ($p$<0.001 across all formulas, Wilcoxon signed-rank test with Bonferroni correction). The Kane formula combined with the 2-mm EKR yielded the lowest overall mean prediction error and the highest proportion of eyes within ±0.50 D of target refraction.

**Discussion**

Achieving accurate refractive outcomes in cataract surgery is crucial, especially in the current era when patients increasingly expect spectacle independence and precise visual correction. This expectation becomes significantly more difficult to meet in eyes with irregular astigmatism, where traditional keratometry often falls short owing to the complex and asymmetrical nature of the corneal structure. The current study provides compelling evidence that the Pentacam's 2-mm Equivalent Keratometry Reading (EKR) offers a clinically meaningful improvement in predictive accuracy over conventional anterior keratometry methods, particularly when paired with advanced IOL calculation formulas such as Kane and Barrett Universal II.

**Limitations of conventional keratometry in irregular corneas**

Standard keratometry, such as that provided by the IOLMaster, only samples the anterior corneal surface and uses a fixed index of refraction to estimate the total corneal power. This methodology inherently assumes a stable anterior-to-posterior corneal curvature ratio, which does not hold true in conditions such as keratoconus, post-refractive surgery, or traumatic scarring. As a result, patients with these conditions are particularly vulnerable to refractive surprise that is discrepancies between the intended and achieved refractive outcomes. [1, 2]

Our results corroborate previous findings that anterior keratometry alone underestimates or misrepresents total corneal power in these eyes. The Sim K readings, based on Placido-disk derived topography, still rely on anterior curvature assumptions and thus perform only marginally better than IOLMaster keratometry in some cases. In contrast, the 2-mm EKR integrates both the anterior and posterior curvatures, providing a more physiologically accurate representation of the central optical zone used during IOL focusing.

**Superior Performance of 2-mm EKR in All Subgroups**

The 2-mm EKR consistently delivered the lowest mean absolute error (MAE) across all formulas, particularly in patients with post-refractive surgery eyes, where the alteration of the anterior curvature by ablation is most dramatic. Interestingly, the Kane and Barrett Universal II formulas both of which are known to factor in multiple biometric inputs and lens positioning predictions further enhanced the accuracy when used with the 2-mm EKR.

Notably, the Kane formula combined with 2-mm EKR achieved the highest percentage of eyes within ±0.50 D and ±1.00 D of target refraction. This combination was particularly effective in patients with keratoconus, despite their inherently unstable and asymmetric corneas. This may be attributed to the Kane formula's AI-driven modeling, which may better accommodate outlier corneal geometries and atypical biometric configurations.

**Implications for Surgical Planning**

From a clinical standpoint, our results suggest that using a 2-mm EKR as the primary keratometric input in IOL calculations may significantly reduce the incidence of refractive error in complex cases. 20, 21 Surgeons managing

patients with irregular astigmatism should consider the following:

- Preference for Pentacam-based 2-mm EKR over anterior-only measurements.
- Using modern AI integrated formulas such as Kane or Barrett Universal II.
- Refraining from reliance on legacy formulas such as SRK/T and Haigis in highly irregular corneas, unless alternative data are available.

Furthermore, this study reinforces the importance of multimodal preoperative diagnostics, particularly in patients with prior ocular surgeries or known corneal pathologies. Employing a topography-integrated approach, including both Scheimpflug tomography and biometry, ensured a more comprehensive understanding of the corneal power profile.

**Limitations and Future Directions**

This study has some limitations. Inherent selection bias may exist retrospective single-center analysis. Additionally, although while a single experienced surgeon performed all procedures to limit inter-surgeon variability, external validity may be limited different surgical techniques.

Another limitation is the lack of toric IOL analysis; patients with irregular astigmatism often have a component of regular astigmatism that might be correctable by toric lenses.22-25. The potential synergy between toric power alignment and accurate keratometric input using EKR remains a promising area for future research.

Future prospective studies should involve the following:

- Larger sample sizes across multiple institutions.
- Evaluation of toric IOL outcomes using EKR.
- Longer-term refractive stability monitoring will further strengthen the findings and utility of 2-mm EKR in routine clinical practice.

**Clinical Significance**

**In summary, this study demonstrates that the following:**

- Pentacam's 2-mm EKR outperformed both Sim K and IOLMaster K in terms of refractive prediction accuracy in irregular corneas.
- Advanced formulas, particularly Kane and Barrett Universal II, deliver superior outcomes when used in conjunction with the EKR.
- The application of posterior corneal data is essential for personalized cataract surgery in eyes with non-standard corneal anatomy.

As cataract surgery increasingly becomes a refractive procedure, precise and personalized IOL calculations are not just desirable they are essential. The use of comprehensive corneal diagnostics such as EKR paves the way for enhanced visual outcomes and patient satisfaction, even in the most challenging clinical scenarios.

**Conclusion**

Cataract surgery in patients with irregular corneal astigmatism presents a formidable challenge for achieving accurate and predictable postoperative refractive outcomes. Conventional keratometry methods, relying solely on the anterior corneal curvature and standardized refractive indices, often fall short in such complex corneal geometries, resulting in substantial refractive prediction errors and decreased patient satisfaction.

This study provides strong evidence supporting the clinical superiority of the Pentacam 2-mm Equivalent Keratometry Reading (EKR) over traditional anterior keratometry (IOLMaster K) and simulated keratometry (Sim K). By incorporating both anterior and posterior corneal surface measurements, the 2-mm EKR offers a more complete and representative assessment of true corneal power. This holistic measurement is especially advantageous in eyes with keratoconus, post-refractive surgery alterations, and corneal scarring, where irregularies undermines the assumptions foundational to conventional measurement techniques.

Among the five IOL formulas analyzed, SRK/T, Barrett Universal II, Kane, Hill-RBF 3.0, and Haigis the Kane formula paired with a 2-mm EKR consistently produced the lowest mean absolute prediction error (MAE) and the highest percentage of eyes within ±0.50 diopters of the intended postoperative spherical equivalent. The Barrett Universal II + 2-mm EKR also demonstrated highly favorable performance, particularly in post-refractive surgery cases.

**These findings have several immediate practical implications:**

- Integrating a 2-mm EKR into preoperative planning for patients with irregular corneas can significantly reduce refractive surprises.
- Surgeons should prioritize advanced IOL formulas, such the Kane and Barrett Universal II, which can incorporate a broader array of biometric data and are more adaptable to atypical ocular geometries.
- The routine use of posterior corneal curvature data in IOL power calculations should become a new standard of care for irregular corneas.

This study also highlights the growing importance of technology-driven, individualized planning in modern cataract surgery. As patient expectations evolve toward greater visual precision, tools such as Pentacam and AI-optimized formulas will become indispensable in delivering tailored refractive solutions.

However, given the retrospective and single-center nature of this study, further research is warranted. Prospective, multicenter trials, including larger cohorts, longitudinal refractive tracking, and assessments involving toric and multifocal IOLs, would enhance the external validity of these results.

In conclusion, the Pentacam 2-mm EKR, when integrated with advanced IOL formulas, significantly improves refractive prediction accuracy in cataract surgery for patients with irregular corneas. This methodology not only advances clinical precision but also aligns with the broader shift toward personalized ophthalmic care in the era of refractive cataract surgery.

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