

Comparative Outcomes of Robotic Laser Arcuate Keratotomy and Toric Intraocular Lenses for the Management of Lower Magnitude Astigmatism at the Time of Cataract Surgery

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Purpose: To compare refractive and visual outcomes between robotic laser-assisted arcuate keratotomy (AK) guided by the Wörtz-Gupta FormulaTM and low-power toric intraocular lens (IOL) implantation using the Barrett Toric Calculator for the management of low-magnitude regular corneal astigmatism during cataract surgery.

Patients and Methods: This retrospective, single-surgeon case series included 105 eyes with robotic laser-assisted AK using the ALLY platform with iris registration (LENSAR, Inc, Orlando, FL), and 53 received a toric IOL, using ALLY's IntelliAxis refractive capsulorhexis for intraoperative toric IOL alignment. The primary outcome measure was postoperative residual refractive cylinder at postoperative week 4. Secondary outcomes included uncorrected distance visual acuity (UDVA), best-corrected distance visual acuity (CDVA), and spherical equivalent (SE) refraction. Subgroup analyses evaluated outcomes by astigmatism orientation (with-the-rule [WTR] versus against-the-rule [ATR]).

Results: Postoperative residual refractive cylinder did not differ significantly between groups (-0.14 ± 0.16 D AK vs -0.21 ± 0.28 D toric, $p = 0.103$), nor did SE refraction (-0.08 ± 0.32 D AK versus -0.11 ± 0.28 D toric, $p = 0.361$), UDVA (0.05 ± 0.08 logMAR both groups, $p = 0.507$), or CDVA (-0.006 logMAR AK versus -0.004 logMAR toric, $p = 0.623$). More than 90% of eyes in both cohorts achieved ≤ 0.50 D of residual astigmatism, and $\geq 87\%$ attained UDVA of 20/25 or better. Subgroup analyses by astigmatism orientation showed no statistically significant differences in residual cylinder, SE, or VA.

Conclusion: In eyes with low-magnitude regular corneal astigmatism undergoing cataract surgery, robotic laser-assisted AK guided by the Wörtz-Gupta FormulaTM achieved non-inferior refractive and visual outcomes to those of low-power toric IOL implantation.

Plain Language Summary: This retrospective study found non-inferiority in visual outcomes at 4 weeks postoperatively from patients with regular corneal astigmatism (between 0.6 and 1.1 D) who underwent cataract surgery with an advanced robotic laser (ALLY, LENSAR) guided by the Wortz-Gupta formula for lower levels of astigmatism and those who underwent cataract surgery with low-level toric lenses (as determined by the Barrett Toric Calculator).

Keywords: Wörtz-Gupta formula, phacoemulsification, FLACS, LENSAR ALLY, robotic surgical procedures

Introduction

Cataract surgery has become the most performed refractive surgery worldwide, with more than 26 million procedures performed yearly.¹ Advances in technology have allowed surgeons to improve visual outcomes by addressing multiple issues to provide patients with superior vision rather than visual rehabilitation. The most common of these refractive

issues is astigmatism.² More than 75% of patients presenting for cataract surgery have >0.5 D of astigmatism that can be corrected at the time of cataract surgery.^{2–6} However, studies and practical experience show that leaving patients with uncorrected astigmatism ≥ 0.5 D postoperatively leaves patients with reduced quality of vision and satisfaction.⁷ Toric intraocular lenses (IOLs) have become the lens-based gold standard in treating moderate corneal astigmatism in cataract patients.⁸ Outside the US, lower powered toric IOLs are available for the correction of lower magnitude astigmatism (<1.0 D). In the US, however, the lowest powered commercially available toric IOL is the Envista MX60ET 125 (Bausch & Lomb, Bridgewater, NJ), which corrects 0.90D of astigmatism at the corneal plane. This leaves a meaningful gap in lens-based astigmatism correction options below 0.9 D.

This treatment gap has led to increased attention of other strategies that can treat lower levels of astigmatism, including arcuate keratotomy (AK). Historically, AKs were used to debulk higher amounts of astigmatism before toric IOLs were available. These were performed manually, and typically with variable precision in optical zone, depth and length.^{9,10} The guidelines for performing AKs were nomogram-based and were unable to provide personalized/individualized recommendations. With the advent of the femtosecond-laser assisted cataract surgery (FLACS), and more recently, second-generation femtosecond (also called robotic) laser cataract surgery, it is now possible to perform AKs with extreme precision. For example, AKs can be performed at a precise optical zone (based on the pupil center or optical center), depth based on percentage of pachymetry, length (within 1 degree), and shape (perpendicular to the corneal plane) in the ALLY system (LENSAR, Orlando, FL). Additionally, advanced imaging using iris registration, along with proprietary software (IntelliAxis) that compensates for cyclotorsion of the eye, ensures that the arcuate incisions, as well as toric IOLs, are placed in the correct axis. The Wörtz-Gupta FormulaTM is a first-of-its-kind femtosecond laser arcuate nomogram that gives guidance for AK incision length and degree of placement and is designed to treat between 0.25 D and 1.25D of astigmatism.¹¹ The efficacy of the Wörtz-Gupta FormulaTM has been demonstrated,¹¹ but it remains unclear whether femtosecond laser AK incisions with this formula can achieve non-inferior or statistically significant outcomes compared to toric IOLs in patients with 0.6–1.1 D of corneal astigmatism.

This retrospective, single-surgeon, single-eye case series compared the outcomes of robotic laser-assisted AK-guided ALLY iris registration and calculated by the Wörtz-Gupta FormulaTM to outcomes of low-power toric IOL implantation using ALLY's IntelliAxis refractive capsulorhexis with power calculated using the Barrett Toric Calculator. The study concentrated on patients with regular corneal astigmatism between 0.6 and 1.1 D—a range in which no standardized best practice currently exists. We hypothesized that femtosecond AK, when performed with the ALLY system using iris registration and a validated nomogram, would provide non-inferior outcomes to those of toric IOL implantation guided by IntelliAxis.

Materials and Methods

This was a retrospective case series of adult patients who underwent robotic laser-assisted cataract surgery using the ALLY system between September 1, 2023, and July 31, 2024, performed by a single surgeon (GW), and who had at least 4 weeks of postoperative follow-up. Eligible eyes had between 0.6 and 1.1 D of regular anterior corneal astigmatism. The study received IRB exemption from Sterling IRB (Atlanta, GA) and was conducted in accordance with the Declaration of Helsinki and the Health Insurance Portability and Accountability Act. A waiver of informed consent was granted due to the retrospective nature of this study. Eyes were excluded if they had a history of prior ocular surgery, significant ocular pathology (eg, corneal dystrophy, keratoectasia, macular degeneration), or if the best-corrected visual acuity (BCVA) potential was worse than 20/20. To eliminate inter-eye correlation, only one eye per patient was included in each treatment cohort. If both eyes met inclusion criteria, one was randomly selected. In five cases, one eye from the same patient was assigned to each treatment group.

Surgical Planning

Preoperative biometric measurements were obtained using the IOLMaster 700 (Carl Zeiss Meditec, Jena, Germany) and confirmed with corneal topography from the OPD-III (Nidek Inc., Tokyo, Japan). All surgical planning was conducted using the Zeiss Veracity Surgery Planner (Carl Zeiss Meditec). IOL power was calculated with the Barrett Universal II formula, and toric IOL planning utilized the integrated Barrett Toric Calculator. For arcuate keratotomy, parameters were

determined using the integrated Wörtz-Gupta Formula™. Patients were offered either treatment option based on surgeon judgment and patient preference.

In the AK group, paired arcuate incisions were used for with-the-rule (WTR) astigmatism (steep axis between 41° and 139°), and single nasal incisions were used for against-the-rule (ATR) astigmatism (steep axis between 0°–40° or 140°–180°). All incisions were placed at a 4.3 mm radius (8.6 mm optical zone diameter), centered on the optical axis, and set to a depth of 80% of local corneal pachymetry. Cyclotorsion compensation was achieved using iris registration with ALLY. Eyes in the AK group received a monofocal MX60 IOL (Bausch & Lomb) targeted for emmetropia or slight myopia. In the toric group, the IntelliAxis refractive capsulorhexis was used to mark the intended axis, and the Envista MX60ET 125 toric IOL was inserted and rotated into alignment with the capsulotomy axis markers. These IOLs were also targeted for plano or slight myopia.

All patients underwent cataract surgery with a temporal near-clear corneal incision measuring 2.75 mm, located at 180° for right eyes and 0° for left eyes. In the AK group, arcuate incisions were opened intraoperatively using a Sinskey hook and irrigated with balanced salt solution via blunt cannula.

The primary outcome measure was postoperative residual refractive astigmatism, as assessed by manifest refraction. Secondary outcomes included uncorrected distance visual acuity (UCVA), best spectacle-corrected visual acuity (BSCVA), and postoperative spherical equivalent (SE). In cases where patients achieved 20/20 or better uncorrected vision and manifest refraction was not recorded, a plano spherical refraction was assumed. Statistical comparisons between the AK and toric IOL groups were performed using the Mann–Whitney *U*-test. A *p*-value of <0.05 was considered statistically significant. Analyses were performed using SPSS (IBM Corp., Armonk, NY, USA).

Results

A total of 105 eyes met the inclusion criteria: 52 in the AK group and 53 in the toric IOL group. The mean preoperative anterior corneal astigmatism was 0.69 ± 0.10 D in the AK group and 0.89 ± 0.13 D in the toric group, a statistically significant difference ($p < 0.0001$). The mean target SE was -0.15 D in the AK group and -0.17 D in the toric group, with no statistically significant difference between groups ($p = 0.371$). All patients with data at 4 weeks postoperatively were included in this analysis.

Postoperative refractive outcomes were comparable between the AK and toric IOL groups, with no statistically significant differences in any measured variable. The mean residual refractive cylinder was -0.14 D in the AK group and -0.21 D in the toric group ($p = 0.103$); see Figure 1. Figure 2 shows the percentage of eyes with refractive cylinder by group. The mean postoperative SE refraction was -0.08 D for the AK group and -0.11 D for the toric group ($p = 0.361$). Uncorrected distance visual acuity (UCVA) was 0.05 logMAR in both groups ($p = 0.507$), and best-corrected visual acuity (BCVA) was -0.006 logMAR in the AK group and -0.004 logMAR in the toric group ($p = 0.623$). A substantially

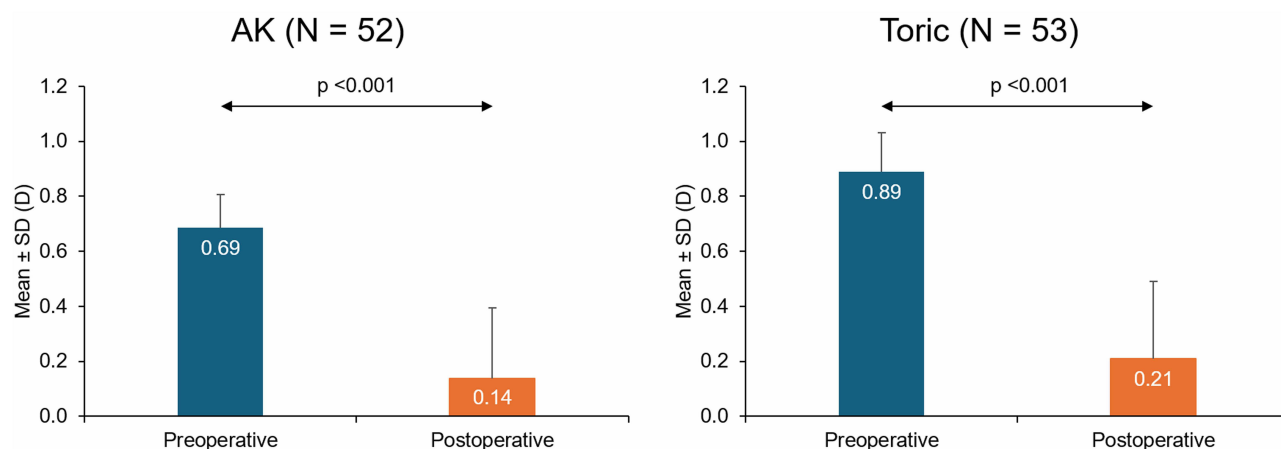


Figure 1 Mean astigmatism by surgical group.

Abbreviation: AK, arcuate keratotomy.

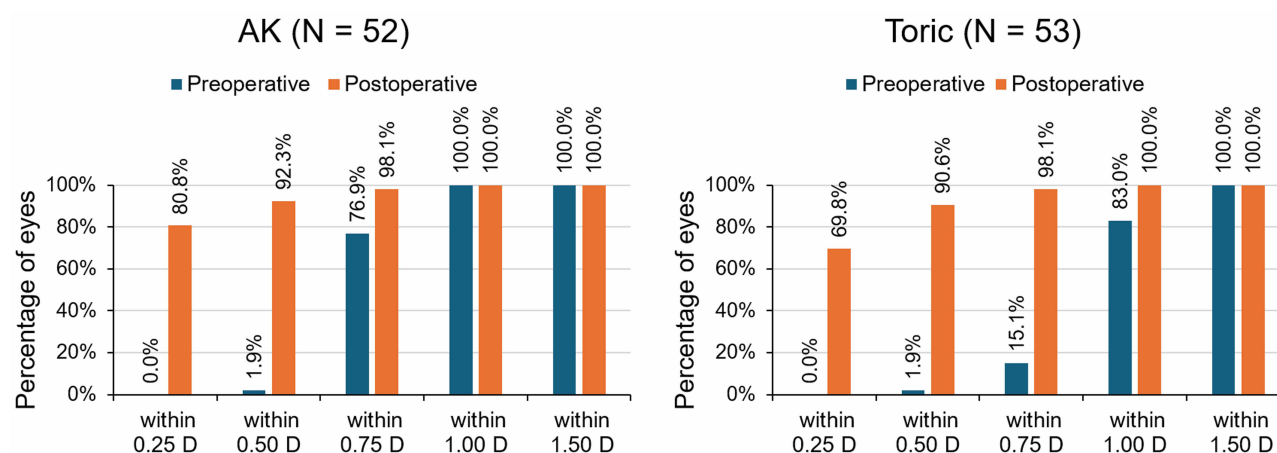


Figure 2 Percentage of eyes with refractive cylinder.
Abbreviation: AK, arcuate keratotomy.

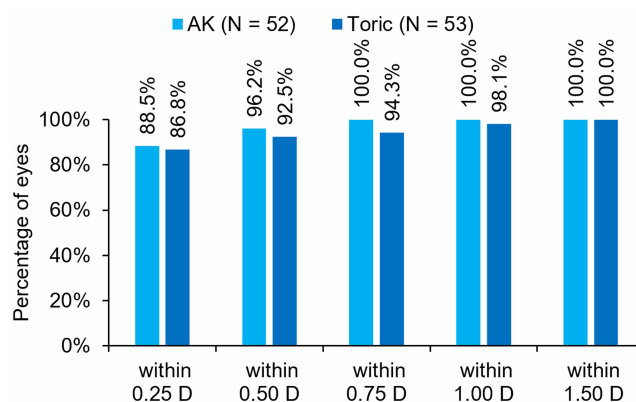


Figure 3 Postoperative MRSE.
Abbreviations: AK, arcuate keratotomy; MRSE, manifest refraction spherical equivalent.

greater percentage of eyes in the AK group reached 20/20 or better (77%) compared to the toric group (66%). The percentage of eyes that had an MRSE within ± 0.25 D was 88.5% in the AK group and 86.8% in the toric group (see Figure 3).

Subgroup analysis by astigmatism orientation was performed to evaluate differences between with-the-rule (WTR, 41° – 139°) and against-the-rule (ATR, 0° – 40° or 140° – 180°) astigmatism. The WTR subgroup ($n=55$) comprised 32 eyes in the AK group and 23 in the toric group, while the ATR subgroup ($n=50$) comprised 20 AK eyes and 30 eyes in the toric group. The WTR and ATR toric subgroups had a slightly higher baseline astigmatism (0.93 D and 0.85 D, respectively) compared to their AK counterparts (0.70 D and 0.68 D, respectively). Postoperative results were again similar across all outcomes. In the WTR subgroup, residual cylinder was -0.14 D (AK) vs -0.15 D (toric; $p = 0.781$), with SE, UCVA, and BCVA also showing no significant differences. Similar equivalency was observed in the ATR subgroup, with residual cylinder of -0.15 D (AK) vs -0.26 D (toric; $p = 0.163$), and comparable SE and VA outcomes.

Both groups demonstrated excellent reduction in astigmatism, with 92.3% of eyes in the AK group and 90.6% in the toric group achieving ≤ 0.50 D of postoperative residual cylinder. Both treatments were well tolerated, and all corneal incisions healed uneventfully. No significant toric IOL rotations were observed, and no secondary interventions were required.

Vector analysis using single-angle and double-angle plots, based on the Alpins method, revealed significant reductions in both arithmetic mean astigmatism and vector mean astigmatism in both groups; see Figures 4 and 5.

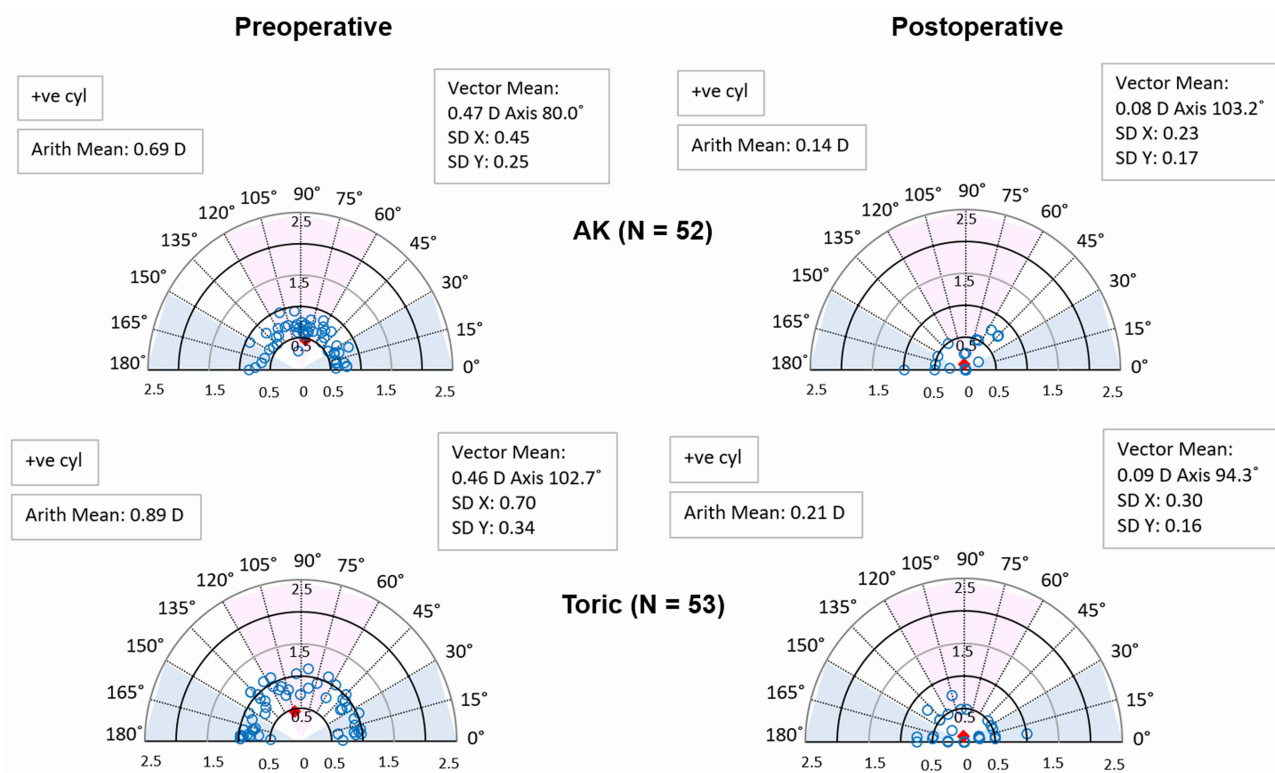


Figure 4 Single-angle vector plots, preoperative and postoperative.
Abbreviation: AK, arcuate keratotomy.

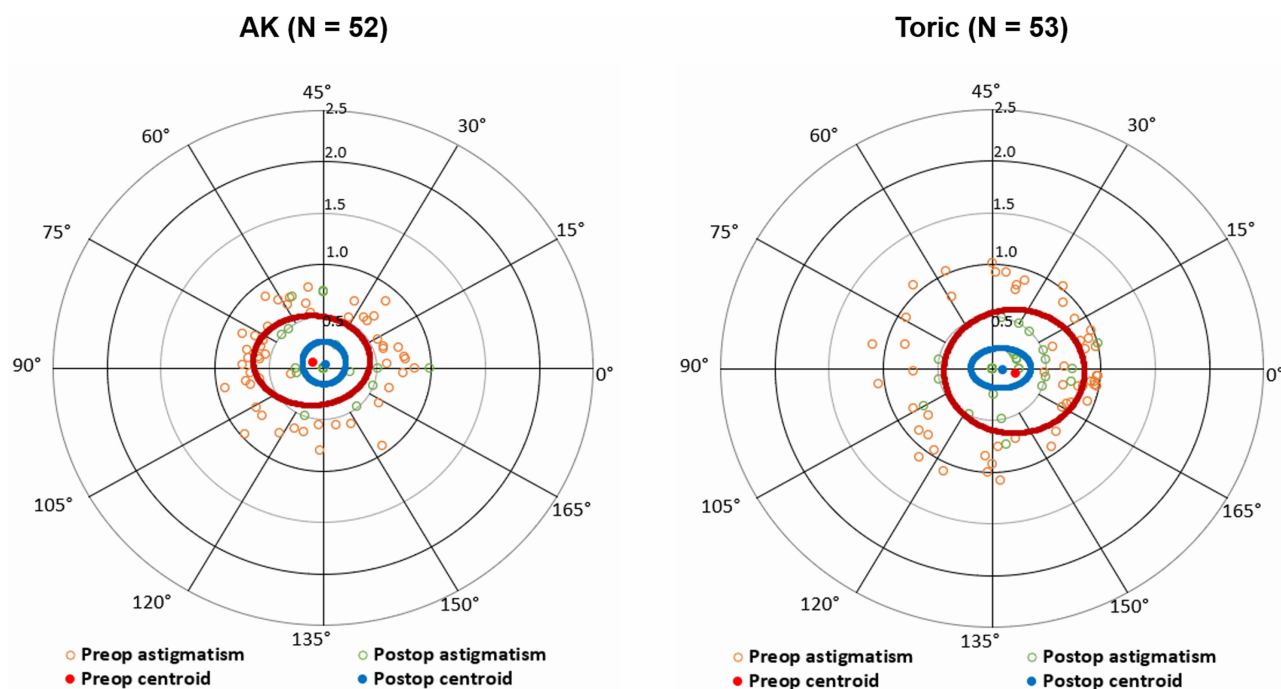


Figure 5 Double-angle vector plots, preoperative and postoperative.
Abbreviations: AK, arcuate keratotomy; Preop, preoperative; Postop, postoperative.

Postoperative centroid vectors on the double-angle plots were small and well-centered, with a more circular distribution observed in the AK group compared to a slightly more ovalized pattern in the toric group.

Discussion

The primary objective of this study was to directly compare the efficacy of advanced technology laser-assisted AK using ALLY's iris registration and the Wörtz-Gupta FormulaTM to correct low levels of regular anterior corneal astigmatism (0.6–1.1 D) to low-powered toric IOLs aligned using IntelliAxis and the Barrett Toric Calculator. In this study, both the AK and toric IOL groups demonstrated excellent refractive outcomes, with no statistically significant differences noted in postoperative residual cylinder, SE refraction, or VA. This is important information for surgeons as they design a surgical plan for the correction of low magnitude astigmatism at the time of cataract surgery.

It is well accepted that ≥ 0.5 D of residual astigmatism can have a negative impact on visual quality, contributing to symptoms such as glare and ghosting, and reducing the likelihood of achieving optimal UCVA.¹² Thus, correcting lower levels of astigmatism (< 1.0 D) at the time of cataract surgery is clinically significant and relevant to best patient outcomes. Our study supports this, as we found more than 90% of eyes in each treatment group achieved ≤ 0.5 D residual cylinder, and 87% obtained a UCVA of 20/25 or better.

A key factor contributing to the exceptional outcomes in the AK group was the methodical and precise execution enabled by this second-generation femtosecond robotic laser technology. All eyes underwent biometric analysis with the IOLMaster 700, facilitating precise alignment with cyclotorsion compensation. The AK incisions were precisely placed at 80% corneal depth, on an 8.6-mm optical zone centered on the optical axis, with the arc length(s) calculated and executed by the Wörtz-Gupta FormulaTM. Manual AK techniques have been associated with complications ranging from corneal perforations to inducing irregular astigmatism.¹³ Previous modifications of traditional manual incision nomograms to be applied to the femtosecond laser, such as those by Baharozian et al,⁹ achieved limited improvement, with residual astigmatism ≤ 0.5 D in only 44–64% of cases. Subsequent nomogram enhancements by Jones et al¹⁴ (LaserArcs.com) showed improvements, with 90% of patients achieving ≤ 0.5 D residual astigmatism, yet only 40% reached 20/20 UCVA. The Castrop nomogram¹⁰ (for correction of 0.75–2.5 D) for use with femtosecond AK incisions found 97% of cases had ≤ 0.5 D of residual astigmatism at 12 months, and slightly under 60% reached 20/20 UCVA, although the majority of their reported cases were between 1.0 and 2.0 D of astigmatism and did not differentiate between the different types of astigmatism. The FemtoAK nomogram¹⁵ makes recommendations in eyes with ≥ 0.5 D of ATR or ≥ 1.0 D of WTR or oblique astigmatism, but ≤ 2.25 D. Truong et al¹⁵ reported 56% of eyes were ≤ 0.5 D of refractive astigmatism at postop month 1, but only 26% of eyes were ≤ 0.5 D of corneal astigmatism at the same time point. The Wörtz-Gupta FormulaTM represents further progress, and in this study, 92% of patients had ≤ 0.5 D of residual astigmatism and 77% achieved 20/20 UCVA or better, and at lower levels of preoperative astigmatism (< 1.1 D).

Toric IOLs have historically represented the gold standard for astigmatism correction, particularly at levels above 1 D.^{3,8,16} Our study adds to the literature showing effectiveness at lower astigmatism levels when using the lowest power FDA-approved toric lens when properly aligned with IntelliAxis. For the toric arm of this study, we report a mean residual astigmatism < 0.25 D and more than 90% of patients achieved ≤ 0.5 D residual cylinder. Emesz et al¹⁷ demonstrated substantial reduction in astigmatism from 1.4 D to 0.36 D, while Wiley et al¹⁸ reported similar results with the same lens we used (Envista MX60ET), reducing astigmatism from 1.47 D to 0.38 D, with 88% achieving ≤ 0.75 D residual astigmatism. Furthermore, a comprehensive data analysis from Potvin et al¹⁹ indicated that approximately 70% of toric IOL recipients typically achieve ≤ 0.5 D postoperative astigmatism. We attribute our superior outcomes to several parameters, including precise biometric measurements, accurate power selection via the Barrett Toric Calculator, and precise intraoperative axis alignment using a robotic laser. Limitations of this study include that only a single toric IOL was used, one laser platform studied, the long-term stability of each of the procedures is not addressed, cost effectiveness was not addressed (as several variables would affect cost and may not be generalizable), and there is a limited level of evidence since the surgeries were performed by one surgeon (GW). Future study is warranted to determine the generalizability of our findings. However, both the IOL used and laser AKs have a long history of stability,^{18,20–25} and we have no reason to believe our outcomes would differ. Other limitations include the limited discussion on complications/adverse events; however, we did not encounter any complications with either method. We

would also recommend future studies include a cost effectiveness analysis and validated patient satisfaction questionnaires.

Previous literature and meta-analyses typically favored toric IOLs over manual corneal incisions for higher astigmatism corrections.^{3,26} However, our study differs from the others by comparing robotic laser AK directly to low-powered toric IOLs in the specific context of low-level astigmatism correction. The non-inferiority of outcomes observed in both overall cohort and subgroup analyses for WTR and ATR astigmatism further supports the clinical effectiveness of both treatment strategies. Although these are the results of a single surgeon and therefore of a limited level of evidence, we believe other surgeons can use our findings to confidently choose either arcuate incisions or a low powered toric IOL when considering treatment options for low levels of corneal astigmatism at the time of cataract surgery. Robotic AK, guided by iris registration and calculated using the Wörtz-Gupta FormulaTM, yields refractive outcomes comparable to those achieved by low-powered toric IOL implantation aligned with IntelliAxis and calculated with the Barrett Toric Calculator.

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Disclosure

Dr Gary Wortz reports grants, consulting fees from Lensar; is a minority shareholder in Arcuate Innovations, LLC, during the conduct of the study. Dr Preeya Gupta reports personal fees from Alcon, Bausch + Lomb, personal fees from Arcuate Innovations, during the conduct of the study. The authors report no other conflicts of interest in this work.

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