Astigmatic Outcomes after Wavefront-Guided and Wavefront-Optimized Refractive Surgeries for Myopia with Low to Moderate Cylinder

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Received date: August 23, 2019; Accepted date: November 19, 2019; Published date: November 25, 2019

Abstract

Purpose: To compare efficacy and accuracy of wavefront-guided (WFG) and wavefront-optimized (WFO) PRK and LASIK for the treatment of myopia with low to moderate astigmatism.

Methods: In this prospective cohort study, 215 active duty military service members (430 eyes, mean spherical equivalent -3.61 ± 1.53 D) electing either PRK or LASIK were randomized to undergo WFG or WFO treatment. Up to 12 months postoperative visual outcomes following surgeries were compared between 4 treatment groups: WFG PRK, WFG LASIK, WFO PRK and WFO LASIK for myopia with 0.25 to 0.50 D astigmatism (< 0.50 D cyl subgroup) and ≥ 0.75 D astigmatism (≥ 0.75 D cyl subgroup). High and low contrast visual acuities were assessed and vector analysis was performed.

Results: At 12 months postoperatively, the surgically induced astigmatism, magnitude of error, correction and flattening indices were significantly different between treatment groups (P values ≤ 0.001) in the ≤ 0.50 D cyl subgroup. In ≥ 0.75 D cyl subgroup, there were no significant differences in vector analysis parameters except for the magnitude of error and correction index (P values ≤ 0.010). The treatment groups were comparable in terms of postoperative uncorrected distance visual acuity, manifest spherical equivalent and best corrected low contrast visual acuity.

Conclusions: No treatment modality showed consistent superiority in correcting low to moderate astigmatism. Overall, both PRK and LASIK using either wavefront-guided or wavefront-optimized laser platform were similarly effective and accurate in treating myopia with low to moderate amount of astigmatism.

Keywords: Wavefront-guided, Wavefront-optimized, PRK, LASIK, Astigmatism

Abbreviations: ANOVA: Analysis of Variance; ASCRS: American Society of Cataract and Refractive Surgery; BSS: Balanced Salt Solution; CDVA: Corrected Distance Visual Acuity; CI: Correction Index; D: Diopter; FI: Flattening Index; IOS: Index of Success; LASIK: Laser in-situ Keratomileusis; LCVA: Low Contrast Visual Acuity; logMAR: Logarithm of the Minimum Angle of Resolution; MSE: Manifest Spherical Equivalent; NVGs: Night Vision Goggles; PRK: Photorefractive Keratectomy; SD: Standard Deviation; SIA: Surgically Induced Astigmatism; TIA: Target Induced Astigmatism; UDVA: Uncorrected Distance Visual Acuity; WFG: Wavefront-guided; WFO: Wavefront-optimized
Introduction

Correcting astigmatism using laser refractive surgery tends to be more technically challenging and less effective compared to treating simple myopia. Elliptical ablation alignment, cyclotorsion and cylinder-sphere coupling effect are some of the technical considerations in the treatment of astigmatism by photoablation [1-3]. While these factors may be more pertinent when treating higher levels of astigmatism, they are not necessarily discounted in lower amounts of astigmatism. Moreover, leaving astigmatism uncorrected in a spherical PRK or LASIK, even 0.25 diopters (D) has been shown to induce an average of approximately 0.50 D of postoperative cylinder [4].

Among available excimer laser platforms, wavefront-guided and wavefront-optimized systems are the most commonly used in the United States with almost an even split amongst 88% of U.S. respondents in the American Society of Cataract and Refractive Surgery (ASCRS) Clinical Survey in 2017 [5]. Wavefront-guided and wavefront-optimized treatments have been extensively evaluated in numerous studies, comparing visual outcomes in either PRK or LASIK, yet the efficacy and accuracy profiles of astigmatic correction seem under-reported with only a few studies performing detailed analysis with regard to the vectoral nature of astigmatism [6-9]. This study was carried out to further evaluate the effect of wavefront-guided and wavefront-optimized treatments on myopia with low to moderate astigmatism using Alpins method of vector analysis [10]. We present the vector analysis parameters using the preoperative manifest refractive cylinder of 0.25 to 0.50 D (≤ 0.50 D cyl subgroup) and more than 0.50 D (≥ 0.75 D cyl subgroup).

Patients and Methods

This prospective study was performed from March 2010 to October 2014. Prior to initiation, the study protocol was reviewed and approved by the Institutional Review Boards at Walter Reed National Military Medical Center, Bethesda and the United States Army Medical Research and Materiel Command, Fort Detrick, Maryland, USA. The work was performed in compliance with the tenets of the Declaration of Helsinki and the U.S. Health Insurance Portability and Accountability Act. All participants provided written informed consent before undergoing any of the study procedures. The study was registered at the U.S. National Institutes of Health Clinical Trials website.

Nearsighted active duty U.S. military personnel were consecutively recruited and offered study enrollment. Study candidates were screened for eligibility for refractive surgery. Individuals who were qualified to undergo either PRK or LASIK were allowed to select their preferred surgery. After the surgical procedure was determined, each study participant was randomly assigned to receive either wavefront-guided or wavefront-optimized treatment allocating the participant to one of the 4 treatment groups: wavefront-guided PRK (WFG PRK), wavefront-guided LASIK (WFG LASIK), wavefront-optimized PRK (WFO PRK) and wavefront-optimized LASIK (WFO LASIK). Randomization was performed using a random number generator at www.randomization.com. The grouping assignment is shown in figure 1.

![Figure 1: Study grouping assignment.](image)

Eligible participants were male or female, aged 21 years or older, with myopia or myopic astigmatism ranging from -1.00 to -10.00 diopters (D) of manifest spherical equivalent (MSE), up to -4.00 D of refractive cylinder, stable refraction for a minimum of 12 months, and corrected distance visual acuity (CDVA) of 20/20 or better in both eyes. Key exclusion criteria were potentially active, residual, or recurrent ocular disease or corneal abnormalities, history of any prior eye surgery including previous refractive surgery, eye trauma, medical condition or systemic medication that may impair healing, and pregnancy.

Surgical procedure

All participants underwent bilateral, same-session refractive surgery which was performed by either one of the five participating surgeons in the study. Wavefront-guided treatments were performed using the VISX Star S4 IR (Johnson & Johnson Vision Care, Inc.) excimer laser with iris registration activated. Participants who were assigned to wavefront-guided treatment group had
wavefront aberrometry using the WaveScan wavefront analyzer (Johnson & Johnson Vision Care, Inc.) prior to surgery. All wavefront-optimized treatments were done using the Allegraet Wave Light Eye-Q 400-Hz (Alcon Surgical, Inc.) excimer laser.

Surgical treatments were planned using individual platform nomograms developed at the surgical center. Wavefront-optimized treatment nomogram included reduction of treatment for cylinder ≥ 1.25 D. Optical zone was 6.50 mm with varying transition zones depending on individual treatment plan. In PRK, the corneal epithelium was removed using a rotary brush (Amoils, Innovative Excimer Solutions, Inc.) over the central 9.0 mm zone of the cornea. Eyes with greater than 49.5 microns of central ablation were given prophylactic mitomycin C. Following photoablation, a corneal shield soaked with MMC 0.2 mg/mL (0.02%) was applied for 20 seconds then the eye was copiously irrigated with balanced salt solution (BSS). A bandage contact lens (omafilcon A, Proclear, Cooper Vision, Inc.) was left in place until complete re-epithelialization. In LASIK, a 9.0 mm diameter, 120 microns thick superior-hinged corneal flap was created using the IntraLase iFS (Johnson & Johnson Vision Care, Inc.) femtosecond laser. After photoablation, the flap was repositioned and the interface was irrigated with BSS. Postoperative topical medications for PRK-treated eyes were moxifloxacin 0.5% 4 times daily for 1 week, fluorometholone 0.1% 4 times daily for 4 weeks followed by a 6-week taper, ketorolac 0.4% up to 4 times daily for 48 hours, preservative-free carboxymethyl cellulose 0.5% every hour for the first week then at least every 2 hours or more for several months.

Postoperative topical medications for LASIK-treated eyes included moxifloxacin 0.5% 4 times daily for 1 week, prednisolone 1% every 2 hours for 72 hours and then 4 times a day for 1 week, ketorolac 0.4% up to 4 times daily during the first 48 hours as needed for pain and preservative-free carboxymethyl cellulose 0.5% every hour for the first week then at least every 2 hours or more for several months.

**Preoperative and postoperative assessments**

Participants underwent detailed ophthalmologic examinations including visual acuity, manifest refraction, contrast sensitivity, and slit lamp biomicroscopy preoperatively and at 1, 3, 6, and 12 months postoperatively.

**High and low contrast visual acuity tests**

Uncorrected distance visual acuity (UDVA) and CDVA were measured using a backlit high contrast Snellen chart viewed at a distance equivalent to 6 m. Best corrected low contrast visual acuity (LCVA) tests were assessed in a dark room using backlit low contrast letter charts (Precision Vision, Inc.) with a test distance of 4 m. The LCVA tests were carried out under photopic condition using 5% and 25% contrast charts with a screen luminance of 106 cd/m² and under mesopic condition using a 25% contrast chart viewed through a neutral density filter with a screen luminance of 4 cd/m². Each correctly identified letter in all LCVA tests was given a value of -0.02 logarithm of the minimum angle of resolution (logMAR). Every line of logMAR change was equivalent to 0.1 logMAR.

**Vector analysis**

The Alpins method was used for astigmatism analysis. Briefly, the Alpins method examines the relationship of three vector parameters: target induced astigmatism (TIA) or the intended change in astigmatic magnitude and axis; surgically induced astigmatism (SIA) or astigmatic magnitude and axis change that the surgery actually induced; and the difference vector (DV) or the astigmatic magnitude and axis change induced by the initial surgery to achieve the intended target. Alpins vector analysis includes: the magnitude of error which is the arithmetic difference between SIA and TIA magnitudes; angle of error, the angle difference between SIA and TIA (could be either absolute or arithmetic value); correction index (CI), the SIA and TIA ratio; flattening index (FI), the flattening effect (the astigmatic reduction resulting from the effective proportion of the SIA at intended meridian) divided by the TIA; and the index of success (IOS), the DV divided by the TIA [10]. Refractive astigmatism values were converted to the corneal plane. Calculations were performed using VECTrAK astigmatism analysis program (ASSORT Pty. Ltd.). Data were exported into a spreadsheet for statistical analysis.

**Statistical considerations**

Primary outcome measures were UDVA, astigmatism difference vector and axis of error (arithmetic value). Categorical data were presented as number and percentage and the Pearson chi square test was used for comparison of the treatment groups. Continuous data were expressed as mean ± standard deviation and a repeated measure analysis of variance (ANOVA) was performed to compare preoperative to postoperative change by treatment group. To account for two primary
outcome measures, a Bonferroni adjustment was applied and a $P$-value of $< 0.017$ was considered statistically significant. All data analyses were performed using SPSS version 25.0 (IBM, Inc.).

**Results**

The study included data from 215 participants (430 eyes), aged 30.8 ± 6.8 years and predominantly male (79.1%). The demographic and baseline refractive characteristics for each treatment group are presented in table 1.

For wavefront-guided treatments, software version 5.22 was used in all PRK and in 60 LASIK eyes. Updated software (version 5.32) was used in 42 WFG LASIK eyes. There were no significant differences in patient age, manifest refraction, uncorrected and corrected visual acuity between those who were treated before and after the software update ($P ≥ 0.31$). Iris registration was successfully activated in all wavefront-guided treatments except in one bilateral PRK and one bilateral LASIK procedure. All PRK surgeries (110 wavefront-guided and 106 wavefront-optimized treatments) were performed without complications. Of the 102 WFG LASIK treatments, there was a suction loss during flap creation in 1 eye; paused flap creation due to patient movement in 1 eye and bandage contact lens application after surgery in 2 eyes both to help in healing an epithelial defect. Of the 112 WFO LASIK treatments, 1 eye had an epithelial defect necessitating a bandage contact lens after the procedure. None of these LASIK complications had any significant visual impact postoperatively. The overall study follow-up rate was 100%, 97.2%, 94.4% and 87.4% at 1 month, 3 months, 6 months and 12 months after surgery, respectively.

At 12 months postoperatively, all treatment groups were comparable in terms of number of eyes achieving postoperative UDVA within 1 line of their preoperative CDVA as well as in achieving UDVA of 20/20 or better in either the ≤ 0.50 D cyl subgroup or ≥ 0.75 D cyl subgroup as shown in table 2. On the other hand, all eyes with ≤ 0.50 D cyl treated with WFO LASIK had MSE within ± 0.50 D of target refraction which showed to be significantly different from the outcome following wavefront-guided PRK (WFG PRK, 25 eyes, 75.8%; $P = 0.002$) in the post-hoc analysis. There were no other significant differences between treatment groups otherwise.

As demonstrated in figure 2, the largest proportion in each treatment group had maintained their best-corrected LCVA at 12 months postoperatively. Gain of ≥ 2 lines of best corrected LCVA did not show statistically significant differences among the groups when tested at 5% photopic ($P ≥ 0.039$), 25% photopic ($P ≥ 0.061$) and 25% mesopic conditions ($P = 0.541$). Loss of ≥ 2 lines of best corrected LCVA was rare except for 1 WFO PRK-treated eye (≤ 0.50 D cyl subgroup) and 1 WFO LASIK-treated eye (≥ 0.75 D subgroup) observed only at 5% photopic condition; and 1 WFG LASIK-treated eye (≥ 0.75 D subgroup) when tested at 5% photopic, 25% photopic and mesopic conditions.

**Astigmatism analysis**

In the ≤ 0.50 D cyl subgroup, the target induced astigmatism (TIA) showed significant correlation to the surgically induced astigmatism (SIA) in all treatment groups: WFG PRK ($r = 0.508$, $P = 0.003$), WFG LASIK ($r = 0.610$, $P = 0.001$), WFO PRK ($r = 0.599$, $P < 0.001$) and WFO LASIK ($r = 0.476$, $P = 0.004$). Similarly, TIA and SIA were significantly correlated in all treatment groups in the ≥ 0.75 D cyl subgroup: WFG PRK ($r = 0.847$, $P < 0.001$), WFG LASIK ($r = 0.641$, $P < 0.001$) and WFO PRK ($r = 0.820$, $P < 0.001$) and WFO LASIK ($r = 0.858$, $P < 0.001$).

The results of astigmatism analyses at 12 months postoperatively are presented in table 3. Vector analysis revealed that in the ≤ 0.50 D cyl subgroup, there were statistically significant differences in the SIA, magnitude of error, CI and FI between treatment groups. Post-hoc analysis, however, showed the significant differences were only between WFG PRK and WFO PRK for the SIA ($P = 0.007$); WFG PRK versus WFO PRK and WFO LASIK for magnitude of error, CI and FI ($P ≤ 0.002$). The angle of error was ≤ 15 degrees in 22 of 33 (66.7%) WFG PRK-treated eyes, 22 of 28 (78.6%) WFG LASIK-treated eyes, 32 of 42 (76.2%) WFO PRK-treated eyes and 26 of 34 (76.5%) of WFO LASIK-treated eyes ($P = 0.696$).

Whereas in ≥ 0.75 D cyl subgroup, vector analysis showed that there were statistically significant differences in magnitude of error and the CI between the treatment groups ($P ≤ 0.010$). The difference though was only significant for the CI between WFG PRK and WFO PRK ($P = 0.011$) in post-hoc analysis. The angle of error was ≤ 15 degrees in 46 of 47 (97.9%) WFG PRK-treated eyes, 36 (100%) WFG LASIK-treated eyes, 36 of 41 (87.8%) WFO PRK-treated eyes and 41 of 44 (93.2%) WFO LASIK-treated eyes ($P = 0.073$).
Significant uncorrected astigmatism can influence an individual's daily visual function and performance. For example, among military service members, a population comprised of relatively young and healthy adults, uncorrected astigmatism can adversely impact task performance during nighttime operations. Image intensification devices such as night vision goggles (NVGs) which can aid in low-light conditions, may have a built-in viewing adjustment feature for those who have low level of refractive error however, visual acuity through NVGs may be degraded if astigmatism of ≥ 1.0 diopter (D) is left uncorrected [11]. Even a lower amount of astigmatism, ranging from 0.50 D to 0.75 D of cylinder, has been shown to significantly reduce high and low contrast visual acuities [12]. According to Wolffsohn et al. [13], uncorrected astigmatism can cause an average loss of visual acuity of 1.5 lines per diopter at high contrast and a similar effect at 50% and 10% contrast. Correcting astigmatism higher than 0.30 D offers improvement in visual acuity but this would only be expected if the axis orientation is perfect [14].

Earlier studies have supported excellent outcomes using either wavefront-guided or wavefront-optimized treatment for myopic astigmatism [15-19]. Moreover, both wavefront-guided and wavefront-optimized platforms have shown similar astigmatic results in either PRK or LASIK except for an apparently slightly more precise application of treatments on-axis by wavefront-guided compared to wavefront-optimized system. There were also previous findings indicating WFO LASIK tended to overcorrect astigmatism and that caution should be taken in treating a full refractive cylinder of ≤ 0.50 D [1,20].

In this report, we evaluated the outcomes following wavefront-guided and wavefront-optimized myopic treatments in PRK and LASIK focusing on the efficacy and accuracy of astigmatic correction. Our study showed the TIA and SIA demonstrated moderate to strong correlation in myopic eyes with ≤ 0.50 D cylinder and showed strong correlation in myopic eyes with ≥ 0.75 D cylinder. There were no indications of systemic error or misalignment in any of the treatments used in the study based on the angle of error (arithmetic and absolute values).

In correcting myopia with astigmatism of 0.50 D or less in this study, the SIA, magnitude of error, CI and FI were most notably different between WFG PRK versus WFO PRK and WFO LASIK, the values of which were suggestive of a tendency to under correct small amounts of astigmatism with WFG PRK and to overcorrect with either WFO PRK or WFO LASIK. Various factors such as corneal healing and alignment [21], could be contributory which, in effect, yielded 68% successful astigmatic correction with WFG PRK, 80% with WFG LASIK, 54% with WFO PRK and 60% with WFO LASIK, based on the IOS (P = 0.322). These findings, however, did not seem to have any significant impact clinically in terms of high contrast UDVA and best-corrected LCVA.

The current findings in the ≤ 0.50 D cylinder subgroup differed from earlier studies by Toy and colleagues [7,8], as they did not find any statistically significant differences in wavefront-guided versus wavefront-optimized treatments in the subgroups of eyes with low amount of astigmatism (0.50 D or less), both in their PRK and LASIK...
studies. Their subgroup analyses, however, were limited by relatively small sample sizes. On the other hand, the astigmatic outcomes of wavefront-optimized treatments in our study were similar to those of the studies by Frings et al. [20], and Katz et al. [1]. They noted that full correction of astigmatism of 0.50 D or less resulted in overcorrection which they believed could potentially contribute to side effects such as night vision problems and halos. The previous study, however, was not able include a formal evaluation to support this assertion. In the present investigation, most eyes with ≤ 0.50 D cylinder that underwent wavefront-optimized treatment maintained their best corrected LCVA in photopic and mesopic conditions. Furthermore, none lost more than 2 lines of LCVA except for 1 (2.6%) WFO PRK-treated eyes when evaluated for 5% contrast under photopic condition.

In correcting astigmatism of ≥ 0.75 D, vector analysis parameters showed the astigmatic correction were comparable among the treatment groups. Although the differences in magnitude of error and CI were most significant between WFG PRK and WFO PRK whose values suggested astigmatic under correction by 17% and overcorrection by 4%, respectively, the IOS indicated that the astigmatism treatment applied were successful in achieving 86% of target correction with WFG PRK, 85% with WFG LASIK, 84% with WFO PRK, and 85% with WFO LASIK (P = 0.814). Similarly, the UDVA, MSE and best-corrected LCVA were comparable between treatment groups.

Schallhorn and associates [22], stated that there are several factors that can potentially affect the accuracy of astigmatic surgical correction with excimer lasers. Factors such as the precise determination of preoperative magnitude and axis of refractive cylinder, the technology involved in adequate centration of the elliptical ablation profile during surgery and one's understanding of the biomechanics of corneal healing should be considered in the treatment nomogram [22]. In developing a wavefront-guided plan using WaveScan wavefront aberrometry, the ability to adjust the second order astigmatism independent of the rest of wavefront aberrometry parameters, is not available [23], to the best of our knowledge. Rather, the surgeons are given the calculated ablation profiles, based on ocular wavefront aberrometry and corneal topographic data [9] in which they can choose a treatment plan that is aligned closer to the manifest refraction, for example. On the other hand, wavefront-optimized cylinder treatments may be adjusted as with the current study for instance, a center-based nomogram incorporated cylinder treatment reduction for astigmatism of -1.25 D or more.

Among those that were treated for simple myopia, the present study found 38 of 71 eyes (53.5%) seen at 12 months postoperatively had astigmatism at an average of 0.20 ± 0.24 D. Although the small amount of astigmatism did not appear to have negative effects on the refractive outcomes (Supplemental table A), these findings underscore the challenges in refractive surgery and the considerations that must be taken to effectively and accurately deliver treatment. Our study

| Parameter            | WFG PRK | WFG LASIK | WFO PRK | WFO LASIK | P Value* |
|----------------------|---------|-----------|---------|-----------|----------|
| Patients/eyes, n     | 55/110  | 51/102    | 53/106  | 56/112    | -        |
| Male/female, n       | 44/11   | 40/11     | 40/13   | 46/10     | 0.855†   |
| Age (years)          | 30.4 ±6.6 | 31.0 ±7.5 | 30.1 ±6.0 | 31.7 ±7.1 | 0.325    |
| Manifest Sphere, mean ±SD (D) | -3.22 ±1.72 | -3.38 ±1.33 | -3.12 ±1.46 | -3.42 ±1.49 | 0.428 |
| (0 to -7.25)         | (-0.75 to -6.75) | (-1.00 to -7.25) | (-1.25 to -7.00) | 0.129    |
| Manifest Cylinder, mean ±SD (D) | -0.76 ±0.61 | -0.58 ±0.54 | -0.63 ±0.52 | -0.68 ±0.67 | 0.151    |
| (0 to -2.50)         | (0 to -2.50) | (0 to -2.50) | (0 to -3.25) | 0.443    |
| Manifest SE, mean ±SD (D) | -3.60 ±1.74 | -3.67 ±1.30 | -3.43 ±1.52 | -3.76 ±1.51 | 0.692    |
| UDVA, mean ±SD (logMAR) | 1.10 ±0.47 | 1.14 ±0.37 | 1.10 ±0.42 | 1.16 ±0.40 | 0.195    |
| CDVA, mean ±SD (logMAR) | -0.10 ±0.05 | -0.10 ±0.04 | -0.11 ±0.05 | -0.10 ±0.04 | 0.151    |

CDVA = corrected distance visual acuity; D = diopter; PRK = photorefractive keratectomy; SE = spherical equivalent; WFG = wavefront guided; WFO = wavefront optimized; UDVA = uncorrected distance visual acuity

*Statistically significant P< 0.017, One-way Analysis of Variance
†Statistically significant at P<0.017, Pearson chi square test
Table 2: Efficacy and accuracy of treatments at 12 months postoperatively.

|                      | WFG PRK | WFG LASIK | WFO PRK | WFO LASIK | P-value |
|----------------------|---------|------------|---------|-----------|---------|
| UDVA within 1 line of preop CDVA (n, %) |         |            |         |           |         |
| ≤0.50 D cyl subgroup | 29 (87.9%) | 27 (96.4%) | 42 (100%) | 33 (97.1%) | 0.077   |
| ≥0.75 D cyl subgroup | 47 (100%) | 35 (97.2%) | 40 (97.6%) | 43 (97.7%) | 0.749   |
| UDVA 20/20 or better (n, %) |         |            |         |           |         |
| ≤0.50 D cyl subgroup | 30 (90.9%) | 26 (92.9%) | 42 (100%) | 33 (97.1%) | 0.226   |
| ≥0.75 D cyl subgroup | 47 (100%) | 35 (97.2%) | 40 (97.6%) | 43 (97.7%) | 0.223   |
| Manifest SE within ±0.50 D (n, %) |         |            |         |           |         |
| ≤0.50 D cyl subgroup | 25a (75.8%) | 26 (92.9%) | 39 (92.9%) | 34a (100%) | 0.006*  |
| ≥0.75 D cyl subgroup | 45 (95.7%) | 36 (100%) | 39 (95.1%) | 42 (95.5%) | 0.288   |

CDVA = corrected distance visual acuity; SE = spherical equivalent; WFG = wavefront guided; WFO = wavefront-optimized; UDVA = uncorrected distance visual acuity
*Statistically significant at P<0.017, Pearson chi-square test
Each superscript letter a denotes the treatment group whose values were significantly different from each other in the post-hoc analysis (P < 0.017).

Table 3: Vector analyses at 12 months postoperatively.

|                      | WFG PRK (n=33) | WFG LASIK (n=28) | WFO PRK (n=42) | WFO LASIK (n=34) | P-value |
|----------------------|----------------|------------------|----------------|------------------|---------|
| ≤0.50 D cyl subgroup |                |                  |                |                  |         |
| TIA, mean ±SD (D)    | 0.40 ±0.10     | 0.33 ±0.12       | 0.36 ±0.12     | 0.36 ±0.12       | 0.106   |
| SIA, mean ±SD (D)    | 0.35 ±0.16a    | 0.37 ±0.22       | 0.55 ±0.30a    | 0.50 ±0.25       | 0.001*  |
| DV, mean ±SD (D)     | 0.19 ±0.17     | 0.14 ±0.20       | 0.27 ±0.26     | 0.23 ±0.21       | 0.084   |
| MoE, mean ±SD (D)    | -0.05 ±0.14a   | 0.04 ±0.17       | 0.18 ±0.25a    | 0.14 ±0.18ab     | <0.001* |
| AoE, absolute value mean ±SD (degrees) | 16.2 ±21.9 | 11.4 ±18.5 | 9.8 ±13.4 | 9.3 ±11.3 | 0.294   |
| AoE, arithmetic mean ±SD (degrees) | -0.58 ±27.4 | 7.4 ±20.5 | -3.0 ±16.4 | -3.0 ±14.4 | 0.144   |
| CI, geometric mean ±SD | 0.79 ±0.38ab  | 1.04 ±0.47       | 1.34 ±0.65a    | 1.34 ±0.63ab     | <0.001* |
| Fl, mean ±SD         | 0.65 ±0.54ab   | 0.92 ±0.66       | 1.30 ±0.77a    | 1.27 ±0.59ab     | <0.001* |
| IOS, geometric mean ±SD | 0.32 ±0.59   | 0.20 ±0.64       | 0.46 ±0.75     | 0.40 ±0.73       | 0.322   |

| ≥0.75 D cyl subgroup | WFG PRK (n=47) | WFG LASIK (n=36) | WFO PRK (n=41) | WFO LASIK (n=44) | P-value |
|----------------------|----------------|------------------|----------------|------------------|---------|
| TIA, mean ±SD (D)    | 1.14 ±0.45     | 1.04 ±0.42       | 1.00 ±0.44     | 1.15 ±0.58       | 0.409   |
| SIA, mean ±SD (D)    | 0.99 ±0.50     | 0.89 ±0.42       | 1.05 ±0.43     | 1.06 ±0.58       | 0.41    |
| DV, mean ±SD (D)     | 0.27 ±0.24     | 0.28 ±0.31       | 0.26 ±0.29     | 0.27 ±0.28       | 0.975   |
| MoE, mean ±SD (D)    | -0.15 ±0.27    | -0.14 ±0.36      | 0.05 ±0.26     | -0.09 ±0.31      | 0.010*  |
| AoE, absolute value mean ±SD (degrees) | 4.0 ±7.2 | 3.1 ±3.3 | 6.0 ±10.1 | 4.1 ±6.0 | 0.312   |
| AoE, arithmetic mean ±SD (degrees) | 1.0 ±8.2 | -0.9 ±4.4 | 2.3 ±11.6 | -0.1 ±7.3 | 0.341   |
| CI, geometric mean ±SD | 0.83 ±0.23a   | 0.83 ±0.31       | 1.04 ±0.35a    | 0.89 ±0.29       | 0.005*  |
| Fl, mean ±SD         | 0.85 ±0.26     | 0.88 ±0.30       | 1.02 ±0.36     | 0.91 ±0.29       | 0.053   |
| IOS, geometric mean ±SD | 0.14 ±0.23   | 0.15 ±0.25       | 0.16 ±0.40     | 0.15 ±0.28       | 0.814   |

AoE = angle of error; CI = correction index; D = diopters; DV = difference vector; Fl flattening index; IOS = index of success; MoE = magnitude of error; PRK = photorefractive keratectomy; SD = standard deviation; SIA = surgically induced astigmatism; TIA = target induced astigmatism; WFG = wavefront guided; WFO = wavefront-optimized
*Statistically significant at P < 0.017, One-way Analysis of Variance
Each superscript letter a,b denotes the treatment group whose values were significantly different from each other in the post-hoc analysis (P < 0.017).
was comprised of only up to 3.25 D of astigmatism thus limiting our generalizations. Nonetheless, the prevalence of individuals with higher amounts of astigmatism is relatively low, with approximately 2.93% having ≥ 3.00 D of cylinder [24].

In conclusion, our findings did not elicit a consistent advantage of one treatment modality based on the parameters evaluated in this study. Our astigmatism analyses suggest wavefront-guided treatments tended to undercorrect and wavefront-optimized treatments over correct low astigmatism. This, notwithstanding, did not seem to have any significant impact on the overall success of astigmatism correction nor visual outcomes. With emerging technologies such as topography-guided treatments and small incision lenticule extraction, there is room for future investigation, the findings of which will ultimately be valuable in providing individualized care for patients needing laser vision correction.

Declarations
Ethics approval and consent to participate

The study was reviewed and approved by the Institutional Review Boards at Walter Reed National Military Medical Center, Bethesda and the United States Army Medical Research and Materiel Command, Fort Detrick, Maryland, USA. All subjects gave written consent to participate in the study.

Consent for publication

Yes Availability of data and material: Data sharing is restricted due to relevant data protection laws.

Competing interests

RKS, DSR, JBE, LAL and BAR report grant from Carl Zeiss Meditech, Inc. and TearSolutions, Inc. outside the submitted work.

Funding

This research was supported by a United States Army Medical Research Acquisition Activity Award (W81XWH-09-2-0018).

Authors’ contributions

Concept and design KSB. Data acquisition RKS, DSR, RDS, JFP, JBE, LAL, KSB. Data analysis/interpretation RKS, DSR, KSB. Drafting manuscript RKS. Critical revision of manuscript DSR, RDS, JFP, JBE, LAL, BAR, KSB. Securing funding KSB. Supervision RDS, BAR, KSB. Final approval RKS, DSR, RDS, JFP, JBE, LAL, BAR, KSB.

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### Supplemental table A: Visual outcomes of eyes with simple myopia at 12 months postoperatively.

|                                | WFG PRK (n=16) | WFG LASIK (n=22) | WFO PRK (n=13) | WFO LASIK (n=20) | P-value |
|--------------------------------|----------------|------------------|----------------|------------------|---------|
| Postoperative astigmatism (n, %) | 7 (43.8%)      | 12 (54.5%)       | 7 (53.8%)      | 12 (60.0%)       | 0.811   |
| (mean ± SD)                     | 0.14 ±0.18     | 0.22 ±0.27       | 0.19 ±0.23     | 0.25 ±0.24       | 0.594   |
| UDVA within 1 line of preop CDVA (n, %) | 16 (100%)   | 21 (95.5%)       | 13 (100%)      | 20 (100%)        | 0.52    |
| UDVA 20/20 or better (n, %)     | 16 (100%)      | 21 (95.5%)       | 13 (100%)      | 20 (100%)        | 0.52    |
| Manifest SE within ±0.50 D (n, %) | 16 (100%)     | 20 (90.9%)       | 13 (100%)      | 20 (100%)        | 0.205   |

CDVA = corrected distance visual acuity; SD = standard deviation; SE = spherical equivalent; WFG = wavefront guided; WFO = wavefront-optimized; UDVA = uncorrected distance visual acuity

Statistically significant at P < 0.017, Pearson chi-square test