



# Visual outcomes for the initial 500 eyes treated with keratorefractive lenticule extraction (KLEx) for myopia and myopic astigmatism at a single-site

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## ABSTRACT

**Background:** Keratorefractive lenticule extraction (KLEx) has become a widely used corneal refractive surgery. Since its approval by the United States Food and Drug Administration (FDA), there are relatively few studies from the U.S. that have evaluated KLEx visual outcomes, often limited by their small sample size and short follow-up duration. To evaluate the one-year visual outcomes using KLEx for myopia and myopic astigmatism in a large U.S. cohort.

**Methods:** This was a retrospective study of 577 eyes from 314 patients who underwent KLEx between March 2017 and May 2024 at a single refractive surgery center. Inclusion criteria were myopia between -9.25 to -1.00 D, cylinder up to -3.00 D, and preoperative corrected distance visual acuity (CDVA) of 20/20 or better. The uncorrected distance visual acuity (UDVA), CDVA, manifest refraction, and complications were evaluated at 3 and 12 months postoperatively. Clinical outcomes were also compared to the U.S. FDA premarket trials and large international cohorts.

**Results:** Of 577 treated eyes, data were available at 3 months for 511 eyes (88.6% follow-up) and 12 months for 440 eyes (76.3% follow-up). The mean spherical equivalent (SEQ) improved from  $-5.35 \pm 1.62$  D ( $-9.63$  to  $-1.38$  D) to  $-0.04 \pm 0.44$  D ( $-1.88$  to  $1.88$  D) ( $P < 0.001$ ). Mean cylinder improved from  $-0.66 \pm 0.66$  D ( $-3.00$  to  $0.00$  D) at baseline to  $-0.40 \pm 0.32$  D ( $-1.75$  to  $0.00$  D) at 12 months ( $P < 0.001$ ). Additionally, postoperative UDVA was 20/20 or better in 81% of eyes and 20/25 or better in 94% of eyes. Postoperative SEQ was within  $\pm 0.50$  D in 85% of eyes and within  $\pm 1.00$  D in 97% of eyes at 12 months. The SEQ remained stable across all postoperative visits, with a mean change of  $-0.03 \pm 0.38$  D from 3 to 12 months. There was a gain of one line of CDVA in 16% of eyes at 12 months, with no eyes losing two or more CDVA lines. Target-induced and surgically induced astigmatism were strongly correlated at both 3 and 12 months, with a mean undercorrection of 20% by one year ( $R^2 = 0.69$ ).

**Conclusions:** KLEx demonstrates predictable and safe correction of myopia and myopic astigmatism over 12 months in a U.S. cohort. Visual outcomes meet or exceed the FDA benchmarks and are consistent with published literature, although a potential need for improved cylindrical correction remains.

## KEYWORDS

myopias, myopic astigmatism, nomogram, wavelight, refractive surgery, laser in situ keratomileusis, SMILE, ReLEx, KLEx, VisuMax

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## INTRODUCTION

Keratorefractive lenticule extraction (KLEx) is a minimally invasive laser refractive surgery indicated for the treatment of myopia and myopic astigmatism. The small incision lenticule extraction (SMILE®) is a KLEx procedure that has become widely adopted since its approval by the U.S. Food and Drug Administration (FDA) in 2016 [1]. Compared to traditional laser-assisted in situ keratomileusis (LASIK) or photorefractive keratectomy (PRK), KLEx eliminates the creation of a flap or epithelial removal. Instead, KLEx uses the VisuMax 500 femtosecond laser system (Carl Zeiss Meditech AG, Jena, Germany) to create an intrastromal lenticule, which is subsequently removed through a small incision [2]. The procedure has been associated with improved corneal structural stability, reduced disruption of corneal nerve fibers, and a lower incidence of dry eye compared to LASIK and PRK [3]. However, KLEx has notable drawbacks compared to traditional LASIK, including slower visual recovery and a steeper learning curve for surgeons [4–6].

Despite its growing popularity, there remain relatively few studies from the United States that report visual outcomes following KLEx, often limited by their small sample size and short follow-up duration [7, 8]. The current literature primarily reflects large Asian and European cohorts with thousands of eyes and follow-ups extending beyond one year [6, 9, 10]. This gap highlights the need for large-scale U.S. data to validate KLEx outcomes against FDA performance benchmarks and to also provide meaningful comparisons to international cohorts. Therefore, the purpose of this study is to evaluate visual outcomes from 577 eyes that underwent KLEx at a single U.S. site. We also compare our findings to those of large international cohorts and the FDA multicenter clinical trial [1, 8].

## METHODS

**Study Design:** This is a single-center retrospective study analyzing 577 eyes from 314 patients who underwent KLEx for myopia or myopic astigmatism in Draper, Utah, between March 2017 and May 2024. Full approval was granted by the Biomedical Research Alliance of New York Institutional Review Board (# A20-12-547-823). The study adhered to the tenets of the Declaration of Helsinki, and HIPAA regulations were followed. All patients provided written informed consent prior to their inclusion in the study.

Inclusion criteria consisted of patients aged 18 years or older with myopia ( $-9.25$  to  $-1.00$  D) with or without astigmatism ( $-3.00$  to  $0.00$  D) in one or both eyes who underwent SMILE® using the VisuMax® 500, had a preoperative corrected distance visual acuity (CDVA) of 20/20 or better, and completed 3-month and 12-month postoperative evaluations. Patients were excluded if they had missing data at 3 and 12 months, or clinically significant dry eyes, ocular disease, infectious or autoimmune disease, hyperopia, or hyperopic astigmatism.

Preoperative visits included a comprehensive ophthalmic examination, including uncorrected distance visual acuity (UDVA), CDVA, manifest refraction, intraocular pressure measurement, slit-lamp biomicroscopy (Haag-Streit BQ 900; Haag-Streit AG, Köniz, Switzerland), dilated fundus examination, and keratometry. Corrected and uncorrected visual acuities were obtained by an optometrist using a Snellen chart (M&S Technologies Inc., Niels, IL, USA) displayed on a high-resolution screen at 4 meters. Corneal topography and pachymetry were assessed using the Pentacam HR (Oculus Optikgeräte GmbH, Wetzlar, Germany). Primary outcome measures included postoperative UDVA, CDVA, and manifest refraction assessed at 1-week, 1-month, 3-month, and 12-month follow-up examinations when data were available.

Visual and refractive outcomes were analyzed at 3 and 12 months postoperatively. Only eyes with data available at each follow-up were included; eyes lost to follow-up were excluded. Data were visualized using the nine standard graphs for reporting refractive surgery outcomes [11, 12]. Eyes targeted for monovision were excluded from the safety and efficacy graphs (parts A and B) of the nine standard but included for all other outcome assessments. Safety (the ratio of postoperative CDVA to preoperative CDVA) and efficacy indices (the ratio of postoperative UDVA to preoperative CDVA) were calculated [13]. The data were compared to FDA standards and relevant literature on KLEx visual outcomes.

**Selection of Published Literature of KLEx:** To identify articles relevant to KLEx with a sufficiently large sample size, we performed a literature search using PubMed and Embase databases on June 17, 2025, with the following keywords: ("keratorefractive lenticule extraction" OR "KLEx" OR "small incision lenticule extraction" OR "SMILE®") AND ("myopia" OR "astigmatism") AND "visual outcome" (Table 3 and 4).

The selection criteria were based on the following parameters: a sample size of  $\geq 95$  eyes, visual outcomes, including safety, efficacy, predictability, and accuracy, were reported, and a postoperative follow-up of at least 3 or 12 months. Studies were excluded if they were duplicates, reviews, case reports, animal studies, non-English,

comparative studies, procedures performed with platforms other than VisuMax 500, or irrelevant to the study objective.

Two relevant studies meeting the criteria were excluded. The study by Ramirez-Miranda et al. was eligible for inclusion in our analysis [14]; however, all procedures were performed by cornea fellows in training. Given the well-documented learning curve of KLEx [15], we decided to exclude this study [14]. Another eligible study by Dishler et al. was excluded because it reported overlapping data that the U.S. FDA already provided in the VisuMax 500 premarket approval study [8].

**Surgical Technique:** All KLEx procedures were conducted at a single site by two surgeons (M.M. and P.C.H.) using the VisuMax 500 kHz femtosecond laser system, with pulse durations ranging from 220 to 580 fs. Before surgery, limbal reference marks were made at the 3 and 9 o'clock positions with the patient seated upright. Intraoperatively, corresponding marks were placed just inside the limbus at the same clock positions. Careful attention was paid to detect any cyclotorsional eye movement following vacuum application. Manual rotational adjustments were made as needed, either clockwise or counterclockwise, to ensure the alignment. Laser parameters were as follows: 3.93 mm superior corneal incision, 7.5 mm cap diameter, 120  $\mu$ m cap thickness, 6.0–6.5 mm lenticule diameter, superior incision position, 90° side cut angle, and 50° incision angle. Laser-bed energy was set to 145 nJ with spot separations of 3  $\mu$ m (lenticule), 2.5  $\mu$ m (side-cut), 3  $\mu$ m (cap), and 2  $\mu$ m (incision side-cut).

For SMILE® performed on the VisuMax 500 kHz platform, we used an established nomogram that was originally developed using Datagraph-med version 5.80 (Datagraph, Chapel Hill, NC, USA) for the treatment of myopia and myopic astigmatism of  $\leq 0.50$  D cylinder. This nomogram increased the sphere by 7.5%, with no adjustments to the cylinder.

Postoperative management consisted of one drop of 0.5% moxifloxacin (Lifestar Pharma LLC, Mahwah, NJ, USA) ophthalmic solution in both eyes following the procedure. Patients continued moxifloxacin eye drops four times per day for one week, and 1% prednisolone acetate (Lupin Pharmaceuticals, Inc., Baltimore, MD, USA) ophthalmic suspension drops four times per day for one week, then twice a day for one week, and then once a day for two weeks postoperatively. Preservative-free artificial tears (Allergan Inc., Irvine, CA, USA) were recommended as needed.

Descriptive statistics were calculated using IBM SPSS Statistics for Windows, version 30.0 (IBM Corp., Armonk, NY, USA). Values are reported as mean  $\pm$  standard deviation for continuous variables and proportions (percentage) for categorical variables. Given that randomly selecting one eye per patient would reduce the sample size, we chose to include both eyes from each patient for our analysis. To appropriately account for correlation between fellow eyes, the general estimating equation (GEE) was applied using Python (version 3.13; Python Software Foundation, Lafayette Boulevard, Fredericksburg, VA, USA). GEE models specified each refractive outcome (spherical equivalent [SEQ], sphere, cylinder, logMAR UDVA, logMAR CDVA) as the dependent variable, and time (preoperative, 3 months, 12 months) as a categorical independent variable, with the preoperative visit designated as the reference category. Pairwise post-hoc contrasts were additionally performed to compare outcomes across timepoints. All available data were included at each visit, and eyes missing at follow-up were not required to have paired data, providing population-level estimates. An identity link function with a Gaussian distribution and an exchangeable working correlation structure was used. Models were adjusted for the covariates age and gender. We report estimated regression coefficients ( $\beta$ ), robust standard errors, Wald test, 95% confidence intervals, and P-values. A P-value of less than .05 was considered statistically significant. Nine standard graphs of visual outcomes were created [11, 12].

## RESULTS

**Patient Demographics:** A total of 577 eyes from 314 patients underwent KLEx (Table 1). A total of 347 eyes (60.1%) were from female patients, and 230 eyes (39.9%) were from male patients. The mean age was  $33.95 \pm 7.45$  years (range: 18 to 57). Of the 577 eyes, 32 were targeted for monovision and had a mean SEQ of  $-6.14 \pm 1.48$  D (range: -9.13 to -3.38 D). A total of 127 eyes were treated for simple myopia with a mean SEQ of  $-5.03 \pm 1.74$  D (range: -8.75 to -1.50 D), while 450 were treated for astigmatic myopia with a mean SEQ of  $-5.47 \pm 1.58$  D (range: -9.63 to -1.38 D). The mean preoperative cylinder for all eyes was  $-0.66 \pm 0.65$  D (range: -3.00 to 0.00 D), and  $-0.85 \pm 0.62$  D (range: -3.00 to -0.25 D) among eyes with astigmatic myopia.

Of the 577 eyes, 3-month data were available for 511 eyes (88.6% follow-up), and 12-month data were available for 440 eyes (76.3% follow-up). After excluding eyes lost to follow-up and those targeted for monovision, 545 eyes

(94.5%) were available at the preoperative visit, 484 eyes (83.9%) at 3 months, and 422 eyes (73.1%) at 12 months (Table 2).

**Efficacy:** The mean UDVA (logMAR) improved from  $1.40 \pm 0.25$  preoperatively to  $0.01 \pm 0.10$  by 12 months ( $P < 0.001$ ) (Table 2). UDVA of 20/20 or better was achieved in 79% of eyes at 3 months, while 99% achieved a UDVA of 20/40 or better (Figure 1A). At 12 months, 81% of eyes achieved a UDVA of 20/20 or better, and 94% achieved 20/25 or better (Figure 2A). All eyes (100%) had a UDVA of 20/40 or better. Additionally, 70% of eyes had a UDVA that was the same or better than preoperative CDVA at both 3 and 12 months (Figures 1B and 2B). The efficacy index at 3 months was  $0.94 \pm 0.17$  ( $n = 484$  eyes), which improved slightly to  $0.95 \pm 0.17$  by 12 months ( $n = 422$  eyes).

**Safety:** The safety index was  $1.01 \pm 0.12$  and  $1.02 \pm 0.13$  at 3 and 12 months, respectively (Table 2). Two eyes (0.4%) lost  $\geq 2$  lines of CDVA at 3 months, while no eyes lost  $\geq 2$  CDVA lines at 12 months (Figures 1C and 2C). At 3 months, more than 12% of eyes gained one line of CDVA, which increased to 16% by 12 months (Figures 1C and 2C).

**Predictability and Stability:** The mean SEQ decreased in magnitude from  $-5.35 \pm 1.62$  D at baseline to  $-0.04 \pm 0.44$  D at 12 months ( $P < 0.001$ ) (Table 2). Of the 511 eyes at 3 months, 87% were within  $\pm 0.50$  D of the intended SEQ target, while 97% were within  $\pm 1.00$  D (Figure 1E). At 12 months, 85% of 440 eyes were within  $\pm 0.50$  D of the intended SEQ target, and 97% of eyes were within  $\pm 1.00$  D (Figure 2E). Postoperative SEQ remained stable across all visits, with a mean change of  $-0.03 \pm 0.38$  D from 3 to 12 months (Figure 2F). Additionally, 16% of eyes experienced a change greater than 0.50 D from 1 week to 12 months

**Table 1. Patients demographics**

| Parameters                             | All Eyes<br>(n = 577)                | Simple Myopia<br>(n = 127)           | Astigmatic Myopia<br>(n = 450)       | Monovision Target<br>(n = 32)        |
|----------------------------------------|--------------------------------------|--------------------------------------|--------------------------------------|--------------------------------------|
| Sex (Male / Female), n (%)             | 230 (39.9) / 347 (60.1)              | 57 (44.9) / 70 (55.1)                | 173 (38.4) / 277 (61.6)              | 10 (31.3) / 22 (68.7)                |
| Laterality (OD / OS), n (%)            | 291 (50.4) / 286 (49.6)              | 64 (50.4) / 63 (49.6)                | 223 (49.6) / 227 (50.4)              | 8 (25.0) / 24 (75.0)                 |
| Age (y), Mean $\pm$ SD<br>(Range)      | 33.95 $\pm$ 7.45<br>(18 to 57)       | 33.13 $\pm$ 6.83<br>(18 to 54)       | 34.18 $\pm$ 7.61<br>(18 to 57)       | 46.06 $\pm$ 4.47<br>(39 to 54)       |
| Sphere (D), Mean $\pm$ SD<br>(Range)   | -5.06 $\pm$ 1.59<br>(-9.25 to -1.00) | -5.03 $\pm$ 1.74<br>(-8.75 to -1.50) | -5.04 $\pm$ 1.54<br>(-9.25 to -1.00) | -5.80 $\pm$ 1.43<br>(-8.5 to -3.00)  |
| Cylinder (D), Mean $\pm$ SD<br>(Range) | -0.66 $\pm$ 0.65<br>(-3.00 to 0.00)  | -                                    | -0.85 $\pm$ 0.62<br>(-3.00 to -0.25) | -0.70 $\pm$ 0.51<br>(-2.00 to 0.00)  |
| SEQ (D), Mean $\pm$ SD<br>(Range)      | -5.39 $\pm$ 1.63<br>(-9.63 to -1.38) | -5.03 $\pm$ 1.74<br>(-8.75 to -1.50) | -5.47 $\pm$ 1.58<br>(-9.63 to -1.38) | -6.14 $\pm$ 1.48<br>(-9.13 to -3.38) |

Abbreviations: n, number; %, percentage; OD, right eye; OS, left eye; y, years; SD, standard deviation; D, diopters; SEQ, spherical equivalent.

**Table 2. Visual acuity and refractive outcomes from preoperative to 12 months**

| Parameters                           | Preop<br>(n = 545 <sup>a</sup> )     | 3 Months Postop<br>(n = 484 <sup>a</sup> ) | 12 Months Postop<br>(n = 422 <sup>a</sup> ) | <sup>1</sup> P-value | <sup>2</sup> P-value |
|--------------------------------------|--------------------------------------|--------------------------------------------|---------------------------------------------|----------------------|----------------------|
| CDVA (logMAR), Mean $\pm$ SD (Range) | -0.02 $\pm$ 0.05<br>(-0.3 to 0.4)    | -0.02 $\pm$ 0.06<br>(-0.3 to 0.2)          | -0.03 $\pm$ 0.06<br>(-0.3 to 0.1)           | 0.674                | 0.306                |
| UDVA (logMAR), Mean $\pm$ SD (Range) | 1.40 $\pm$ 0.25<br>(0.4 to 1.7)      | 0.02 $\pm$ 0.1<br>(-0.3 to 0.4)            | 0.01 $\pm$ 0.10<br>(-0.3 to 0.8)            | <b>&lt; 0.001</b>    | <b>0.001</b>         |
| Sphere (D), Mean $\pm$ SD (Range)    | -5.02 $\pm$ 1.58<br>(-9.25 to -1)    | 0.18 $\pm$ 0.39<br>(-2.00 to 1.75)         | 0.16 $\pm$ 0.43<br>(-1.75 to 2.25)          | <b>&lt; 0.001</b>    | 0.797                |
| Cylinder (D), Mean $\pm$ SD (Range)  | -0.66 $\pm$ 0.66<br>(-3.00 to 0.00)  | -0.36 $\pm$ 0.32<br>(-2.00 to 0.00)        | -0.40 $\pm$ 0.32<br>(-1.75 to 0.00)         | <b>&lt; 0.001</b>    | 0.042                |
| SEQ (D), Mean $\pm$ SD (Range)       | -5.35 $\pm$ 1.62<br>(-9.63 to -1.38) | -0.01 $\pm$ 0.38<br>(-2.13 to 1.38)        | -0.04 $\pm$ 0.44<br>(-1.88 to 1.88)         | <b>&lt; 0.001</b>    | 0.637                |
| Efficacy Index <sup>b</sup>          | -                                    | 0.94 $\pm$ 0.17                            | 0.95 $\pm$ 0.17                             | -                    | -                    |
| Safety Index <sup>c</sup>            | -                                    | 1.01 $\pm$ 0.12                            | 1.02 $\pm$ 0.13                             | -                    | -                    |

Abbreviations: CDVA, corrected distance visual acuity; logMAR, logarithm of minimum angle of resolution; UDVA, uncorrected distance visual acuity; SD, standard deviation; D, diopters; SEQ, spherical equivalent; Preop, preoperative; Postop, postoperative. Note: P-values < 0.05 are shown in bold; P-values were derived using generalized estimating equation Wald tests; <sup>1</sup> P-value compares preoperative values with 3 months postoperative values; <sup>2</sup> P-value compares 3 months postoperative values with 6 months postoperative values; SEQ, spherical equivalent was calculated by adding the spherical component of the refraction to half of the cylindrical component; <sup>a</sup> Monovision targeted eyes were excluded from these measurements; <sup>b</sup> Efficacy index, postoperative UDVA / preoperative CDVA; <sup>c</sup> Safety Index, postoperative CDVA / preoperative CDVA.



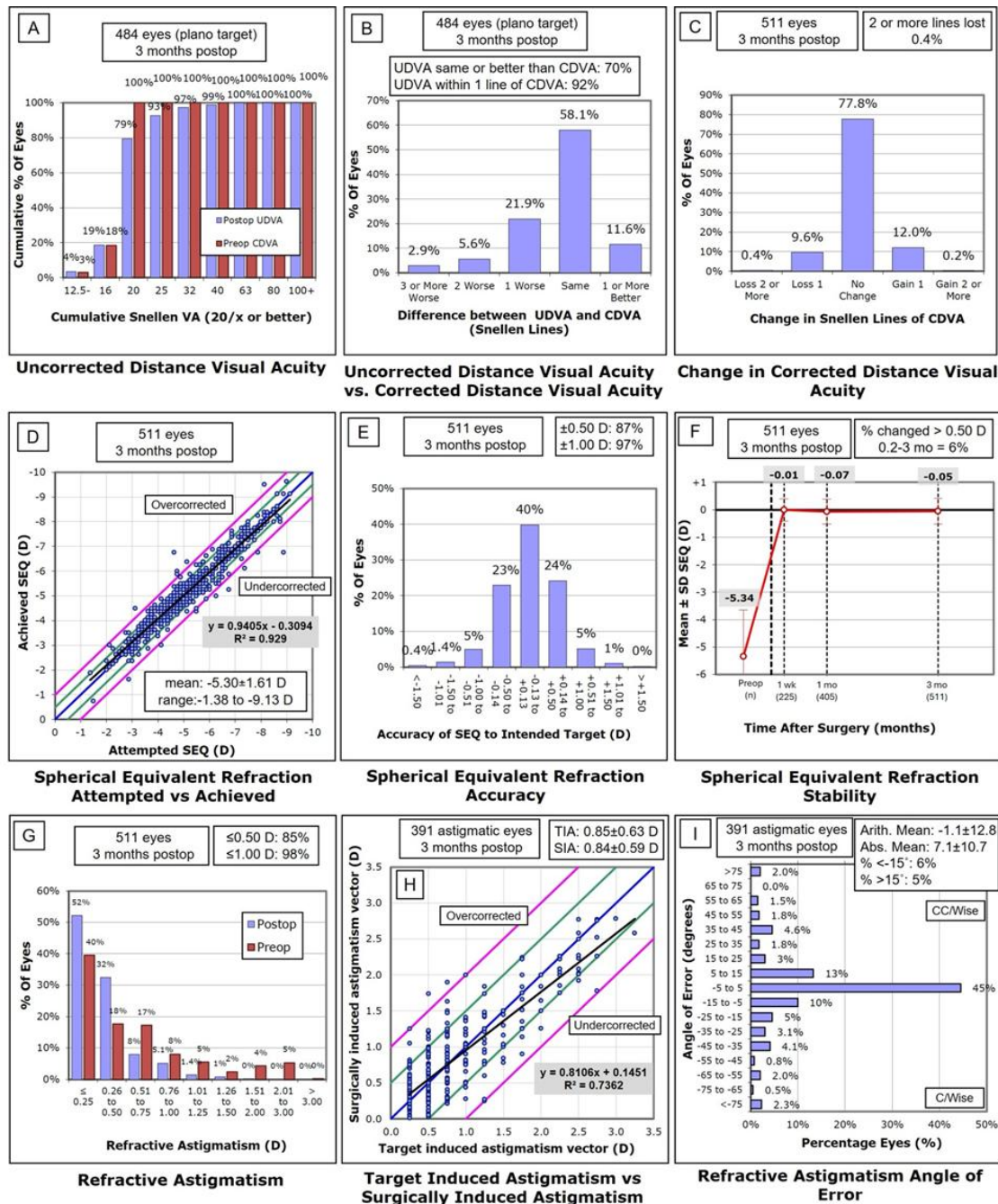
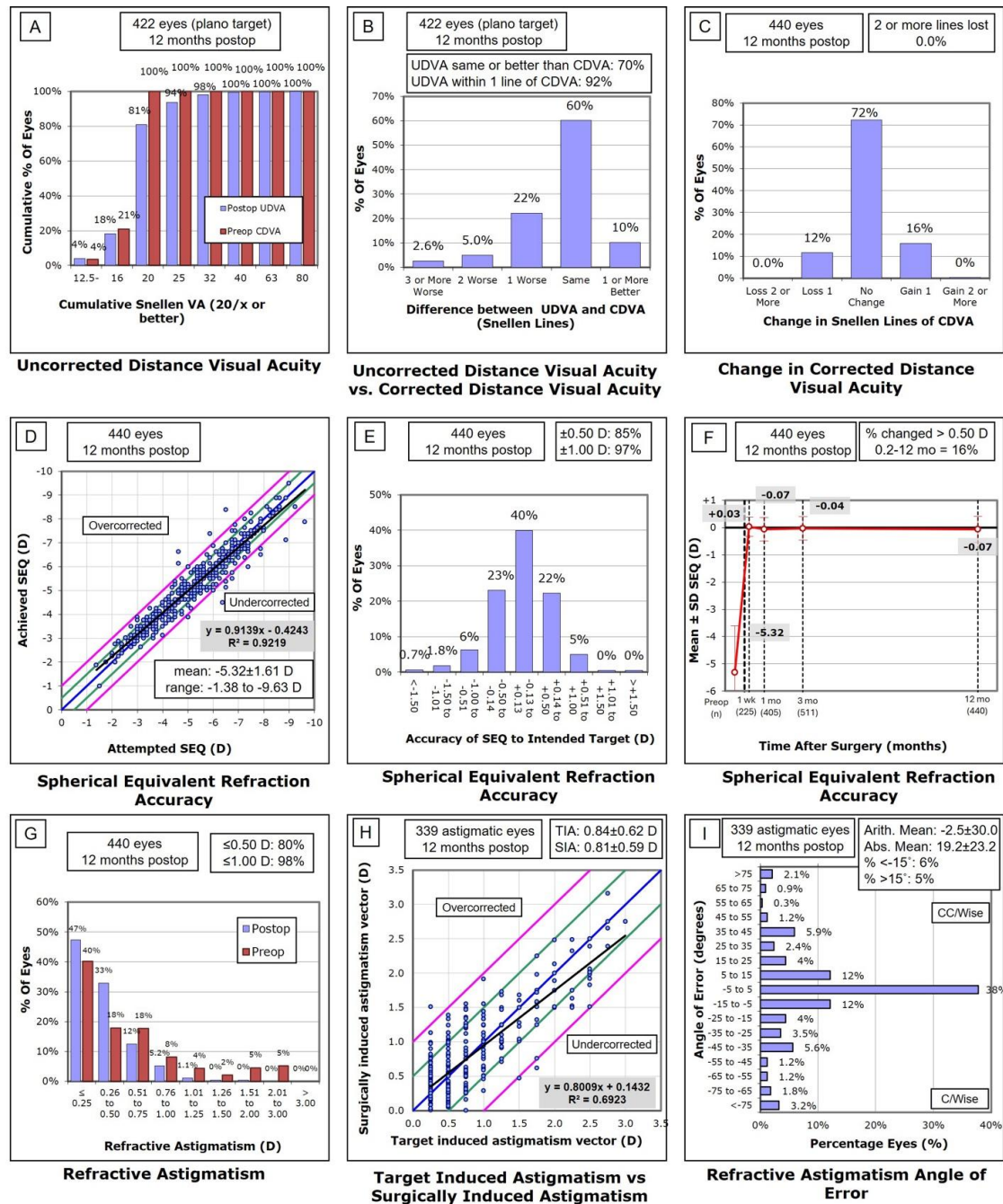


Figure 1. Standard nine graphs after keratorefractive lenticule extraction at 3 months. Abbreviations: UDVA, uncorrected distance visual acuity; CDVA, corrected distance visual acuity; D, diopters; SIA, surgically induced astigmatism; TIA, target-induced astigmatism.

Refractive Astigmatism: At 3 months postoperatively, 85% of eyes had a refractive cylinder of  $\leq 0.50$  D, whereas 80% of eyes had this outcome at 12 months (Figures 1G and 2G). Mean postoperative cylinder improved from  $-0.66 \pm 0.66$  D at baseline to  $-0.36 \pm 0.32$  D at 3 months ( $P < 0.001$ ) (Table 2). Between 3 and 12 months, cylinder improved slightly to  $-0.40 \pm 0.32$  D ( $P = 0.042$ ). The mean target-induced astigmatism (TIA) vector at 12 months was  $0.84 \pm 0.62$  D, and the surgically induced astigmatism (SIA) vector was  $0.81 \pm 0.59$  D (Figure 2H). Correlation between TIA and SIA showed a coefficient of determination ( $R^2$ ) of 0.69, indicating an undercorrection of 20% per diopter of attempted correction. This is further supported by the correction index ( $CI = SIA/TIA$ ), which was found to be 0.96, although close to the ideal value of 1.00. At 3 months, the angle of error for 45% of eyes ( $n = 176$ ) was within  $-5^\circ$  to  $5^\circ$  (Figure 1I), whereas 38% of eyes ( $n = 129$ ) fell within this range at 12 months (Figure 2I).



**Figure 2.** Graphs of refractive and visual outcomes after keratorefractive lenticule extraction at 12 months. Abbreviations: UDVA, uncorrected distance visual acuity; CDVA, corrected distance visual acuity; D, diopters; SIA, surgically induced astigmatism; TIA, target-induced astigmatism.

**Complications and Enhancements:** Out of 577 eyes, one eye (0.17%) was converted to LASIK because of suction loss. Intraoperatively, one eye (0.17%) experienced a small corneal cap tear. Postoperatively, epithelial ingrowths occurred in 9 eyes (1.56%), epithelial defects in 14 eyes (2.42%), diffuse lamellar keratitis (DLK) in 2 eyes (0.34%), Staphylococcal marginal keratitis in 1 eye (0.17%), and corneal erosions in 2 eyes (0.34%). Additionally, 4 eyes (0.69%) developed postoperative microstriae, though not visually significant.

Seventeen eyes (2.9%) required subsequent PRK enhancement. Before enhancement, 15 of these 17 eyes (88.2%) had a UDVA of 20/40 or better, and no eyes had an UDVA of 20/20 or better. Following enhancement, all eyes had a UDVA of 20/40 or better, and 15 eyes (88.2%) had a UDVA of 20/20 or better. Additionally, no eyes experienced a change in UDVA from baseline CDVA, and no eyes had lost any lines of CDVA.

## DISCUSSION

Since the introduction of KLEx over 15 years ago, this flap-free technique has gained global prominence with several international studies supporting its safety and efficacy profile [9, 10, 16–20]. This single-center U.S. study is among the largest in a North American population to report 1-year clinical outcomes following KLEx for the correction of myopia and myopic astigmatism.

Of the 308 relevant studies screened, 13 studies met the inclusion criteria and evaluated visual and refractive outcomes of KLEx [1, 6, 7, 9, 10, 17–24]. Among these studies, an average of 57% to 96% of eyes achieved a postoperative UDVA of 20/20 or better at 12 months [9, 10, 17–19]. Although Pedersen et al. [17] reported acceptable UDVA 20/40 or better outcomes, the proportion of eyes achieving 20/20 was 24% lower than that observed in our study. In contrast, most other studies reported greater efficacy outcomes in comparison to our findings, including those by Reinstein et al. [10] and Chuckpaiwong et al. [9], which showed 14% and 11% more eyes achieving UDVA 20/20 or better, respectively. Nevertheless, the efficacy index in our study was  $0.95 \pm 0.17$ , which is well-above the accepted threshold of 0.80 [25]. Additionally, the FDA target criteria require at least 85% of eyes with a preoperative CDVA of 20/20 or better to achieve a UDVA of 20/40 or better at 12 months postoperatively [1], with our results exceeding these targets at both 3 and 12 months.

Regarding safety outcomes at one year, no eyes lost more than two lines of CDVA, and the safety index was  $1.02 \pm 0.13$ . The safety profile of KLEx may be attributed to its minimally invasive nature, which results in less corneal biomechanical disruption [26]. These findings surpass the accepted safety index benchmark of 0.85 [25] and meet the FDA requirement that no more than 5% of eyes can experience a loss of more than two lines of CDVA [1]. Our findings were relatively comparable to the findings of Chuckpaiwong et al. [9], who reported a safety index of  $1.07 \pm 0.15$ . In contrast, other large cohort studies reported greater safety indices, such as Wu et al. [20], who observed a safety index of  $1.13 \pm 0.13$  ( $\geq -6.0$  D of SEQ) and  $1.17 \pm 0.14$  ( $< -6.0$  D of SEQ). Direct comparisons across analyzed studies were limited, as not all studies reported safety or efficacy indices. A recent meta-analysis by Liu et al. [27], however, found that KLEx achieved comparable safety outcomes to other corneal refractive surgeries for the treatment of myopia, supporting its use as a safe treatment option.

KLEx is approved for the correction of myopia up to  $-10.00$  D and astigmatism up to  $-3.00$  D (up to  $-5.00$  D in countries requiring CE marking [1]. Previous studies have demonstrated a tendency toward undercorrection of astigmatism following KLEx [18, 28–31]. This is evidenced by the correlational analysis between SIA and TIA at 12 months ( $R^2 = 0.69$ ) and a CI of 0.96 in our study, indicating 20% undercorrection. In contrast to KLEx, excimer lasers like the WaveLight Allegretto have shown a CI of 1.18 in the FDA approval studies, indicating overcorrection in predominantly low astigmatic eyes [32]. Slight undercorrection, however, may be preferred clinically, as overcorrection with axis shift is often less tolerated by patients [31].

The astigmatic outcomes in our study are likely attributed to the limitations in rotational alignment inherent to the VisuMax 500 platform, which lacks automated cyclotorsion control [29]. Compared to wavefront-guided LASIK, which incorporates automated iris registration and eye tracking, KLEx demonstrated a higher angle of error, a larger difference vector, and a lower CI [30]. Several methods have been proposed to improve the astigmatic outcomes in KLEx, including intraoperative manual cyclotorsion to reduce axis misalignment [31], preoperative limbal marking in the upright position with subsequent rotational alignment once supine [17], and nomogram-based adjustments [33]. To date, a standardized astigmatic nomogram for KLEx has not been widely implemented, though a 10% adjustment in the magnitude of astigmatism correction has been suggested [17]. However, this should be considered with caution, as one study of 180 eyes with myopic astigmatism (2.50 to 4.50 D) and predominantly with-the-rule astigmatism found that applying such an adjustment led to postoperative against-the-rule astigmatism and subsequent visual complaints [33]. Although limbal markings, intraoperative manual cyclotorsion, and nomogram adjustments were used at our refractive surgery center, residual misalignment remains a plausible contributor to undercorrected cylinder, particularly in patients with high astigmatism. Perhaps the integration of automated eye tracking and cyclotorsion, as seen in newer KLEx platforms like the VisuMax 800, along with further refinement of the cylindrical nomogram, may help mitigate the astigmatic undercorrection observed with KLEx [34].

At one year, 85% of eyes achieved a SEQ within  $\pm 0.50$  D of target and 97% within  $\pm 1.00$  D of target. Our findings exceed the FDA criteria at both 3 and 12 months, which states that at least 50% of eyes must achieve a SEQ within  $\pm 0.50$  D of the target and 75% of eyes within  $\pm 1.00$  D of the target outcome [1]. In terms of SEQ within  $\pm 0.50$  D of target, our findings fall modestly below the accuracy reported in other large cohort studies, which range from 88% to 96% [9, 10, 20]. This discrepancy may be attributed to the higher preoperative SEQ in our study. For example, Pedersen et al. [17] reported the highest mean preoperative SEQ ( $-6.47 \pm 1.90$  D) among the included studies, but also the lowest SEQ accuracy, with 74%



within  $\pm 0.50$  D and 93% within  $\pm 1.00$  D of the SEQ target. A prior study reported that higher baseline SEQ is associated with an increased likelihood of myopic regression, along with older age, female sex, and steeper corneas [35]. In the same study, the authors found KLEx resulted in a greater than 0.50 D myopic shift in 10% of patients after one year, compared to 3.4% with LASIK and 4.5% with PRK [35]. There are multiple factors that may explain this, including greater keratocyte activation or significant epithelial hyperplasia in high myopes after KLEx [20]. In contrast, refractive outcomes in our study remained stable between 3 and 12 months, indicating that most changes occur early during the acute healing phase. However, there is still a possibility of myopic shifts after one year, particularly in patients with higher baseline myopia [35] (Tables 3 and 4).

Table 3. Summary of 3-month visual outcomes following keratorefractive lenticule extraction reported in published studies

| Study                | Year | Country | Eyes | %UDVA<br>$\geq 20/20$ | %UDVA<br>$\geq 20/40$ | %CDVA<br>Loss of<br>$\geq 2$ lines | %CDVA<br>Loss of<br>1 line | %CDVA<br>No Change | %CDVA<br>Gain of<br>1 Line | %CDVA<br>Gain of<br>$\geq 2$ Lines | %Cyl<br>$\leq 0.5$ D | %SEQ<br>within<br>$\pm 0.5$ D | %SEQ<br>within<br>$\pm 1.0$ D | Efficacy<br>Index | Safety<br>Index   |
|----------------------|------|---------|------|-----------------------|-----------------------|------------------------------------|----------------------------|--------------------|----------------------------|------------------------------------|----------------------|-------------------------------|-------------------------------|-------------------|-------------------|
| Current Study        | 2025 | USA     | 511  | 79.0                  | 99.0                  | 0.4                                | 9.6                        | 77.8               | 12.0                       | 0.2                                | 85.0                 | 87.0                          | 97.0                          | $0.94 \pm 0.17^a$ | $1.01 \pm 0.12^b$ |
| Taneri et al. [21]   | 2019 | Germany | 206  | 76.0                  | 99.0                  | 2.4                                | 11.7                       | 73.8               | 10.2                       | 1.5                                | 88                   | 87.0                          | 99.0                          | 0.87              | 1.00              |
| Liu et al. [7]       | 2021 | USA     | 462  | 93.0                  | 100.0                 | 0.0                                | 2.0                        | 76.0               | 21.0                       | 0.0                                | 98.0                 | 98.0                          | 100.0                         | -                 | -                 |
| Kamiya et al. [22]   | 2019 | Japan   | 252  | 100.0                 | 100.0                 | 0.8                                | 11.0                       | 65.0               | 23.0                       | 0.0                                | 92.0                 | 88.0                          | 99.0                          | -                 | -                 |
| Hjordtal et al. [23] | 2012 | Denmark | 670  | -                     | 92.8                  | 2.4                                | -                          | -                  | -                          | 3.7                                | -                    | 80.0                          | 94.0                          | $0.90 \pm 0.25$   | $1.07 \pm 0.22$   |
| Ivarsen et al. [6]   | 2014 | Denmark | 1574 | -                     | -                     | 1.5                                | -                          | -                  | -                          | 3.4                                | -                    | -                             | -                             | -                 | $1.05 \pm 0.32$   |
| Hansen et al. [24]   | 2016 | Denmark | 722  | -                     | 83.0 <sup>c</sup>     | 1.6                                | -                          | -                  | -                          | -                                  | 83.0                 | 88.0                          | 98.0                          | -                 | -                 |

Abbreviations: SEQ, spherical equivalent; sph, sphere; cyl, cylinder; D, diopters; FDA PMA, Food and Drug Administration Premarket Approval; USA, United States; UK, United Kingdom.

Note: <sup>a</sup> Calculated using postoperative UDVA/preoperative CDVA; <sup>b</sup> Calculated using postoperative CDVA/preoperative CDVA; <sup>c</sup> Reported  $\geq 20/25$ .

Table 4. Summary of 12-month visual outcomes following keratorefractive lenticule extraction reported in published studies

| Study                               | Year | Country  | Eyes              | %UDVA<br>$\geq 20/20$ | %UDVA<br>$\geq 20/40$ | %CDVA<br>Loss of<br>$\geq 2$ lines | %CDVA<br>Loss of<br>1 line | %CDVA<br>No Change | %CDVA<br>Gain of<br>1 Line | %CDVA<br>Gain of<br>$\geq 2$ Lines | %Cyl<br>$\leq 0.5$ D | %SEQ<br>within<br>$\pm 0.5$ D | %SEQ<br>within<br>$\pm 1.0$ D | Efficacy<br>Index | Safety<br>Index   |
|-------------------------------------|------|----------|-------------------|-----------------------|-----------------------|------------------------------------|----------------------------|--------------------|----------------------------|------------------------------------|----------------------|-------------------------------|-------------------------------|-------------------|-------------------|
| Current Study                       | 2025 | USA      | 440               | 81.0                  | 100.0                 | 0.0                                | 12.0                       | 72.0               | 16.0                       | 0.0                                | 80.0                 | 85.0                          | 97.0                          | $0.95 \pm 0.17^a$ | $1.02 \pm 0.13^b$ |
| VisuMax 500 FDA PMA [1]             | 2018 | USA      | 311               | 88.1                  | 99.7                  | 0.0                                | 2.6                        | 72.0               | 22.8                       | 2.6                                | -                    | 93.9                          | 98.7                          | -                 | -                 |
| Chuckpaiwong et al. [9]             | 2023 | Thailand | 5953              | 92.4                  | 99.4                  | 0.1                                | 6.9                        | 63.6               | 28.6                       | 0.8                                | 88.1                 | 88.4                          | 98.6                          | $0.99 \pm 0.19$   | $1.07 \pm 0.15$   |
| Pedersen et al. [17]                | 2017 | Denmark  | 87                | 57.0                  | 95.0                  | 0.0                                | 9.0                        | 55.0               | 26.0                       | 9.0                                | 70.0                 | 74.0                          | 93.0                          | -                 | -                 |
| Zhang et al. [18]                   | 2015 | China    | 98                | 79.6                  | -                     | 0.0                                | 1.0                        | 36.7               | 57.1                       | 5.1                                | 95.9                 | -                             | -                             | -                 | -                 |
| Reinstein et al. [19]               | 2014 | UK       | 110               | 96.0                  | 100.0                 | -                                  | 9.0                        | -                  | -                          | -                                  | -                    | 84.0                          | -                             | -                 | -                 |
| Reinstein et al. [10]               | 2022 | UK       | 3722              | 95.5                  | 100.0                 | 0.1                                | 3.0                        | 45.5               | 46.3                       | 3.1                                | 91.0                 | 88.1                          | 99.6                          | -                 | -                 |
| Wu et al. [20]<br>SEQ < -6.0 D      | 2016 | China    | /156 <sup>c</sup> | -                     | -                     | -                                  | -                          | -                  | -                          | -                                  | -                    | 96.7                          | 100.0                         | -                 | $1.17 \pm 0.14$   |
| Wu et al. [20]<br>SEQ $\geq -6.0$ D | 2016 | China    | /156 <sup>c</sup> | -                     | -                     | -                                  | -                          | -                  | -                          | -                                  | -                    | 95.4                          | 100.0                         | -                 | $1.13 \pm 0.13$   |

Abbreviations: SEQ, spherical equivalent; sph, sphere; cyl, cylinder; D, diopters; FDA PMA, Food and Drug Administration Premarket Approval; USA, United States; UK, United Kingdom. Note: <sup>a</sup> Calculated using postoperative UDVA/preoperative CDVA; <sup>b</sup> Calculated using postoperative CDVA/preoperative CDVA; <sup>c</sup> (n/N) Total number of eyes: 156.

Long-term studies further support the safety, efficacy, and stability of KLEx for myopia and myopic astigmatism [36, 37]. Blum et al. [36] reported that 16 of 56 eyes (29%) gained one or two lines of CDVA after 10 years, with no eyes losing two or more lines. The authors also found a mild regression of -0.30 D over 10 years, with most of the change occurring by 5 years (-0.48 D). They attributed this to either an increase in axial length because of eye globe growth, or early nuclear sclerosis and associated myopization, rather than true regression at the corneal level [36]. Although another 10-year study observed a -0.32 D regression ( $-0.03 \pm 0.06$  D/year change), it found stable refraction even after excluding axial length, proposing the contrary [37].

The learning curve of KLEx is significantly steeper than that of other corneal refractive surgeries [15], with complications often related to lenticule creation, dissection, and extraction [5]. The overall intraoperative and postoperative complication rates in our study were 5.9%, which is relatively lower compared to those of other studies. For example, Ivarsen et al. [6] reported a higher overall incidence of 8.6% in a cohort of 1800 eyes. Vision-threatening complications were infrequent in our cohort, including diffuse lamellar keratitis (0.34%), corneal erosions (0.34%), and staphylococcal marginal keratitis (0.17%), as were minor complications like microstriae (0.96%). These rates were within the FDA-recommended



threshold of less than 1% incidence for each complication [1]. However, the most common etiology for complications in the large international studies was interface haze (trace to grade II), with an average incidence rate of 9.9% [19, 21, 22]. Our rate of suction loss (0.2%) was also lower compared to the 0.8% suction loss rate found in studies by Reinstein et al. [19] and Ivarsen et al. [6]. In our study, 17 eyes (2.9%) required PRK enhancement within one year following KLEx, a rate that closely aligns with the findings of Liu et al. [38], who reported an overall enhancement rate of 2.7% among 524 eyes. Epithelial defects (2.42%) occurred at a higher rate than other complications in our cohort, but still less frequently than the average incidence rate of 3.3% of eyes treated with KLEx [39]. Taneri et al. [21] experienced an epithelial defect rate of 26.2%; however, these resolved by the following day. In comparison, the rate of epithelial defects in LASIK ranges from 0.6% to 14.0% [39]. Given the increased risk of subsequent ingrowth or recurrent corneal erosions depending on the defect location, a low threshold for bandage contact lens placement is advised [40].

Limitations of our study include its retrospective, single-center design. There were 71 eyes (16%) lost to follow-up between 3 and 12 months, which potentially introduced attrition bias [41]. This may, in part, be due to patient satisfaction with early postoperative outcomes. Our study cohort was within the broader investigational ranges used in the pivotal PMA clinical trials (−1.00 D to −10.00 D sphere, up to −0.50 D cylinder, MRSE ≤ −10.25) [1]. However, these parameters extend beyond the narrower ranges specified in the current FDA-approved labeling (−1.00 D to −8.00 D sphere, up to −0.50 D cylinder, MRSE ≤ −8.25). As such, a portion of our population falls outside the approved treatment indications, which may limit the generalizability of the results. Another limitation is the inclusion of both eyes in the analysis, rather than single-eye randomization, which some may argue could bias findings. Not all eyes contributed data at every time point due to loss to follow-up, resulting in unbalanced longitudinal data. To address this, we used GEE, which provides population-level estimates under the assumption that the data are missing at random [42]. This statistical approach allowed us to use all available data rather than limiting the sample to complete cases only, which increased our statistical power. In addition, the procedures were performed by two surgeons, whose surgical techniques may vary slightly.

Given that KLEx is a relatively new platform with limited large-scale studies evaluating its visual outcomes, we compared our results to the FDA criteria, the PMA clinical trials, and other large-cohort studies. Despite most published literature originating from Asia and Europe [43], our U.S. study established the safety, efficacy, and refractive predictability of KLEx at both the 3- and 12-month postoperative visits.

## CONCLUSIONS

The visual and refractive outcomes observed in this large, single-site U.S. cohort met or exceeded the FDA criteria and are consistent with other large international studies, though there is a potential need for refined cylindrical correction. This study supports KLEx as a safe, effective, and stable procedure in a North American population, where long-term data remain relatively limited.

## ETHICAL DECLARATIONS

**Ethical approval:** Full approval was granted by the Biomedical Research Alliance of New York Institutional Review Board (# A20-12-547-823). The study adhered to the tenets of the Declaration of Helsinki, and HIPAA regulations were followed. All patients provided written informed consent prior to their inclusion in the study.

**Conflict of interest:** None.

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## REFERENCES

1. FDA SSED SMILE (VisuMax) (2026). 'Device: VISUMAX FEMTOSECOND LASER; Generic Name: Femtosecond laser system for refractive correction; Premarket Approval (PMA) P150040. Available at: <https://www.accessdata.fda.gov/scripts/cdrh/cfdocs/cfpma/pma.cfm?id=P150040> (Accessed June 12, 2025)
2. Sekundo W, Kunert K, Russmann C, Gille A, Bissmann W, Stobrawa G, Sticker M, Bischoff M, Blum M. First efficacy and safety study of femtosecond lenticule extraction for the correction of myopia: six-month results. J

- Cataract Refract Surg. 2008 Sep;34(9):1513-20. doi: [10.1016/j.jcrs.2008.05.033](https://doi.org/10.1016/j.jcrs.2008.05.033). Erratum in: J Cataract Refract Surg. 2008 Nov;34(11):1819. PMID: [18721712](https://pubmed.ncbi.nlm.nih.gov/18721712/).
3. Reinstein DZ, Archer TJ, Gobbe M. Small incision lenticule extraction (SMILE) history, fundamentals of a new refractive surgery technique and clinical outcomes. Eye Vis (Lond). 2014 Oct 16;1:3. doi: [10.1186/s40662-014-0003-1](https://doi.org/10.1186/s40662-014-0003-1). PMID: [26605350](https://pubmed.ncbi.nlm.nih.gov/26605350/); PMCID: [PMC4604118](https://pubmed.ncbi.nlm.nih.gov/PMC4604118/).
  4. Wang Y, Ma J, Zhang J, Dou R, Zhang H, Li L, Zhao W, Wei P. Incidence and management of intraoperative complications during small-incision lenticule extraction in 3004 cases. J Cataract Refract Surg. 2017 Jun;43(6):796-802. doi: [10.1016/j.jcrs.2017.03.039](https://doi.org/10.1016/j.jcrs.2017.03.039). PMID: [28732614](https://pubmed.ncbi.nlm.nih.gov/28732614/).
  5. Krueger RR, Meister CS. A review of small incision lenticule extraction complications. Curr Opin Ophthalmol. 2018 Jul;29(4):292-298. doi: [10.1097/ICU.0000000000000494](https://doi.org/10.1097/ICU.0000000000000494). PMID: [29782336](https://pubmed.ncbi.nlm.nih.gov/29782336/).
  6. Ivarsen A, Asp S, Hjortdal J. Safety and complications of more than 1500 small-incision lenticule extraction procedures. Ophthalmology. 2014 Apr;121(4):822-8. doi: [10.1016/j.ophtha.2013.11.006](https://doi.org/10.1016/j.ophtha.2013.11.006). Epub 2013 Dec 21. PMID: [24365175](https://pubmed.ncbi.nlm.nih.gov/24365175/).
  7. Liu ET, Sella R, Goernert P, Kim K, Chen H, Lin RT. Refractive results with SMILE using lower energy settings in the United States. PLoS One. 2021 Oct 22;16(10):e0258835. doi: [10.1371/journal.pone.0258835](https://doi.org/10.1371/journal.pone.0258835). PMID: [34679121](https://pubmed.ncbi.nlm.nih.gov/34679121/); PMCID: [PMC8535172](https://pubmed.ncbi.nlm.nih.gov/PMC8535172/).
  8. Dishler JG, Slade S, Seifert S, Schallhorn SC. Small-Incision Lenticule Extraction (SMILE) for the Correction of Myopia with Astigmatism: Outcomes of the United States Food and Drug Administration Premarket Approval Clinical Trial. Ophthalmology. 2020 Aug;127(8):1020-1034. doi: [10.1016/j.ophtha.2020.01.010](https://doi.org/10.1016/j.ophtha.2020.01.010). Epub 2020 Jan 15. PMID: [32173114](https://pubmed.ncbi.nlm.nih.gov/32173114/).
  9. Chuckpaiwong V, Chansue E, Lekhanont K, Tanehsakdi M, Jongkhajornpong P, Nonpassopon M. 12-Month Outcomes of Small Incision Lenticule Extraction With Proper Head Positioning but No Reference Marking for the Correction of Astigmatism. J Refract Surg. 2023 Oct;39(10):683-692. doi: [10.3928/1081597X-20230824-01](https://doi.org/10.3928/1081597X-20230824-01). Epub 2023 Oct 1. PMID: [37824301](https://pubmed.ncbi.nlm.nih.gov/37824301/).
  10. Reinstein DZ, Carp GI, Archer TJ, Vida RS, Yammouni R. Large Population Outcomes of Small Incision Lenticule Extraction in Young Myopic Patients. J Refract Surg. 2022 Aug;38(8):488-496. doi: [10.3928/1081597X-20220623-01](https://doi.org/10.3928/1081597X-20220623-01). Epub 2022 Aug 1. PMID: [35947004](https://pubmed.ncbi.nlm.nih.gov/35947004/).
  11. Waring GO 3rd, Reinstein DZ, Dupps WJ Jr, Kohnen T, Mamalis N, Rosen ES, Koch DD, Obstbaum SA, Stulting RD. Standardized graphs and terms for refractive surgery results. J Refract Surg. 2011 Jan;27(1):7-9. doi: [10.3928/1081597X-20101116-01](https://doi.org/10.3928/1081597X-20101116-01). Erratum in: J Refract Surg. 2011 Feb;27(2):88. PMID: [21229953](https://pubmed.ncbi.nlm.nih.gov/21229953/).
  12. Gauvin M, Wallerstein A. mEYEstro software: an automatic tool for standardized refractive surgery outcomes reporting. BMC Ophthalmol. 2023 Apr 21;23(1):171. doi: [10.1186/s12886-023-02904-6](https://doi.org/10.1186/s12886-023-02904-6). PMID: [37085797](https://pubmed.ncbi.nlm.nih.gov/37085797/); PMCID: [PMC10120175](https://pubmed.ncbi.nlm.nih.gov/PMC10120175/).
  13. Li HY, Ye Z, Li ZH. Postoperative efficacy, safety, predictability, and visual quality of implantable collamer lens implantation versus small incision lenticule extraction in myopic eyes: a Meta-analysis. Int J Ophthalmol. 2023 Mar 18;16(3):442-452. doi: [10.18240/ijo.2023.03.16](https://doi.org/10.18240/ijo.2023.03.16). PMID: [36935780](https://pubmed.ncbi.nlm.nih.gov/36935780/); PMCID: [PMC10009601](https://pubmed.ncbi.nlm.nih.gov/PMC10009601/).
  14. Ramirez-Miranda A, Mota AD, Rosa GG, Serna-Ojeda JC, Valdez-García JE, Fábregas-Sánchez-Woodworth D, Navas A, Jiménez-Corona A, Graue-Hernandez EO. Visual and refractive outcomes after SMILE versus FS-LASIK: a paired-eye study. Cir Cir. 2024;92(6):758-768. English. doi: [10.24875/CIRU.23000261](https://doi.org/10.24875/CIRU.23000261). PMID: [39591576](https://pubmed.ncbi.nlm.nih.gov/39591576/).
  15. Titiyal JS, Kaur M, Rath A, Falera R, Chaniyara M, Sharma N. Learning Curve of Small Incision Lenticule Extraction: Challenges and Complications. Cornea. 2017 Nov;36(11):1377-1382. doi: [10.1097/ICO.0000000000001323](https://doi.org/10.1097/ICO.0000000000001323). PMID: [28799958](https://pubmed.ncbi.nlm.nih.gov/28799958/).
  16. Ganesh S, Brar S, Arra RR. Refractive lenticule extraction small incision lenticule extraction: A new refractive surgery paradigm. Indian J Ophthalmol. 2018 Jan;66(1):10-19. doi: [10.4103/ijo.IJO\\_761\\_17](https://doi.org/10.4103/ijo.IJO_761_17). PMID: [29283117](https://pubmed.ncbi.nlm.nih.gov/29283117/); PMCID: [PMC5778540](https://pubmed.ncbi.nlm.nih.gov/PMC5778540/).
  17. Pedersen IB, Ivarsen A, Hjortdal J. Changes in Astigmatism, Densitometry, and Aberrations After SMILE for Low to High Myopic Astigmatism: A 12-Month Prospective Study. J Refract Surg. 2017 Jan 1;33(1):11-17. doi: [10.3928/1081597X-20161006-04](https://doi.org/10.3928/1081597X-20161006-04). PMID: [28068441](https://pubmed.ncbi.nlm.nih.gov/28068441/).
  18. Zhang J, Wang Y, Wu W, Xu L, Li X, Dou R. Vector analysis of low to moderate astigmatism with small incision lenticule extraction (SMILE): results of a 1-year follow-up. BMC Ophthalmol. 2015 Jan 24;15:8. doi: [10.1186/1471-2415-15-8](https://doi.org/10.1186/1471-2415-15-8). PMID: [25618419](https://pubmed.ncbi.nlm.nih.gov/25618419/); PMCID: [PMC4328987](https://pubmed.ncbi.nlm.nih.gov/PMC4328987/).

19. Reinstein DZ, Carp GI, Archer TJ, Gobbe M. Outcomes of small incision lenticule extraction (SMILE) in low myopia. *J Refract Surg.* 2014 Dec;30(12):812-8. doi: [10.3928/1081597X-20141113-07](https://doi.org/10.3928/1081597X-20141113-07). Erratum in: *J Refract Surg.* 2015 Jan;31(1):60. Erratum in: *J Refract Surg.* 2015 Jan;31(1):60. doi: [10.3928/1081597X-20141229-02](https://doi.org/10.3928/1081597X-20141229-02). PMID: [25437479](https://pubmed.ncbi.nlm.nih.gov/25437479/).
20. Wu W, Wang Y, Zhang H, Zhang J, Li H, Dou R. One-year visual outcome of small incision lenticule extraction (SMILE) surgery in high myopic eyes: retrospective cohort study. *BMJ Open.* 2016 Sep 21;6(9):e010993. doi: [10.1136/bmjopen-2015-010993](https://doi.org/10.1136/bmjopen-2015-010993). PMID: [27655258](https://pubmed.ncbi.nlm.nih.gov/27655258/); PMCID: [PMC5051337](https://pubmed.ncbi.nlm.nih.gov/PMC5051337/).
21. Taneri S, Kießler S, Rost A, Schultz T, Dick HB. Small-incision lenticule extraction for the correction of myopic astigmatism. *J Cataract Refract Surg.* 2019 Jan;45(1):62-71. doi: [10.1016/j.jcrs.2018.08.030](https://doi.org/10.1016/j.jcrs.2018.08.030). Epub 2018 Nov 10. PMID: [30424903](https://pubmed.ncbi.nlm.nih.gov/30424903/).
22. Kamiya K, Takahashi M, Nakamura T, Kojima T, Toda I, Kariya M. A Multicenter Study on Early Outcomes of Small-Incision Lenticule Extraction for Myopia. *Sci Rep.* 2019 Mar 11;9(1):4067. doi: [10.1038/s41598-019-40805-1](https://doi.org/10.1038/s41598-019-40805-1). PMID: [30858493](https://pubmed.ncbi.nlm.nih.gov/30858493/); PMCID: [PMC6411974](https://pubmed.ncbi.nlm.nih.gov/PMC6411974/).
23. Hjortdal JØ, Vestergaard AH, Ivarsen A, Ragunathan S, Asp S. Predictors for the outcome of small-incision lenticule extraction for Myopia. *J Refract Surg.* 2012 Dec;28(12):865-71. doi: [10.3928/1081597X-20121115-01](https://doi.org/10.3928/1081597X-20121115-01). PMID: [23231737](https://pubmed.ncbi.nlm.nih.gov/23231737/).
24. Hansen RS, Lyhne N, Grauslund J, Vestergaard AH. Small-incision lenticule extraction (SMILE): outcomes of 722 eyes treated for myopia and myopic astigmatism. *Graefes Arch Clin Exp Ophthalmol.* 2016 Feb;254(2):399-405. doi: [10.1007/s00417-015-3226-5](https://doi.org/10.1007/s00417-015-3226-5). Epub 2015 Nov 20. PMID: [26589231](https://pubmed.ncbi.nlm.nih.gov/26589231/).
25. Gomel N, Negari S, Frucht-Pery J, Wajnsztajn D, Strassman E, Solomon A. Predictive factors for efficacy and safety in refractive surgery for myopia. *PLoS One.* 2018 Dec 14;13(12):e0208608. doi: [10.1371/journal.pone.0208608](https://doi.org/10.1371/journal.pone.0208608). PMID: [30550575](https://pubmed.ncbi.nlm.nih.gov/30550575/); PMCID: [PMC6294382](https://pubmed.ncbi.nlm.nih.gov/PMC6294382/).
26. Vestergaard A, Ivarsen AR, Asp S, Hjortdal JØ. Small-incision lenticule extraction for moderate to high myopia: Predictability, safety, and patient satisfaction. *J Cataract Refract Surg.* 2012 Nov;38(11):2003-10. doi: [10.1016/j.jcrs.2012.07.021](https://doi.org/10.1016/j.jcrs.2012.07.021). Epub 2012 Sep 14. PMID: [22981612](https://pubmed.ncbi.nlm.nih.gov/22981612/).
27. Liu J, Lu Y, Liu J, Wei C. Meta-analysis of efficacy, safety, stability and predictability of Small Incision Lenticule Extraction (SMILE) for myopia. *Lasers Med Sci.* 2024 Feb 8;39(1):57. doi: [10.1007/s10103-024-04007-0](https://doi.org/10.1007/s10103-024-04007-0). PMID: [38329555](https://pubmed.ncbi.nlm.nih.gov/38329555/).
28. Ivarsen A, Hjortdal J. Correction of myopic astigmatism with small incision lenticule extraction. *J Refract Surg.* 2014 Apr;30(4):240-7. doi: [10.3928/1081597X-20140320-02](https://doi.org/10.3928/1081597X-20140320-02). PMID: [24702575](https://pubmed.ncbi.nlm.nih.gov/24702575/).
29. Yoo TK, Kim D, Kim JS, Kim HS, Ryu IH, Lee IS, Kim JK, Na KH. Comparison of early visual outcomes after SMILE using VISUMAX 800 and VISUMAX 500 for myopia: a retrospective matched case-control study. *Sci Rep.* 2024 May 25;14(1):11989. doi: [10.1038/s41598-024-62354-y](https://doi.org/10.1038/s41598-024-62354-y). PMID: [38796537](https://pubmed.ncbi.nlm.nih.gov/38796537/); PMCID: [PMC11127987](https://pubmed.ncbi.nlm.nih.gov/PMC11127987/).
30. Khalifa MA, Ghoneim AM, Shaheen MS, Piñero DP. Vector analysis of astigmatic changes after small-incision lenticule extraction and wavefront-guided laser in situ keratomileusis. *J Cataract Refract Surg.* 2017 Jun;43(6):819-824. doi: [10.1016/j.jcrs.2017.03.033](https://doi.org/10.1016/j.jcrs.2017.03.033). PMID: [28732617](https://pubmed.ncbi.nlm.nih.gov/28732617/).
31. Ganesh S, Brar S, Pawar A. Results of Intraoperative Manual Cyclotorsion Compensation for Myopic Astigmatism in Patients Undergoing Small Incision Lenticule Extraction (SMILE). *J Refract Surg.* 2017 Aug 1;33(8):506-512. doi: [10.3928/1081597X-20170328-01](https://doi.org/10.3928/1081597X-20170328-01). PMID: [28787514](https://pubmed.ncbi.nlm.nih.gov/28787514/).
32. FDA SSED WaveLight ALLEGRETTO Wave (2003). 'Device: WAVELIGHT ALLEGRETTO WAVE EXCIMER LASER SYSTEM; Generic Name: Excimer laser system Premarket Approval (PMA) P020050'. Available at: <https://www.accessdata.fda.gov/scripts/cdrh/cfdocs/cfpma/pma.cfm?id=P020050> (Accessed June 23, 2025).
33. Yu N, Hou X, Liu C, Chen P, Ye Y, Lan M, Zhuang J, Yu K. A Nomogram to Improve the Predictability of High Myopic Astigmatism in Small Incision Lenticule Extraction Surgery. *J Refract Surg.* 2025 Jan;41(1):e65-e72. doi: [10.3928/1081597X-20241126-01](https://doi.org/10.3928/1081597X-20241126-01). Epub 2025 Jan 1. PMID: [39783819](https://pubmed.ncbi.nlm.nih.gov/39783819/).
34. Varman A, Varman A, Balakumar D. Comparison of Visual and Refractive Outcomes of Keratorefractive Lenticule Extraction for Compound Myopic Astigmatism Between VisuMax and VISUMAX 800. *Clin Ophthalmol.* 2024 Nov 30;18:3557-3566. doi: [10.2147/OPTH.S492552](https://doi.org/10.2147/OPTH.S492552). PMID: [39635258](https://pubmed.ncbi.nlm.nih.gov/39635258/); PMCID: [PMC11616419](https://pubmed.ncbi.nlm.nih.gov/PMC11616419/).
35. Manion GN, Moin KA, Brown AH, Olson TV, Kezirian GM, Hoopes PC, Moshirfar M. Preoperative Risk Factors of Keratometry, Myopia, Astigmatism, Age, and Sex for Myopic Regression After Laser-Assisted In Situ

- Keratomileusis, Photorefractive Keratectomy, and Keratorefractive Lenticule Extraction. *Cornea*. 2025 Nov 1;44(11):1367-1375. doi: [10.1097/ICO.0000000000003874](https://doi.org/10.1097/ICO.0000000000003874). Epub 2025 Apr 8. PMID: 40199570.
36. Blum M, Lauer AS, Kunert KS, Sekundo W. 10-Year Results of Small Incision Lenticule Extraction. *J Refract Surg*. 2019 Oct 1;35(10):618-623. doi: [10.3928/1081597X-20190826-02](https://doi.org/10.3928/1081597X-20190826-02). PMID: 31610002.
  37. Xia F, Chen Z, Miao H, Wei R, Li M, Zhao J, Zhou X. Ten-year outcomes following small incision lenticule extraction for up to -10Dioptres myopia. *Clin Exp Optom*. 2024 Apr;107(3):285-290. doi: [10.1080/08164622.2023.2203313](https://doi.org/10.1080/08164622.2023.2203313). Epub 2023 May 16. PMID: 37194118.
  38. Liu YC, Rosman M, Mehta JS. Enhancement after Small-Incision Lenticule Extraction: Incidence, Risk Factors, and Outcomes. *Ophthalmology*. 2017 Jun;124(6):813-821. doi: [10.1016/j.ophtha.2017.01.053](https://doi.org/10.1016/j.ophtha.2017.01.053). Epub 2017 Mar 15. PMID: 28318639.
  39. Moshirfar M, Santos JM, Wang Q, Stoakes IM, Porter KB, Theis JS, Hoopes PC. A Literature Review of the Incidence, Management, and Prognosis of Corneal Epithelial-Related Complications After Laser-Assisted In Situ Keratomileusis (LASIK), Photorefractive Keratectomy (PRK), and Small Incision Lenticule Extraction (SMILE). *Cureus*. 2023 Aug 22;15(8):e43926. doi: [10.7759/cureus.43926](https://doi.org/10.7759/cureus.43926). PMID: 37614825; PMCID: PMC10443604.
  40. Moshirfar M, Zhang S, Pandya S, Stoakes IM, Hoopes PC. Incidence and Management of Epithelial-Related Complications After SMILE. *Clin Ophthalmol*. 2023 Sep 20;17:2777-2789. doi: [10.2147/OPTH.S426547](https://doi.org/10.2147/OPTH.S426547). PMID: 37750098; PMCID: PMC10518173.
  41. Schallhorn JM, Schallhorn SC, Hannan SJ. Impact of Refractive Outcomes on Bias in Follow-up and Completion of Patient-Reported Outcome Measures after Laser Vision Correction. *Ophthalmology*. 2021 Sep;128(9):1284-1291. doi: [10.1016/j.ophtha.2021.01.030](https://doi.org/10.1016/j.ophtha.2021.01.030). Epub 2021 Feb 2. PMID: 33545171.
  42. Liang KY, Zeger SL. Longitudinal data analysis using generalized linear models. *Biometrika*. 1986 Apr 1;73(1):13-22. doi: [10.1093/biomet/73.1.13](https://doi.org/10.1093/biomet/73.1.13).
  43. Han T, Zhao L, Shen Y, Chen Z, Yang D, Zhang J, Sekundo W, Shah R, Tian J, Zhou X. Twelve-year global publications on small incision lenticule extraction: A bibliometric analysis. *Front Med (Lausanne)*. 2022 Sep 8;9:990657. doi: [10.3389/fmed.2022.990657](https://doi.org/10.3389/fmed.2022.990657). PMID: 36160168; PMCID: PMC9493269.