ARTICLE

Comparison of early visual outcomes after low-energy SMILE, high-energy SMILE, and LASIK for myopia and myopic astigmatism in the United States

D. Rex Hamilton, MD, MS, Angela C. Chen, BS, Roxana Khorrami, OD, Max Nutkiewicz, BS, Mitra Nejad, MD

Purpose: To compare uncorrected distance visual acuities (UDVAs) and induced higher-order aberrations (HOAs) in the early postoperative period between low-energy (LE) small-incision lenticule extraction (SMILE), high-energy (HE) SMILE, and femtosecond laser–assisted laser in situ keratomileusis (FS-LASIK) procedures.

Setting: University based refractive surgery center.

Study design: Retrospective cohort study.

Methods: Records of patients who underwent SMILE or FS-LASIK were retrospectively reviewed. SMILE patients were separated into 2 groups: HE settings (125 nJ, 3.0 μm spot spacing) and LE settings (125-130 nJ, 4.5 μm spot spacing). UDVA was measured at postoperative day (POD) 1. Corneal HOAs and UDVA were measured at postoperative month (POM) 1. Induced spherical aberration, vertical coma, horizontal coma, total coma, and total HOAs were calculated.

Results: The study included 147 eyes of 106 patients, 49 in each group. For SMILE patients, the difference in mean UDVA at POD1 was highly statistically significant in favor of the LE group (−0.003 vs 0.141, $P < .0001$). No significant difference in mean UDVA at POD1 was noted between the LE group and FS-LASIK group (−0.003 vs −0.011, $P = .498$). Induced change in spherical aberration was less in LE SMILE than that in FS-LASIK (0.136 vs 0.186 μm, $P = .02$) at POM1. No significant differences in POM1 mean UDVA (−0.033 vs −0.036) or induced change in all other HOAs were noted between LE SMILE and FS-LASIK.

Conclusions: LE settings were associated with significantly improved POD1 UDVA. POD1 and POM1 UDVA were comparable with those of FS-LASIK. Spherical aberration induction was less with LE SMILE than that with FS-LASIK, whereas all other induced HOAs were comparable with FS-LASIK.

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Small-incision lenticule extraction (SMILE) has been growing in popularity globally, but adoption rates in the United States have been slow since its initial U.S. Food and Drug Administration (FDA) approval for myopia in 2016 and myopic astigmatism in 2018. Numerous studies have shown similar long-term predictability and safety results between SMILE and femtosecond laser–assisted laser in situ keratomileusis (FS-LASIK),[1–6] and some studies have demonstrated unique advantages to SMILE, including shorter duration of postoperative dry-eye symptoms and faster recovery of corneal sensation.[7–10] One of the main barriers to higher adoption rates of SMILE has been a slower visual recovery postoperatively, with postoperative day (POD) 1 visual acuity reported to be lower than that of LASIK.[9,11] Therefore, despite similar visual acuity outcomes at 1 month, LASIK surgeons are used to the "wow factor" achieved on POD1 and, consequently, have been reluctant to adopt the newer SMILE technique. In addition, there are conflicting reports on whether SMILE or LASIK induces more higher-order aberrations (HOAs), which can play a significant role in long-term visual quality and patient satisfaction.[12–15]

In October 2018, the U.S. FDA approved new indications for SMILE (myopia up to 10 diopters [D] and astigmatism up to 3 D) and new parameters for laser settings. Specifically, the incision size can be shortened to 60 degrees from 90 degrees, and more importantly, spot spacing can be

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From the Stein Eye Institute, David Geffen School of Medicine, University of California, Los Angeles (Chen, Khorrami, Nejad), Los Angeles, and Hamilton Eye Institute (Hamilton, Nutkiewicz), Los Angeles, California, USA.

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Corresponding author: D. Rex Hamilton, MD, MS, Hamilton Eye Institute, 10884 Santa Monica Boulevard, Los Angeles, CA 90025. Email: rex@rexhamiltonmd.com

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increased from 3.0 to 4.5 μm, allowing for a significant lower-energy (LE) deposition to the cornea (LE SMILE). The purpose of this study was to directly address the apprehension of U.S. LASIK surgeons by comparing the early visual acuity results of LE SMILE (wider spot spacing and LE deposition) with SMILE with the previous tighter spot spacing settings (higher-energy deposition [HE SMILE]) and with wavefront-optimized FS-LASIK. We hypothesized that LE SMILE would allow patients to achieve improvements in POD1 vision compared with those by HE SMILE and which are comparable with those seen with LASIK. In addition, we hypothesized that LE SMILE would induce HOAs of a similar magnitude as with FS-LASIK.

METHODS

Institutional Review Board (IRB)/Ethics Committee approval was obtained at the University of California, Los Angeles (IRB #19-00364), prior to the initiation of this study. Medical records of patients who had SMILE or LASIK for surgical correction of myopia or myopic astigmatism performed by a single surgeon (D.R.H.) were retrospectively reviewed. All patients who had SMILE from June 2017 to January 2019 were reviewed. Patients who had myopic FS-LASIK with the same surgeon (D.R.H.) during a similar date range were also reviewed. Patients who had other ocular diseases, abnormal topography, or preoperative corrected distance visual acuities (CDVAs) less than 20/20 were excluded.

Preoperative and Postoperative Evaluations

All patients were evaluated in clinic following a standard preoperative assessment for refractive surgery. A full ophthalmic examination was performed, including uncorrected distance vision (UDVA), CDVA, manifest and cycloplegic refraction, slit-lamp evaluation, tonometry (Goldman applanation), and fundoscopy. Visual acuity measurements were completed using an illuminated Snellen chart, and topography was performed using a Galilei G4 topographer (Ziemer Ophthalmic Systems AG). Corneal HOAs measured at a 6.0 mm optical zone on the Galilei G4 topographer were recorded. Data from follow-up visits at 1 day and 1 month were included in the study. Postoperative data recorded included UDVA at POD1 and UDVA, CDVA, manifest refraction, and corneal HOAs at postoperative month (POM) 1.

With myopic astigmatism approval for SMILE in 2018, cylinder of 0.75 D or greater can be treated, whereas cylinder of less than 0.75 D cannot be treated. For all patients considering SMILE, those with manifest cylinder of 0.5 D were shown both full cylinder correction and sphere-only correction (adjusted to manifest spherical equivalent). If the patient preferred the full cylinder correction or had topographic cylinder of greater than 0.5 D in the same axis as the manifest axis, the patient was treated with LASIK. If the patient did not have a preference and had topographic cylinder of 0.5 D or less, they were treated with SMILE with no cylinder correction.

Surgical Technique

For the LASIK procedure, the VisuMax 500 kHz femtosecond laser (Carl Zeiss Meditec AG) was used to create an 8.1 mm diameter, 110 μm flap with a superior or temporal hinge, and a 50-degree hinge angle. Ablations were performed using an Allegretto EX500 laser (Alcon Laboratories, Inc.) using a wavefront-optimized algorithm with a 6.5 mm optical zone and 1.25 mm blend zone. For the SMILE procedure, the VisuMax laser was programmed with the following parameters: 6.5 mm lenticule diameter, 7.5 mm cap diameter, 120 μm thickness, 60- to 90-degree incision angle, 90-degree incision position, 15 μm minimum lenticule edge thickness, and 90-degree side-cut angle for both the incision and the lenticule. No calculated residual stromal beds were less than 260 μm. Lenticular dissection was performed using a standard technique described in detail in the literature.[16] To maximize efforts for proper centration of the lenticule over the visual axis, the position of the visual axis relative to the pupil from the Verify image on the Galilei topographer was printed out and used as a visual guide during applanation of the cornea with the VisuMax patient interface prior to firing the laser. Postoperatively, all patients received topical 0.5% moxifloxacin (Vigamox) and topical difluprednate ophthalmic suspension (Durezol) to use 3 times daily for 1 week. All surgeries were performed by a single surgeon (D.R.H.).

Chart Review and Grouping

Patient age and preoperative manifest sphere, cylinder, and axis were recorded. Total coma (TC), vertical coma (VC), horizontal coma (HC), spherical aberration (SA), and total higher-order aberrations (THOAs) were recorded. All operative notes were reviewed, and sphere, cylinder, axis treated, and target refraction were recorded. An optical zone of 6.5 mm with a 1.25 mm transition zone was used for all FS-LASIK cases. For SMILE cases, the lenticule size, cap parameters (diameter, thickness, and side-cut angle) and incision parameters (position, angle, and width) were recorded, as were the laser energy level and spot spacing. POD1 and POM1 UDVA and POM1 corneal aberrations using the same topographer were noted.

For the SMILE patients, the energy density, a measure of the total energy deposited into the cornea during the laser treatment, was determined from the combination of spot energy and spot separation through a proprietary calculation provided by Carl Zeiss Meditec AG. SMILE patients were divided into 2 groups based on the total energy density used: low-energy density (LE) (<10) or high-energy density (HE) (>10).

The LE SMILE group had the fewest eyes (49) meeting the above-mentioned criteria because the study was initiated soon after implementation of the newer, LE settings were made available with the myopic astigmatism approval. It became qualitatively apparent that the POD1 UDVAs were improved with lowered energy settings than what had been observed previously with LE settings. A power study was conducted on 13 eyes from each of the LE SMILE and HE SMILE groups to determine the sample size required to detect a statistically significant difference in mean UDVA on POD1 (http://poweranalysis.com/Calculators/Compare-2-Means/2-Sample-Equality). Based on this calculation, a sample size of 37 eyes would provide a power of 95% with a 5% type I error rate. With a sample size of 49 eyes, the power was calculated to be 99% with a 5% type I error rate. To avoid biasing the LASIK and HE SMILE groups toward worse UDVA by including eyes with higher MRSE attempted corrections, eyes were chosen from the FS-LASIK and HE SMILE group using 1:1 matching of the preoperative MRSE treated in the LE SMILE group. One-to-one matching was also used to match astigmatic attempted correction between the FS-LASIK and the LE SMILE groups. Because cylinder treatment was approved simultaneously with wider spot spacing, nearly all of the HE SMILE eyes were performed prior to the approval of cylinder correction. Therefore, it was not possible to match the astigmatic attempted correction between the HE SMILE group and the other groups.

Statistical Analysis

Visual acuities were converted to logarithm of the minimum angle of resolution (logMAR) before the statistical analysis. Statistical analysis, *P* values, and associated graphics were generated using Microsoft Excel (2017, Microsoft Corp.). Pairwise *t* test was performed to evaluate differences between 2 groups (LE SMILE vs HE SMILE and LE SMILE vs FS-LASIK) and analysis of variance was used to evaluate differences between all 3 groups. Minimum detectable mean differences were calculated for pairwise *t* tests

Table 1. Preoperative characteristics.

Parameter	Low-Energy SMILE (n = 49)	High-Energy SMILE (n = 49)	FS-LASIK (n = 49)	*P* Value (ANOVA)
Age, years	31.6 ± 6.3	29.1 ± 5.1	31.0 ± 4.7	.062
Range	20, 45	19, 39	22, 41	
Preop sphere (D)	−3.77 ± 1.60	−4.02 ± 1.39	−3.75 ± 1.55	.610
Range	−8.00, −0.50	−8.00, −2.25	−7.50, −0.50	
Preop cylinder (D)	−0.50 ± 0.46	−0.10 ± 0.19	−0.66 ± 0.50	<.0001*
Range	−1.75, 0	−0.50, 0	−1.75, 0	
Preop MRSE (D)	−4.02 ± 1.55	−4.07 ± 1.43	−4.08 ± 1.52	.980
Range	−8.00, −1.13	−8.00, −2.25	−7.50, −1.13	

ANOVA = analysis of variance; FS-LASIK = femtosecond laser–in situ keratomileusis; MRSE = mean refraction spherical equivalent; preop = preoperative; SMILE = small-incision lenticule extraction
*Statistically significant difference.

that resulted in a nonsignificant *P* value using SAS statistical software (SAS Institute, Inc.).

RESULTS

For this study, 376 charts were reviewed. In total, 173 eyes that underwent SMILE and 136 eyes that underwent LASIK met the inclusion criteria. Of the SMILE eyes, 49 qualified for the LE SMILE group and 124 qualified for the HE SMILE group. Mean energy densities for the 2 groups were 6.2 for LE SMILE group and 13.9 for HE SMILE group. The LE SMILE group included eyes that underwent SMILE with laser settings of 4.5 spot spacing and 125 to 130 nJ energy per spot. The HE SMILE group included eyes that underwent SMILE with laser settings of 3.0 spot spacing and 125 nJ energy per spot. All surgeries were uneventful, and there were no significant postoperative complications. SMILE surgeries with 4.5 spot spacing had less treatment time under the femtosecond laser than SMILE surgeries with 3.0 spot spacing (24 to 25 vs 38 to 40 seconds). Thirteen patients from LE SMILE group 12 patients from HE SMILE group and 10 patients from the LASIK group did not have postoperative topographies. Preoperative HOAs of only the eyes that had POM1 data were analyzed.

Table 1 summarizes the preoperative demographics and characteristics. There was no significant difference in age. Preoperative mean sphere and spherical equivalent were statistically similar between all 3 groups; however, preoperative cylinder was lower in the HE SMILE group as expected. Preoperative HOAs are reported in Table 2. There was no significant difference in preoperative total HOAs, SA, TC, VC, and HC between the 3 groups.

Visual Acuity

Table 3 tabulates the mean postoperative UDVA at POD1 and POM1 for the 3 study groups. Among patients who had SMILE, the difference in mean UDVA at POD1 was highly statistically significant in favor of the LE SMILE group ($P < .0001$). In addition, the mean UDVA at POD1 in the LE SMILE group was not statistically significantly different than that of the FS-LASIK group ($P = .498$). The minimum mean detectable difference was 0.03 logMAR (ie, one third of a Snellen line) and 0.05 logMAR (one half of a Snellen line) for 80% and 99% power, respectively. Similarly, the statistical difference in favor of the LE SMILE group over the HE SMILE group was maintained at the POM1 timepoint. The lack of difference between the LE SMILE group and FS-LASIK group was also maintained at the POM1 timepoint ($P = .868$). The residual refractive error (ie, the difference between the target and the postoperative mean refractive spherical equivalent) was more myopic in the LE SMILE group (−0.16) compared with that of the FS-LASIK group (−0.06).

Table 2. Preoperative higher-order aberrations.

Parameter	Low-Energy SMILE (n = 36)	High-Energy SMILE (n = 37)	FS-LASIK (n = 38)	*P* Value (ANOVA)
Preop total HOAs (μm)	0.39 ± 0.12	0.40 ± 0.12	0.38 ± 0.12	.957
Range	0.25, 0.80	0.18, 0.68	0.24, 0.91 μm	
Preop spherical aberration (μm)	0.18 ± 0.06	0.21 ± 0.04	0.20 ± 0.06	.089
Range	0.05, 0.29	0.08, 0.28	0.10, 0.32	
Preop total coma (μm)	0.23 ± 0.09	0.25 ± 0.15	0.24 ± 0.10	.197
Range	0.06, 0.41	0.04, 0.54	0.03, 0.58	
Preop horizontal coma (μm)	−0.002 ± 0.16	0.04 ± 0.22	−0.01 ± 0.20	.462
Range	−0.41, 0.34	−0.37, 0.53	−0.37, 0.58	
Preop vertical coma (μm)	−0.03 ± 0.19	−0.02 ± 0.19	−0.03 ± 0.17	.927
Range	−0.30, 0.36	−0.35, 0.52	−0.30, 0.31	

ANOVA = analysis of variance; HOA = higher-order aberrations; FS-LASIK = femtosecond laser–in situ keratomileusis; preop = preoperative; SMILE = small-incision lenticule extraction

Table 3. Postoperative uncorrected distance visual acuity (UDVA).

	LE SMILE	HE SMILE	FS-LASIK	*P* Value (ANOVA)	*P* Value (*t* Test) LE SMILE vs HE SMILE	*P* Value (*t* Test) LE SMILE vs LASIK
Day 1 UDVA	−0.003 (n = 49)	0.141 (n = 49)	−0.011 (n = 49)	<.0001*	.0001*	.498
Month 1 UDVA	−0.033 (n = 40)	0.037 (n = 35)	−0.036 (n = 38)	.001*	.002*	.868
Month 1 RRE (D)	−0.16 ± 0.17 (n = 38)	−0.09 ± 0.26 (n = 35)	−0.06 ± 0.20 (n = 34)	<.0001*	.18	.02*

ANOVA = analysis of variance; HE = high energy; FS-LASIK = femtosecond laser–in situ keratomileusis; LE = low energy; RRE = mean of difference between actual postoperative MRSE and target postoperative MRSE; SMILE = small-incision lenticule extraction; UDVA = uncorrected distance visual acuity
*Statistically significant difference.

Figure 1 demonstrates the percentage of patients with 20/20 vision or better at POD1. Only 18/49 (37%) of HE SMILE patients had 20/20 vision or better on POD1 compared with 45/49 (92%) and 44/49 (90%) in the LE SMILE and FS-LASIK groups, respectively. Moreover, 49/49 (100%) of both FS-LASIK and LE SMILE patients had 20/30 vision or better on POD1. Although only 42/49 (86%) of patients with HE SMILE achieved 20/40 vision or better on POD1, 34/35 (97%) achieved 20/40 by POM1 (Figure 2).

Higher-Order Aberrations

THOA, SA, TC, VC, and HC for all 3 groups preoperatively and postoperatively (measured at POM1) are presented in Tables 2 and 4, respectively. All indices increased postoperatively in all 3 groups. Comparative changes in THOA, SA, and TC for HE SMILE, LE SMILE and FS-LASIK groups are presented in Figure 3. There was statistically significantly less induction of SA in eyes that underwent LE SMILE compared with those that underwent HE SMILE ($P = .02$) or FS-LASIK ($P = .03$) (Figure 4). Induction of all other HOAs were similar, with no statistically significant difference found between the LE SMILE and FS-LASIK groups (Figure 5). The minimum mean detectable difference was calculated for TC, which had the lowest of the nonsignificant *P* values (.07) was and found to be 0.09 μm and 0.14 μm for 80% and 99% power, respectively.

DISCUSSION

Although SMILE is a relatively new surgical procedure in the United States, numerous international studies have demonstrated similar efficacy, predictability, and safety profiles between SMILE and LASIK.[1–5,10,12,13,17] In a meta-analysis of 2 randomized control trials and 25 cohorts, Yan et al. found no significant difference in postoperative UDVA between SMILE and LASIK groups at 6 months.[18] A more recent prospective randomized paired eye clinical trial revealed similar safety and efficacy indices between SMILE and LASIK eyes.[19] Despite this positive long-term visual acuity data, one of the criticisms of SMILE has been the delay in visual recovery. In a study reported by Shah et al., at postoperative week 1, 66% of eyes had a UDVA of better than 20/20, and although this improved to 91% at 6 months, the authors commented that initial visual recovery at postoperative week 1 was delayed compared with that of modern refractive surgery.[11] This delay in visual recovery was also noted in a recent review of studies comparing SMILE with LASIK.[9]

The cause of the different visual recovery times between LASIK and SMILE is widely considered to be because of the interface irregularities caused by femtosecond laser bubbles and subsequent dissection. In FS-LASIK, any irregularities in the stromal interface created by femtosecond bubbles are effectively polished by the excimer laser ablation. Conversely, in SMILE, the femtosecond bubbles can cause micro-irregularities on both the anterior and posterior lenticule surfaces and there is no excimer ablation smoothing either surface, which might potentially lead to transient decreased visual acuity, decreased visual quality, and light scatter.[20] This finding was nicely demonstrated with confocal microscopy analysis of fellow eyes randomized to SMILE vs FS-LASIK. Agca et al. found increased corneal backscatter for the first 3 months in SMILE eyes vs LASIK eyes.[21]

To understand this concept, we must first understand what happens with each burst of femtosecond laser energy within the cornea. There are 2 effects: (1) Tissue separation occurs. This is the desired effect that allows the femtosecond laser to function as a high-precision microscalpel. (2) Gas is produced (Figure 6). Gas production is an undesired effect for 2 reasons. First, it causes local tissue distortion and can cause laser pulses to settle in a different location, leading to micro-irregularities described earlier. Second, with higher energies

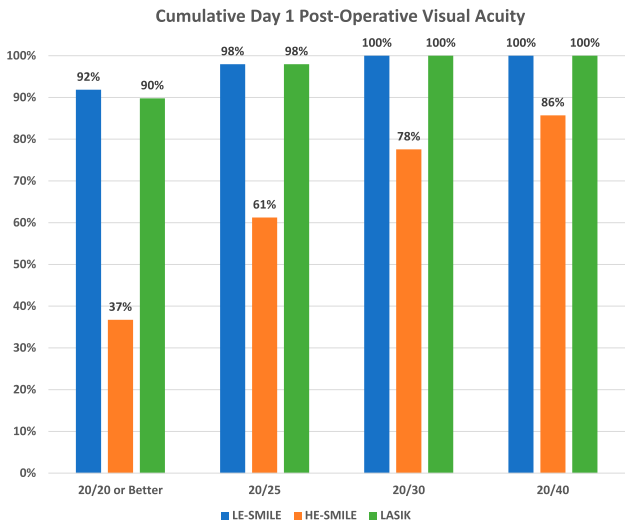


Figure 1. Cumulative percentage of eyes attaining specified cumulative levels of uncorrected distance visual acuity at postoperative day 1 after FS-LASIK, LE SMILE, and HE SMILE (FS-LASIK = femtosecond laser–assisted in situ keratomileusis; HE = high energy; LE = low energy; SMILE = small-incision lenticule extraction).

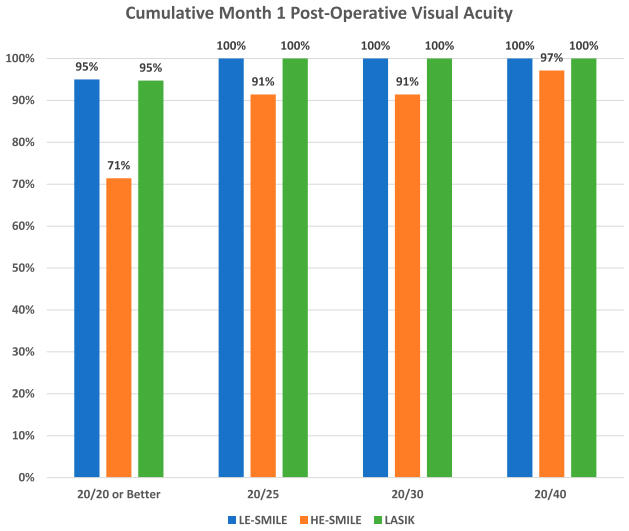


Figure 2. Cumulative percentage of eyes attaining specified cumulative levels of uncorrected distance visual acuity at post-operative month 1 after FS-LASIK, LE SMILE, and HE SMILE (FS-LASIK = femtosecond laser–assisted in situ keratomileusis; HE = high energy; LE = low energy; SMILE = small-incision lenticule extraction).

and/or closer spacing, adjacent spots of overlapping gas produce opaque bubble layer (OBL)—a whitening effect that decreases the efficacy of subsequent laser pulses. Figure 7 demonstrates the effects 2 different energy settings have on tissue plane dissection. In Figure 7, A, the high spot energy together with close spot spacing creates significant OBL, whereas, in Figure 7, B, the use of low energy with wider spot spacing greatly reduces OBL. Figure 7, C and D shows the bubble appearance in clinical cases after SMILE laser application when HE (*A*) vs LE (*B*) settings were used. In Figure 7, C, the significant OBL present in the visual axis (*open arrow*) and the fluffy border at the lenticule edge (*small arrow*) create more difficult tissue separation due to reduced efficacy of subsequent femtosecond laser pulses, despite the closer spot spacing. These findings are largely absent in Figure 7, D where LE settings are used, resulting in the ideal bubble pattern appearance (Video 1, available at http://links.lww.com/JRS/A161). Despite the presence of tissue bridges resulting from noncontiguous tissue separation, the tissue plane dissection is easier, and the resulting surface is smoother. Multiple microscopy studies on extracted lenticule have demonstrated that lowering energy settings resulted in improved surface quality.[22–25] However, it is important to consider that lower energies and wider spot spacing can make tissue separation challenging and can lead to tearing of tissue and more macroirregularities. Thus, the surgeon's goal is to fine-tune laser settings to allow for manageable separation while minimizing surface irregularity to achieve faster visual recovery.

During the U.S. FDA trial for SMILE treating spherical myopia, participating surgeons were limited to spot spacing of 3.0 μm and a minimum energy of 125 nJ. On FDA approval, clinical sites in the United States were limited to these same energy parameters. However, during the years of the FDA trial and after approval of spherical myopia treatments in the United States, international experience continued to progress, and clinical studies analyzed the effect of different laser settings on visual acuity. Donate and Thaëron kept a fixed spot spacing (4.5 μm) in their study but compared high energy (180 nJ) with very low energy (100 nJ). As expected, the LE group had a significantly higher percentage of eyes seeing 20/20 or better at POD1 and at all timepoints analyzed up to POM3.[26] Li et al. also fixed spot spacing at 4.5 and incrementally lowered energy from 160 to 125 nJ. They found a significant association with LE settings and better POM3 UDVA.[27] Finally, a group from South Korea conducted a similar study recently using energies ranging from 100 nJ to 150 nJ with a fixed spot spacing of 4.5, grouping their patients into low energy (100-110 nJ) and high energy (115-150 nJ).[28] They found a statistically significant difference in UDVA at POD1 and postoperative week 1, in favor of the low-energy group. Of interest, they also found a similar trend showing less induction of THOA and SA at POM1 with LE settings. Because of this outside the U.S. experience, it became clear that minimizing laser energy density leads to a more rapid recovery of UDVA.

Unfortunately, in the United States, surgeons could not access spot spacing wider than 3.0 μm until the FDA approval of myopic astigmatism treatments in October

Table 4. Postoperative higher-order aberrations.

Parameter	Low-Energy SMILE (n = 36)	High-Energy SMILE (n = 37)	FS-LASIK (n = 38)	*P* Value (ANOVA)
Postop total HOAs (μm)	0.58 ± 0.15	0.63 ± 0.13	0.57 ± 0.13	.101
Range	0.32, 0.93	0.40, 0.92	0.29, 1.12	
Postop spherical aberration (μm)	0.32 ± 0.12	0.40 ± 0.10	0.39 ± 0.11	.003*
Range	0.10, 0.57	0.13, 0.61	0.18, 0.65	
Postop total coma (μm)	0.37 ± 0.14	0.39 ± 0.15	0.32 ± 0.14	.079
Range	0.12, 0.68	0.05, 0.65	0.11, 0.71	
Postop horizontal coma (μm)	−0.07 ± 0.23	−0.10 ± 0.24	−0.06 ± 0.21	.757
Range	−0.53, 0.59	−0.52, 0.38	−0.67, 0.39	
Postop vertical coma (μm)	−0.10 ± 0.30	−0.06 ± 0.33	−0.03 ± 0.28	.429
Range	−0.68, 0.51	−0.61, 0.62	−0.52, 0.46	

ANOVA = analysis of variance; HOA = higher-order aberrations; FS-LASIK = femtosecond laser–in situ keratomileusis; MRSE = mean refraction spherical equivalent; postop = postoperative; SMILE = small-incision lenticule extraction
*Statistically significant difference.

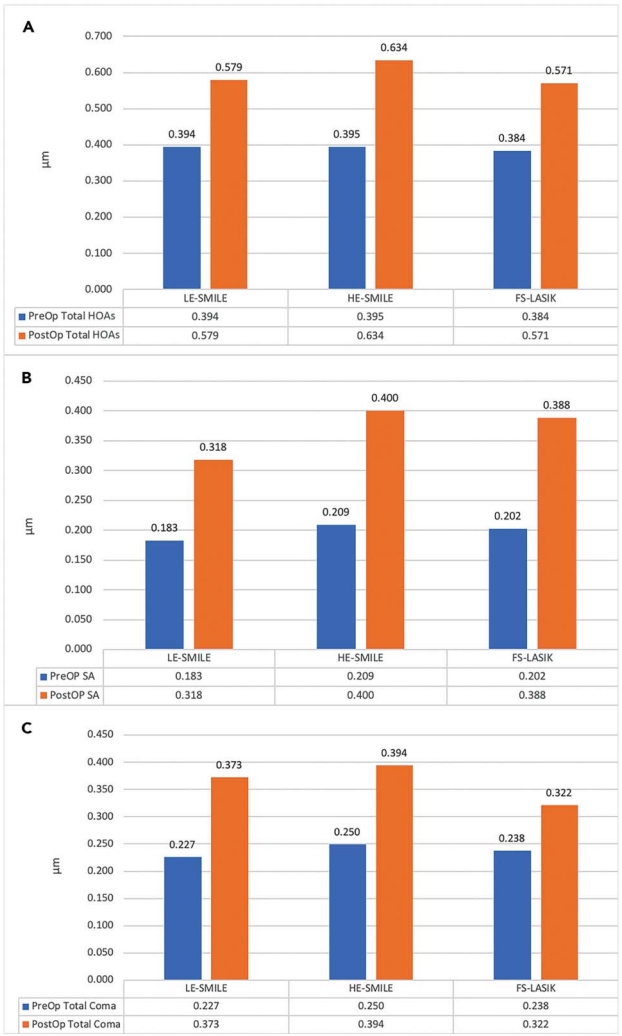


Figure 3. Preoperative and postoperative total HOAs (*A*), spherical aberration (SA) (*B*), and total coma (*C*) for LE SMILE, and HE SMILE, and FS-LASIK (FS-LASIK = femtosecond laser–assisted in situ keratomileusis; HE = high energy; HOA = higher-order abberation; LE = low energy; SMILE = small-incision lenticule extraction).

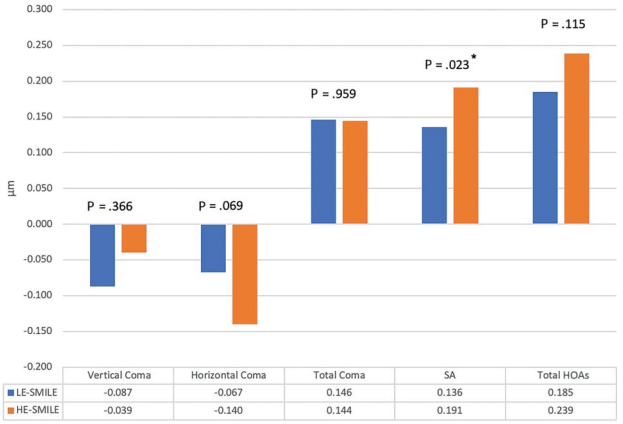
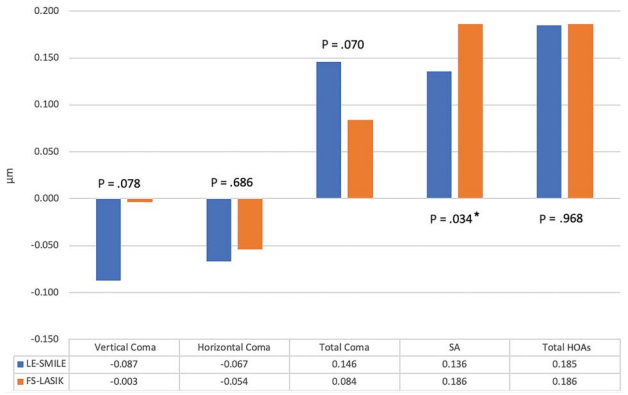


Figure 4. Amount of induced HOAs including vertical coma, horizontal coma, total coma, spherical aberration (SA), and total HOA from preoperative examination to postoperative month 1 for LE SMILE vs HE SMILE (HE = high energy; HOA = higher-order abberation; LE = low energy; SMILE = small-incision lenticule extraction).

2018.[29] With the approval of myopic astigmatism, the U.S. surgeon was also allowed access to spot spacing up to 4.5 µm and an incision width reduced from 90 to 60 degrees. However, minimum spot energy is still restricted to 125 nJ in the United States. To the authors' knowledge, prior to this study, articles looking at SMILE results within the United States have been limited and have used the HE settings and tighter spot spacing. A single-surgeon study comparing SMILE and LASIK concluded that superior results were obtained with a recent generation LASIK platform when compared with SMILE.[17] However, SMILE was performed with HE settings (145 nJ and 3.0 spot spacing), and POD1 results were not reported. The authors alluded to the possibility of visual outcomes improving with lowered energy settings. In our study, patients who had SMILE with LE settings had visual acuities on POD1 statistically similar to FS-LASIK and significantly better than those who had SMILE with HE settings. To the authors' knowledge, this is the first U.S. study reporting POD1 visual acuity results after SMILE to be similar to that of FS-LASIK. This is despite our inability in the United States to access energy per spot below 125 nJ, which is available outside the United States. The LE density afforded by the 4.5 spot spacing minimizes the surface irregularity while maintaining an ease of dissection, allowing for a more rapid visual recovery. Eyes in the LE SMILE cohort presented in this study represent cases performed by the surgeon in the early period after approval of myopic astigmatism. Given the low standard deviation of the MRSE outcomes, the mild residual refractive error in the LE SMILE group has been eliminated in more recent cases after a small nomogram adjustment.

One criticism of SMILE has been the inability to use wavefront- or topography-guided treatments to minimize the induction or perhaps even reduce HOAs. There have been conflicting reports on whether SMILE induces more or less HOAs than wavefront-optimized or wavefront-guided FS-LASIK. Lin et al. reported an increase of 0.12 µm in THOAs and 0.27 µm increase in SA at POM3 after SMILE. This was significantly less than corresponding results in their LASIK (wavefront optimized with "aspheric smart ablation") group, which showed an increase of 0.21 µm in THOAs and 0.69 µm in SA.[12] Their results were similar to those of another study comparing HOAs between SMILE and wavefront-optimized FS-LASIK, finding less THOAs and SA in the SMILE group than those in the LASIK group. The second study, however, noted an increased amount of induced VC after SMILE surgery.[15] In fact, several studies have noted higher levels of VC after SMILE and have alluded to decentrations of the SMILE lenticule to be the cause.[14,30,31]

In the meta-analysis by Yan et al., there was no significant difference in either induced HC or VC between the SMILE and FS-LASIK groups and less SA in the SMILE group ($P < .0001$).[18] However, it was not distinguished whether the FS-LASIK group had wavefront-optimized or wavefront-



	Vertical Coma	Horizontal Coma	Total Coma	SA	Total HOAs
LE-SMILE	-0.087	-0.067	0.146	0.136	0.185
FS-LASIK	-0.003	-0.054	0.084	0.186	0.186

Figure 5. Amount of induced HOAs including vertical coma, horizontal coma, total coma, spherical aberration (SA), and total HOA from preoperative examination to postoperative month 1 for LE SMILE vs FS-LASIK (FS-LASIK = femtosecond laser–assisted in situ keratomileusis; HOAs = higher-order abberations; LE = low energy; SMILE = small-incision lenticule extraction).

guided LASIK in the individual studies. The authors concluded that the lower SA seen after SMILE was due to the lack of transition zone and that it achieves a larger optical zone than LASIK does. Our study showed an increase in THOAs, SA, TC, VC, and HC 1 month after either LASIK or SMILE surgery, which is consistent with results from other studies.[32–34] Our results are consistent with the results of the meta-analysis by Yan et al. in that we found statistically significant less induction of SA in our LE SMILE group than that with FS-LASIK. Our findings are also similar to those of the study by Ji et al., which compared HOAs induction at different energy levels. Patients who underwent HE SMILE had significantly more postoperative SA than those with LE SMILE.[28] Unlike a few previous studies,[14,30,31] our group did not find higher induction of VC in our LE SMILE group compared with the FS-LASIK group. This might be partly due to the fact that the surgeon (D.R.H.) uses a reference image of the visual axis position relative to the pupil ("Verify" image Galilei G4 Dual Scheimpflug Analyzer) as a guide for accurate lenticule centration over the visual axis in an attempt to minimize lenticule decentration.

A limitation of this retrospective study involves the approval of wider spot spacing in October of 2018. Because it was clear then from international experience that LE density was associated with improved visual recovery, the surgeon did not perform SMILE surgery on a cohort with HE density after October 2018. Thus, all of the HE SMILE eyes were performed earlier in the surgeon's experience. Therefore, lower early postoperative visual acuities could have been affected by learning curve issues with lenticule dissection in addition to the HE density. A recent study by Titiyal et al. concluded that the learning curve with SMILE is surgically challenging but that most complications that result in delayed visual recovery are in the initial 50 cases.[35] To help avoid an early learning curve bias in this study, only SMILE cases that were performed after 2017, several months and more than 50 eyes after the surgeon began

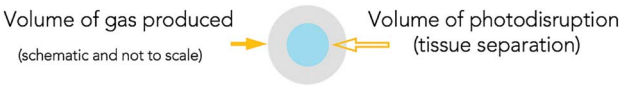


Figure 6. Schematic depicting volumes of gas production and photodisruption with femtosecond laser.

performing SMILE, were included. Again, because of simultaneous approval of astigmatism correction and LE parameters, there was an absence of eyes that had both cylinder correction and HE settings, and it was impossible to eliminate differences in preoperative attempted cylinder correction. Considering that the main purpose of this study was to demonstrate improved early uncorrected visual acuity with LE settings with SMILE compared with HE settings, the fact that less cylinder was treated in the HE SMILE group should, if anything, bias the UDVA results in favor of the HE SMILE group. Furthermore, our study presents several conclusions that rely on nonsignificant *P* values, specifically the lack of significant difference in POD1 and POM1 vision between LE SMILE and FS-LASIK and the lack of difference in HOAs (other than SA) between LE SMILE and FS-LASIK. To avoid falsely rejecting the null hypothesis, we calculated the minimum mean detectable difference for POD1 UDVA, POM1 UDVA, and TC. At the 80% power level, if we do not reject the null hypothesis, the true POD1 UDVA for LE SMILE and FS-LASIK would differ by at most 0.03 logMAR or 2 letters. The true POM1 UDVA for LE SMILE and FS-LASIK would differ by at most 0.05 logMAR or one half of a Snellen line. For TC, the true induced TC for LE SMILE and FS-LASIK would differ by at most 0.09 µm. This analysis strengthens the validity of our conclusions deriving from nonsignificant *P* values and avoids the risk of a type II error given the smaller sample size. Finally, this study reports outcomes out to 1 month postoperatively. Although later postoperative data continue

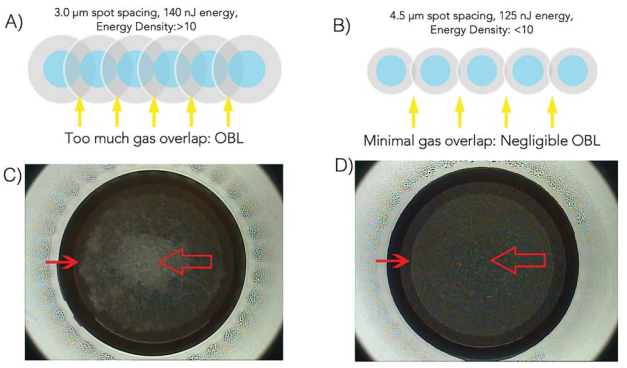


Figure 7. *A–D*: Schematic depicting volume of gas produced and amount of photodisruption at different energy levels and spot spacing (*A*, *B*) with corresponding clinical photographs of amount of OBL formation present in HE SMILE (*C*) and LE SMILE (*D*). Note central visual axis OBL (*open arrow*) present in the HE SMILE case and absent in the LE SMILE case. In addition, note the fluffy lenticular border (*small arrow*) in the HE SMILE case compared with the clean lenticular edge seen in the LE SMILE case (LE = low energy; HE = high energy; OBL = opaque bubble layer; SMILE = small-incision lenticule extraction).

to be collected, the purpose of this study was to investigate the critical question regarding the very early postoperative visual acuities afforded by SMILE compared with those of LASIK. It is clear from multiple studies in the literature that SMILE outcomes only improve over time.[1,17,33,34,36,37] As such, only an improvement in UDVA with longer follow-up should be expected.

In conclusion, this study demonstrates that the visual recovery lag that had been associated with the early generation SMILE procedure available in the United States is significantly improved with the availability of LE settings. With lowered energy settings (eg, 4.5 spot spacing and 125 nJ energy per spot), POD1 and POM1 UDVA is significantly improved in comparison with that achieved with the previous, HE settings and is now comparable with the postoperative uncorrected vision attainable with FS-LASIK. These LE settings also allow for lower induced SA compared with FS-LASIK. It is important to note that SMILE is a very different procedure from LASIK and uses much lower FS energy settings to create the lenticule than what is used to create the LASIK flap. Accordingly, it is imperative that the energy settings be carefully optimized for each individual VisuMax laser installation to provide the best POD1 visual acuity. If this is done, refractive surgeons and their patients will enjoy the POD1 wow factor in addition to the predictability and safety that we have come to expect from LASIK.

WHAT WAS KNOWN

- Small-incision lenticule extraction (SMILE) and femtosecond laser–assisted in situ keratomileusis (FS-LASIK) are safe and effective procedures for treatment of myopic astigmatism.
- Lower femtosecond energy levels cause less lenticule surface irregularity and has been associated with faster visual recovery among international cohorts.

WHAT THIS PAPER ADDS

- SMILE with lower energy settings (125-130 nJ and 4.5 μm spot spacing) achieved postoperative day 1 vision comparable with that of FS-LASIK.
- To the authors' knowledge, this is the first U.S. study to report improved visual recovery with U.S. FDA-approved lowered energy settings.
- Lower-energy SMILE caused less induced spherical aberration compared with that by FS-LASIK.

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First author:
D. Rex Hamilton, MD, MS

Hamilton Eye Institute, Los Angeles, CA, USA