

One-year results of photorefractive keratectomy and laser in situ keratomileusis for myopia using a 213 nm wavelength solid-state laser

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PURPOSE: To study the long-term results of photorefractive keratectomy (PRK) and laser in situ keratomileusis (LASIK) in low to moderate myopic corrections using the Pulzar Z1 system (CustomVis), a 213 nm wavelength solid-state laser.

SETTING: University refractive surgery center.

METHODS: This prospective noncomparative case series comprised 20 patients (40 eyes) who had refractive surgery using the Pulzar Z1 laser system. Manifest refraction, uncorrected visual acuity, best spectacle-corrected visual acuity (BSCVA), safety, predictability, stability, and confocal microscopy images were evaluated.

RESULTS: Ten patients (20 eyes) had PRK and 10 patients (20 eyes) had LASIK. The mean follow-up was 13.9 months \pm 1.1 (SD) (range 12 to 17 months) and 14.6 \pm 1.2 months (range 12 to 18 months) in the PRK group and LASIK group, respectively. No eye lost a line of Snellen BSCVA during the follow-up period; 2 eyes (10%) gained 2 Snellen lines. There was a statistically significant decrease in spherical equivalent manifest refraction postoperatively in both groups ($P < .05$). Refractive stability was obtained during the first postoperative month and remained stable during the follow-up period, with no significant changes between any interval in both groups ($P > .05$). At the last follow-up, 95% of all eyes were within \pm 1.00 diopter of emmetropia. No late postoperative complications were observed.

CONCLUSION: Refractive surgery using the Pulzar Z1 213 nm wavelength solid-state laser was a safe, effective procedure in the treatment of low to moderate myopia.

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Photoablation of the cornea within the range of 190 to 220 nm (ultraviolet wavelength) offers a high degree of precision with minimum collateral damage¹ and a small risk for cellular inactivation and mutation.^{2–4} Over the past years, solid-state lasers have been gaining popularity for refractive surgery because many reports^{5–14} indicate they can be a reliable alternative to traditional excimer laser systems with a 193 nm wavelength. In vitro⁵ and in vivo⁶ studies with a 213 nm solid-state laser found smooth ablation surfaces with a clinical course and histopathological findings similar to those of excimer laser photorefractive keratectomy (PRK).¹⁵ Moreover, newly developed solid-state laser platforms have been used in myopic or irregular astigmatism treatments with promising results.^{12–14}

The present study evaluated the long-term results of PRK or laser in situ keratomileusis (LASIK) using the Pulzar Z1 213 nm wavelength solid-state laser (CustomVis).

PATIENTS AND METHODS

This prospective noncomparative case series comprised patients who had refractive surgery with the Pulzar Z1 laser system. Before their participation in the study, all patients gave informed consent in accordance with institutional guidelines and the Declaration of Helsinki.

The Pulzar Z1 laser system is a solid-state, quintupled, diode-pumped neodymium:YAG (Nd:YAG) device generating a 213 nm wavelength (one fifth of a standard Nd:YAG laser). It uses a 0.6 mm diameter scanning flying spot with a Gaussian profile and a pulse repetition rate of 300 Hz. The solid-state eye-tracking system locks onto the limbus

with a detection rate of 5 KHz, an eye-tracker delay time of 0.5 ms, and a closed-loop response of 1 KHz.

All patients had a complete ophthalmic examination preoperatively to exclude ocular disease. Exclusion criteria were active anterior segment disease; residual, recurrent, or active ocular disease; previous intraocular or corneal surgery; history of herpes keratitis; diagnosed autoimmune disease; systemic connective tissue disease or atopic syndrome; and corneal topographic findings suspicious for keratoconus.

Preoperative assessments included uncorrected visual acuity (UCVA), best spectacle-corrected visual acuity (BSCVA), manifest and cycloplegic refractions, slitlamp examination with fundus evaluation, applanation tonometry, corneal topography (C-Scan, Technomed Arnold-Sommerfeld-Ring1), ultrasonic pachymetry (Pac Scan 300P, Sonomed), and confocal microscopy (Heidelberg Engineering GmbH). The latter was performed with a modified confocal scanning laser ophthalmoscope (HRT II/Rostock Cornea Module, Heidelberg Engineering). The principle of operation of the modified scanning laser ophthalmoscope has been described.¹⁶ In-depth qualitative evaluation of the central corneal images was performed, with special attention paid to the subepithelial nerve plexus, ablated zone, and deep stroma.

All procedures were performed by the same surgeon (I.G.P.) using an identical technique. In the PRK group, deepithelialization was achieved using a brush. In the LASIK group, a 110 μm head Carriazo-Pendular microkeratome (Schwind GmbH) was used in the manual mode to create a superiorly hinged flap. A soft contact lens was applied to all PRK eyes until the epithelium healed completely. The targeted correction in all eyes was emmetropia.

Postoperatively, the PRK patients received sodium flurbiprofen 0.03% drops (Ocufleur) 4 times a day for 2 days, dexamethasone-tobramycin drops (TobraDex) 4 times a day until the removal of the contact lens, and then fluorometholone drops (FML) 4 times a day tapered over the following month. Sodium hyaluronate 0.18% drops (Vismed) were used hourly at first and then, depending on patients' needs, for a month thereafter. The LASIK patients received Ocufleur drops 4 times a day for 2 days, TobraDex drops 4 times a day for 2 weeks, and Vismed drops hourly at first and then, depending upon patients' needs, for a month thereafter.

Follow-up examinations were performed 1, 3, 6, and 12 months postoperatively. The following were assessed at each visit: UCVA, BSCVA, corneal topography, slitlamp examination, and confocal microscopy.

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Statistical analysis was performed using the Student *t* test for continuous variables. Differences in categorical variables were tested by the chi-square test. Results are presented as mean \pm standard deviation. A *P* value less than 0.05 was considered statistically significant.

RESULTS

Initially, 25 patients (50 eyes) participated in a clinical trial for the safety, efficacy, and predictability of refractive surgery (PRK or LASIK) using the Pulzar Z1 solid-state laser. Twenty of the patients had primary bilateral PRK (10 eyes; 4 men and 6 women) or LASIK (10 eyes; 5 men and 5 women) for myopic corrections (compound or not with less than 1.00 diopter [D] astigmatism) and completed at least a 1-year follow-up. These patients were included in the study. Table 1 shows the patients' demographic and refractive data.

Uncorrected Visual Acuity

The mean UCVA significantly improved from finger counting preoperatively to 20/40 or better at the last follow-up examination. One month after PRK or LASIK, 18 eyes (90%) achieved a UCVA of 20/30 or better and 11 eyes (55%) of 20/20 or better. At the

Table 1. Patients' demographic and refractive data.

Parameter	PRK	LASIK
Eyes, n	20	20
Patients, n	10	10
Sex		
Male	4	5
Female	6	5
Age (y)		
Mean \pm SD	27.8 \pm 5.87	29.1 \pm 4.95
Range	19 to 42	21 to 35
Preop corneal pachymetry (μm)		
Mean \pm SD	545.3 \pm 29.4	565.3 \pm 27.6
Range	478 to 572	518 to 618
Preop sphere (D)		
Mean \pm SD	-3.19 \pm 0.56	-5.16 \pm 1.21
Range	-2.25 to -4.50	-2.50 to -7.00
Preop cylinder (D)		
Mean \pm SD	-0.56 \pm 0.39	-0.50 \pm 0.72
Range	0 to -0.75	0 to -0.75
Last postop visit (mo)		
Mean \pm SD	13.9 \pm 1.1	14.6 \pm 1.2
Range	12 to 17	12 to 18
Last postop sphere (D)		
Mean \pm SD	-0.013 \pm 0.15	-0.18 \pm 0.46
Range	0.25 to -0.25	0.25 to -1.25
Last postop cylinder (D)		
Mean \pm SD	-0.125 \pm 0.17	-0.29 \pm 0.29
Range	0 to -0.50	0 to -0.75

LASIK = laser in situ keratomileusis; PRK = photorefractive keratectomy

last postoperative examination, all PRK eyes achieved a UCVA of 20/25 or better and 19 (95%) of 20/20 or better and 18 LASIK eyes (90%) achieved a UCVA of 20/25 or better and 17 (85%) of 20/20 or better.

Best Spectacle-Corrected Visual Acuity

Figure 1 shows the changes in the BSCVA during the follow-up. In the PRK group, 1 eye lost 1 Snellen line by the 1-month postoperative examination as a result of severe dry eye. No eye lost a line of Snellen BSCVA; 8 eyes (40%) gained 1 line and 2 eyes (10%) gained 2 lines by the last follow-up. In the LASIK group, no eye lost a line of Snellen BSCVA line; 7 eyes (35%) had gained 1 line by the last postoperative examination.

Refractive Error

In the PRK group, the mean spherical equivalent (SE) refraction was $-3.46 \text{ D} \pm 0.52 \text{ (SD)}$ preoperatively. It decreased to $-0.24 \pm 0.45 \text{ D}$ at 1 month, $-0.04 \pm 0.31 \text{ D}$ at 3 months, $-0.05 \pm 0.29 \text{ D}$ at 6 months, and $-0.08 \pm 0.21 \text{ D}$ at the last postoperative examination ($P < .05$). Refractive stability was obtained

by the first postoperative month, and the mean residual refractive error remained stable during all the follow-up examinations with no significant changes between any interval ($P > .05$) (Figure 2, A). One eye (5%) had a change in SE of more than 0.50 D between 6 months postoperatively and the last examination. One month after surgery, the postoperative SE refraction was within $\pm 0.50 \text{ D}$ of emmetropia in 16 eyes (80%) and within $\pm 1.00 \text{ D}$ in 19 eyes (95%). At the last follow-up, all eyes in the PRK group were within $\pm 0.50 \text{ D}$ of emmetropia. The correlation between the attempted myopic correction and achieved myopic correction at the last follow-up was highly linear, with 14 eyes (70%) at $\pm 0.25 \text{ D}$ and all eyes at $\pm 0.50 \text{ D}$ (Figure 3, A).

In the LASIK group, the mean SE refraction ($-5.41 \pm 1.21 \text{ D}$) was $-5.41 \pm 1.21 \text{ D}$ (range -2.62 to -7.25 D) preoperatively. It decreased to $-0.45 \pm 0.55 \text{ D}$ at 1 month, $-0.40 \pm 0.59 \text{ D}$ at 3 months, $-0.35 \pm 0.48 \text{ D}$ at 6 months, and $-0.32 \pm 0.49 \text{ D}$ at the last follow-up ($P < .05$). There were no significant changes in SE refractive error between any interval ($P > .05$) (Figure 2, B). The SE refraction did not change by more than

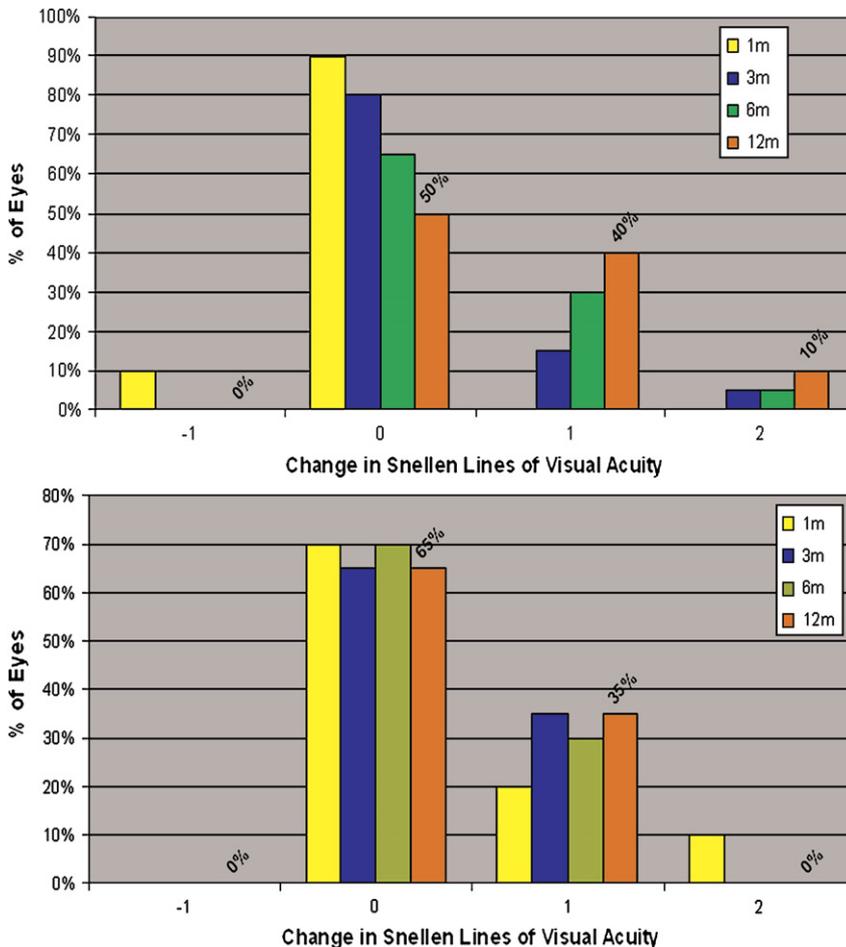


Figure 1. Change in BSCVA 1, 3, 6, and 12 months after PRK (top) and LASIK (bottom).

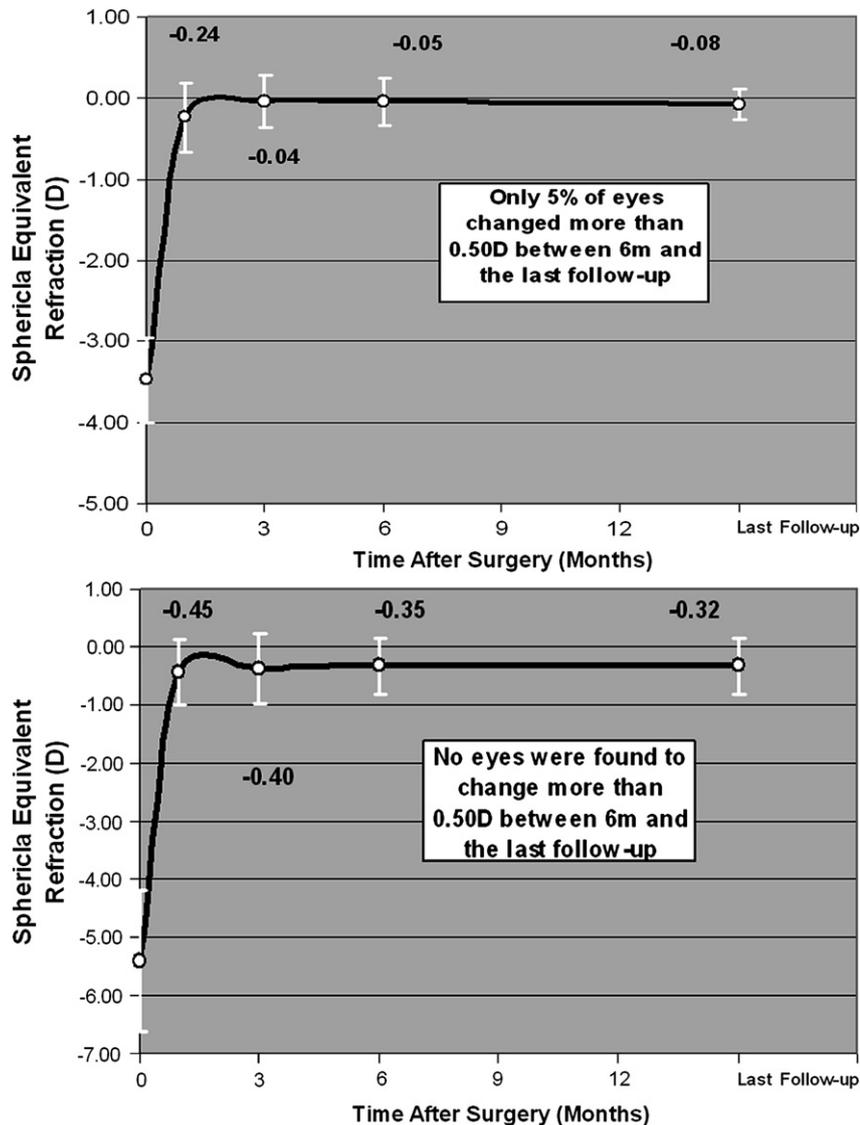


Figure 2. Stability of intended correction during the follow-up period after PRK (*top*) and LASIK (*bottom*).

0.50 D between 6 months postoperatively and the last examination in any eye. One month after surgery, the postoperative SE refraction was within ± 0.50 D of emmetropia in 12 eyes (60%) and within ± 1.00 D in 17 eyes (85%). At the last follow-up, predictability showed that 11 eyes (55%) were within ± 0.25 D and 18 eyes (90%) were within ± 0.50 D (Figure 3, B). One 1 patient (2 eyes; 10%) had an SE refraction greater than 1.00 D of emmetropia.

Confocal Microscopy Analysis

Corneal images in the PRK group and LASIK group showed normal epithelial structures. The subepithelial nerve plexus in both groups appeared regenerated after 1 year of surgery (Figures 4 and 5, *top left*). Increased scattering was observed at the ablation site in all PRK-treated corneas, even 1 year after surgery (Figure 4, *top right*). Highly reflective particles and

scattering were observed at the flap interface in LASIK-treated corneas, even 1 year after surgery (Figure 5, *top right*). Moreover, keratocyte activation and abnormal scattering of the nuclei of the keratocytes were observed at the stromal layers immediately posterior to the ablation site (Figures 4 and 5, *bottom left*). In contrast, deeper stromal layers had normal keratocyte activation and scattering of the nuclei of the keratocytes with an oval shape (Figures 4 and 5, *bottom right*). Finally, the endothelial cells appeared normal in shape and size (cell density within normal range) in both groups.

Adverse Effects and Postoperative Complications

No eye had intraoperative, early, or late postoperative complications. The epithelium healed completely within 3 to 5 days after surgery in all PRK-treated eyes. Trace haze was documented in 2 PRK-treated

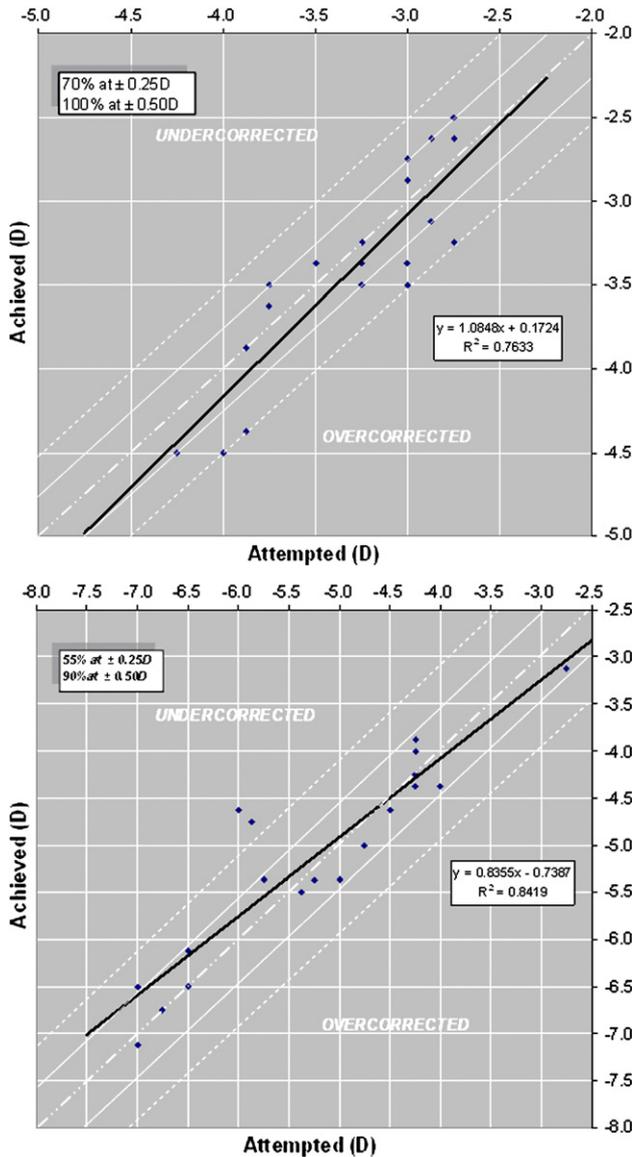


Figure 3. Correlation between the attempted and the achieved myopic correction at the last follow-up examination (12 months) after PRK (*top*) and LASIK (*bottom*).

eyes 3 months postoperatively and in 1 eye at the last follow-up examination.

DISCUSSION

Solid-state lasers provide a technical platform that could eliminate some of the excimer laser system's disadvantages such as the absence of toxic gas with the solid-state laser. Moreover, the Pulzar Z1 laser system has characteristics that may prove useful in refractive surgery (especially in customized treatments). The small spot size (0.6 mm diameter, 2.5 times smaller than a typical excimer laser spot), uniform Gaussian intensity beam distribution, high pulse-to-pulse

stability, and ultra-fast tracking system contribute to the accurate transfer of the planned treatment onto the corneal stroma, creating a smooth ablation surface. Another potential benefit of the smaller spot size is less mechanical stress on the cornea during ablation,¹⁷ which might cause fewer cellular alterations and less damage to the corneal structure.¹⁸ In addition, the Pulzar Z1 laser system emits at a 213 nm wavelength, which is close to the absorption peak of corneal collagen,¹ and it is less sensitive (1 to 4 orders of magnitude) to corneal hydration than at 193 nm.¹⁹ Thus, corneal hydration²⁰ and environmental humidity,²¹ factors that affect the final outcomes with conventional excimer laser systems, are limited with the solid-state laser.

Despite the theoretical advantages of solid-state laser systems, there are few clinical studies of them and all were of the results after PRK.^{6,12-14} The current study found promising results after PRK¹⁴ as well as after LASIK using the solid-state laser over a minimum follow-up of 1 year. Of the 40 study eyes (20 PRK, 20 LASIK), 38 (95%) had a UCVA of 20/25 and 36 (90%) achieved 20/20 or better by the last follow-up. No eye had lost a line of Snellen BSCVA at the last postoperative examination. Predictability improved during the follow-up period, from 20 eyes (70%) within ± 0.50 D of emmetropia at the 1-month postoperative examination to 38 eyes (95%) within ± 0.50 D of emmetropia at the last follow-up. Epithelial healing time²² and the haze rate²³ were similar to those found after PRK using the excimer laser.

Confocal microscopy images showed findings similar to those in previous studies that used the excimer laser.²⁴⁻²⁷ Subepithelial nerve plexus regeneration has been observed even 7 days after PRK treatments²² and 3 months after LASIK surgery,²⁴ while morphological recovery of corneal innervation may take more than 12 months with either procedure.^{24,25} Moreover, previous studies found keratocyte activation, morphological changes of keratocyte nuclei, and deposition of extracellular matrix (ECM) near the ablation site in PRK patients²⁵ or near the lamellar cut in LASIK patients.²⁶ Nonetheless, the increased scattering caused by the keratocyte activation and/or deposition of ECM was not of clinical importance as UCVA was not influenced by haze in any patient in the present study. Finally, the small reflective particles at the flap interface have been observed in previous studies. These particles have been described as small metal particles from the microkeratome blade and salt precipitates from the tear film.

This study had limitations that preclude a viable conclusion. These were the small sample of treated eyes, the small range of the attempted SE correction (-2.50 to -7.00 D), and the lack comparison with a group having excimer laser treatment. Whether the

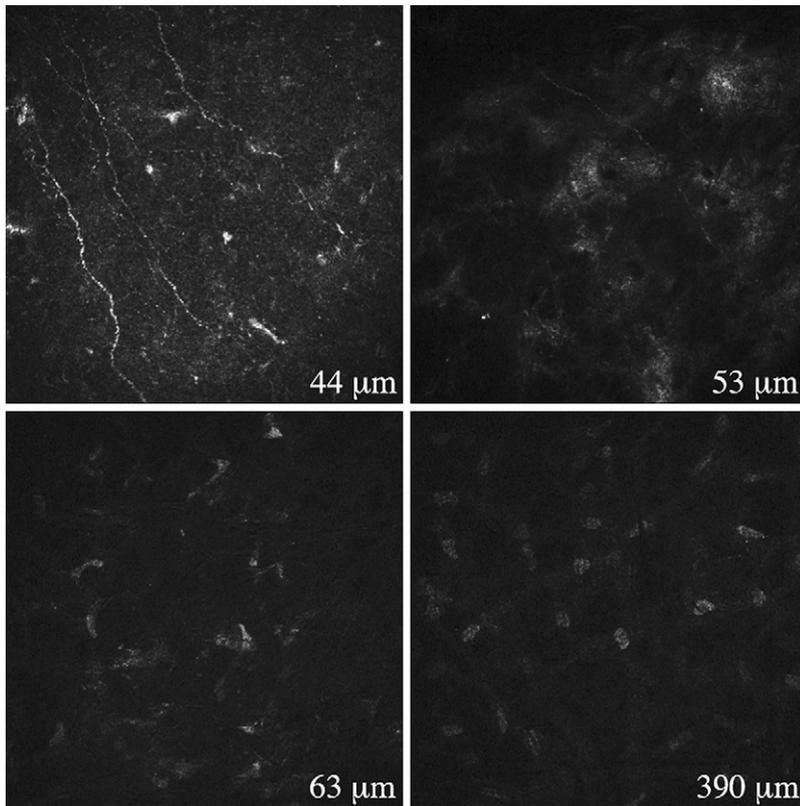


Figure 4. Confocal microscopy in PRK patients. *Top left:* Regenerated subepithelial nerve plexus. *Top right:* Surface ablation site. *Bottom left:* Stromal layer immediately posterior to ablation site. *Bottom right:* Deep stromal layer.

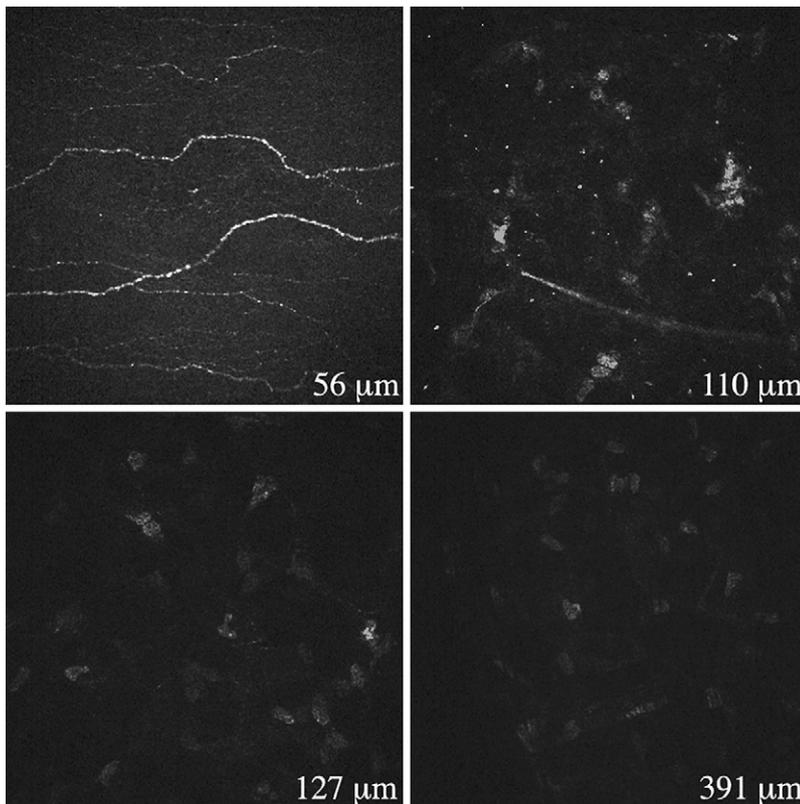


Figure 5. Confocal microscopy in LASIK patients. *Top left:* Regenerated subepithelial nerve plexus. *Top right:* Flap interface with highly reflective particles. *Bottom left:* Stromal layer immediately posterior to the ablated zone. *Bottom right:* Deep stromal layer.

theoretical advantages of the solid-state laser platform over excimer laser systems have a practical impact on corneal healing, and therefore on the patient's quality of vision, remains to be studied.

In conclusion, refractive surgery with the Pulzar Z1 213 nm solid-state laser system seemed to be a safe and effective procedure for treating low to moderate myopia, despite the limitations of this study.

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