Treatment of irregular astigmatism with a 213 nm solid-state, diode-pumped neodymium:YAG ablative laser

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Purpose: To present the outcome of photorefractive keratectomy (PRK) using a new neodymium:YAG (Nd:YAG) laser in patients with irregular astigmatism.

Setting: Claremont Eye Clinic, Claremont, and the University of Western Australia, Perth, Australia.

Methods: In 3 patients with irregular astigmatism, PRK was performed with a solid-state, 213 nm wavelength, 300 Hz scanning-spot, diode-pumped Nd:YAG ablative laser (CustomVis® Pulzar® laser system). The 3 patients had had previous PRK with penetrating keratoplasty, astigmatic keratotomy, or limbal relaxing incisions. At 3 and 6 months, best spectacle-corrected visual acuity (BSCVA), uncorrected visual acuity (UCVA), manifest refraction, contrast sensitivity, and corneal topography were measured.

Results: The first patient had a 1-line improvement in BSCVA and a 4-line improvement in UCVA, a 3.00 diopter (D) decrease in keratometric cylinder, and improvement in contrast sensitivity. The second patient had a 7.00 D decrease in myopia in 1 meridian and a 4.25 D decrease in the refractive cylinder in the other meridian. The third patient had a 2-line improvement in BSCVA, a 5-line improvement in UCVA, a 2.00 D decrease in the refractive cylinder, and improvement in contrast sensitivity.

Conclusion: The laser's combination of a small spot, a fast pulse rate, and ultrafast tracking/scanning resulted in good results in 3 patients with difficult irregular astigmatism.

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A refractive surgeon needs a consistent and efficacious method for treating irregular astigmatism, whether it is from disease, trauma, or previous refractive surgery. Custom wavefront or topography-driven ablation with ablative lasers seems to be the most promising approach. However, clinical reports of excimer laser treatments have demonstrated inconsistent results.[1–10] A solid-state ablative laser was recently developed to perform custom ablation in irregular and normal corneas. This report presents the first 3 patients treated with this laser; all had irregular astigmatism.

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Dr. Sanders is a research and regulatory consultant to CustomVis, and Dr. Ardrey is an employee. Dr. van Saarloos has a financial interest in the company. Dr. Anderson has no financial or proprietary interest in any material or method mentioned.

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Patients and Methods

Ablation was performed with the CustomVis® Pulzar® laser system (Figure 1). The laser is a solid-state, frequency-quintupled, diode-pumped neodymium:YAG (Nd:YAG) laser generating a 213 nm wavelength. It uses a 0.6 mm

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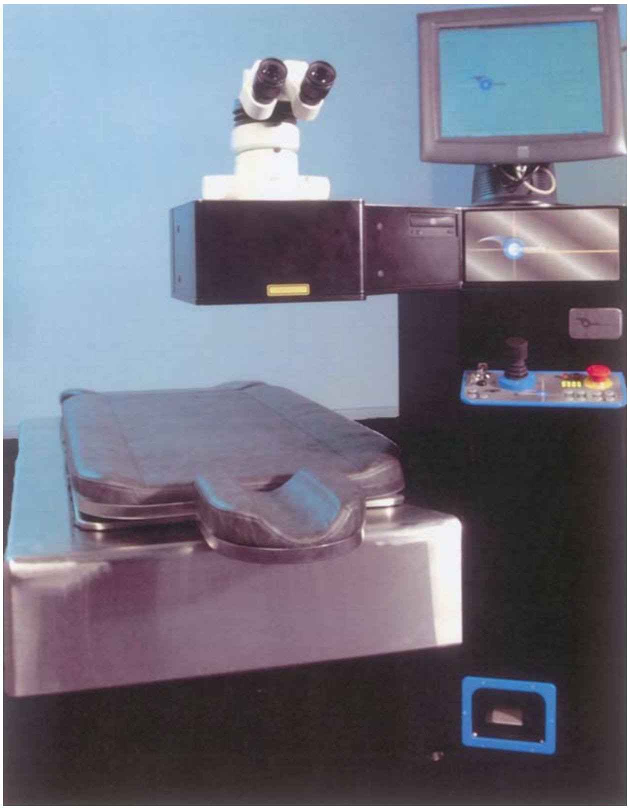


Figure 1. (Anderson) The CustomVis Pulzar solid-state laser system.

Gaussian profile, scanning flying spot with a pulse repetition rate of 300 Hz. The laser was scanned using a new solid-state-based scanning system. Eye-tracking technologies that lock onto the limbus were used. The solid-state scanning technology allows the laser to respond to eye-tracking measurements faster than mechanical galvanometer-based systems; the solid-state scanner has a detection rate of 5 KHz, an eye-tracker delay time of 0.5 ms, and a closed-loop response of 1 KHz.

The CustomVis treatment algorithm for the 3 patients was manifest refraction and topography elevation data to determine the ablation profile. The treatment plan was calculated earlier using special computer-aided design software (ZCAD®) and was written to a compact disk. This software registered the preoperative maps, pupil positions, and treatment plans to the limbus.

Patients were approved for treatment through the Australian regulatory body (Therapeutic Goods Administration) and signed appropriate informed consent. Photorefractive keratectomy (PRK) was performed in all patients. Postoperatively, tobramycin 0.3% was administered 4 times a day for 1 week and fluorometholone 0.1% (FML®) was started on the third day for up to 6 weeks. The best spectacle-corrected visual acuity (BSCVA), uncorrected visual acuity (UCVA), manifest refraction, contrast sensitivity using the Baylor Visual Acuity Tester (BVAT, Mentor), and corneal topography using Orbscan® (Orbtek) were measured preoperatively and at 3 and 6 months. Keratometry measurements averaged over the central 3.0 mm optical zone were measured with Orbscan. The Orbscan topography figures shown have a scale of 1.0 mm between each circular overlay, elevation maps at a scale of 0.005 mm color steps, and axial power maps at a scale of 1.0 diopter (D) color steps; comparisons between preoperative and postoperative elevation maps have the same sphere parameters (preoperative best-fit sphere radius).

Results

The 3- and 6-month results in the 3 treated patients are presented in Table 1.

Case 1

A 54-year-old white man had penetrating keratoplasty (PKP) in the left eye in 1989 for keratoconus with high astigmatism. In 1990, 2 astigmatic keratotomies (AKs) were performed in the same eye and compression sutures were placed. Photorefractive keratectomy was performed in 1991 and repeated in 1993. Before treatment with the CustomVis laser, the patient had a UCVA of 20/400 and a best corrected visual acuity (BCVA) of 20/30 with a refraction of –4.00 +3.25 × 90. The keratometric cylinder at 3.0 mm measured by Orbscan was 8.4@95. The central pachymetry was 530 μm despite previous refractive surgery, although the periphery was noted to be abnormally thin.

Photorefractive keratectomy with a 4.8 mm optical zone and a 6.8 mm total treatment zone was planned so no portion of the residual stromal tissue under the ablation would be less than 300 μm. Treatment was performed on September 15, 2002. At 1 week and 1 month, the BSCVA was 20/20 and the UCVA 20/50. At 3 months, the UCVA was 20/80, the BSCVA remained 20/20, and the refraction was −3.50 +1.50 × 65. The keratometric cylinder was 5.7@83. At 6 months, the UCVA was 20/50, the BSCVA 20/25, and the refraction −3.50 +1.50 × 110. The BCVA improved at all contrast levels (Figure 2, *left*) and the UCVA at all contrast levels except 10% (Figure 2, *right*). The axial radius of curvature maps and a difference map clearly show a reduction in corneal cylinder and reduced range of refractive power within the optical zone (Figure 3). The patient had a 1-line improvement in BSCVA (20/30 to 20/25), a 4-line improvement in UCVA

Table 1. Outcomes following treatment of postrefractive surgery irregular astigmatism with the Custom Vis Pulzar laser system.

Patient	Previous Procedures	Time (Mo)	BSCVA	UCVA	Sph (D)	Cyl (D)	Axis	K Cyl (D)
1	Post PKP irregular astigmatism	Preop	20/30	20/400	–4.00	+3.25	90	8.4@95
	Post AK, Post PRK ×2	3	20/20	20/80	–3.50	+1.50	65	5.7@83
		Change	↑ *2 lines*	↑ *3 lines*		↓ *1.75*		↓ *2.7*
		6	20/25	20/50	–3.50	+1.50	110	5.4@90
		Change	↑ *1 line*	↑ *4 lines*	—	↓ *1.75*	—	↓ *3.0*
2	Post PKP irregular astigmatism, Post AK	Preop	20/40	CF	–11.00	+9.25	75	11.1@80
	with compression sutures	3	20/40	20/50	+0.50	+3.00	75	3.2@98
		Change	—	↑ *4 lines*	—	↓ *6.25*	—	↓ *7.9*
		6	20/50	20/100	–4.00	+5.00	70	7.1@78
		Change	↓ *1 line*	↑ *2 lines*	—	↓ *4.25*	—	↓ *4.0*
3	Post LRI, post PRK	Preop	20/30	20/80	–0.50	+3.25	90	6.5@78
		3	20/20	20/20	–0.50	+1.00	120	4.1@74
		Change	↑ *2 lines*	↑ *5 lines*	—	↓ *2.25*	—	↓ *2.4*
		6	20/20	20/20	–0.25	+1.25	90	3.5@74
		Change	↑ *2 lines*	↑ *5 lines*	—	↓ *2.00*	—	↓ *3.0*

AK = Astigmatic keratotomy; BSCVA = best spectacle-corrected visual acuity; CF = counting fingers; Cyl = cylinder; LRI = limbal relaxing incision; PKP = Penetrating keratoplasty; PRK = photorefractive keratectomy; Sph = sphere; UCVA = uncorrected visual acuity

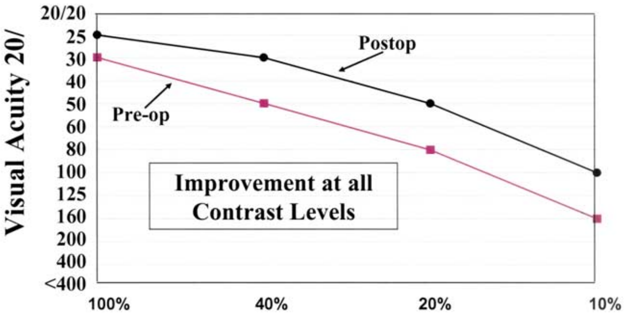
(20/400 to 20/50), a 1.75 D decrease in refractive cylinder (3.25 D to 1.50 D), and a 3.00 D decrease in keratometric cylinder (8.4@95 to 5.4@90).

Case 2

A 42-year-old white man had PKP in 1983 for keratoconus with high astigmatism. In 1993, AK was performed with compression sutures for residual astigmatism. Before treatment with the CustomVis laser, the patient had a UCVA of counting fingers (CF), a BCVA of 20/40 with a refraction of −11.00 +9.25 × 75, and a keratometric cylinder of 11.1@80.

Photorefractive keratectomy with a 5.0 mm optical zone and a 7.6 mm total treatment zone was planned with a maximum achieved ablation depth of 145 μm so no portion of the residual stromal tissue under the ablation would be less than 300 μm. Treatment was performed on September 15, 2002. Figure 4 compares the attempted ablation profile calculated with laser planning software to the achieved elevation change measured by preoperative and postoperative Orbscan examinations.

At 3 months, the UCVA was 20/50, the BSCVA 20/40, the refraction +0.50 +3.00 × 75, and the keratometric cylinder 3.2@98. At 6 months, the UCVA was



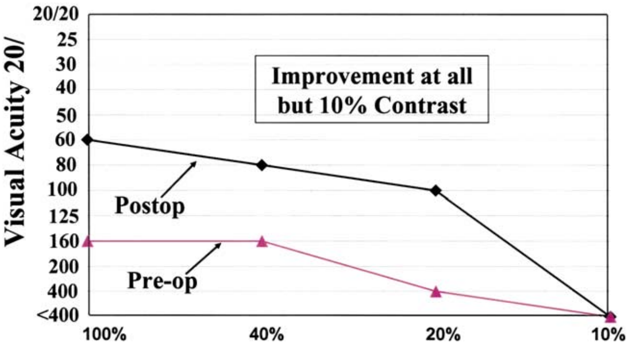


Figure 2. (Anderson) Contrast sensitivity measurements in Case 1 at 4 levels of contrast. *Left*: Comparison of preoperative and postoperative best corrected contrast acuity. *Right*: Comparison of preoperative and postoperative uncorrected contrast acuity.

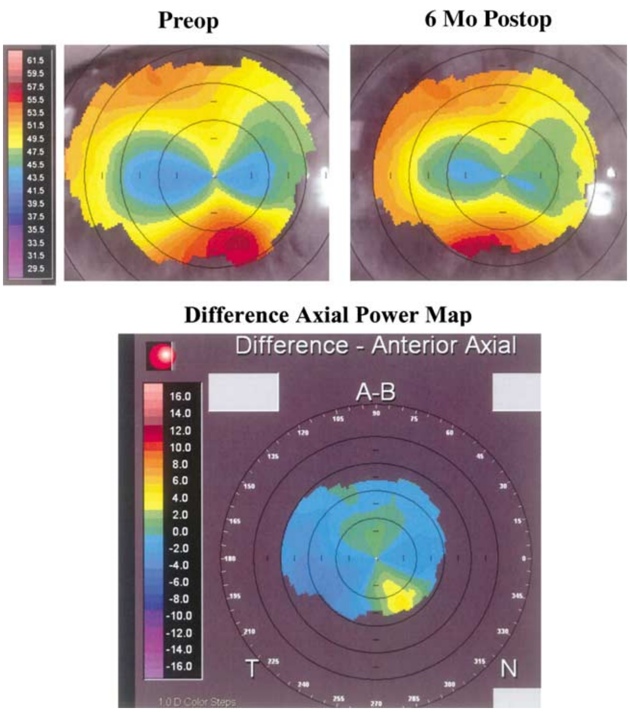


Figure 3. (Anderson) Axial radius of curvature (power) maps comparing the preoperative and the 6-month postoperative examinations in Case 1.

20/100, the BSCVA 20/50, the refraction −4.00 +5.00 × 70, and the keratometric cylinder 7.1@78. Thus, the patient had a 7.00 D decrease in myopia in 1 meridian (−11.00 D to −4.00 D), a 4.25 D decrease in the refractive cylinder (9.25 D to 5.00 D), a 4.00 D decrease in the keratometric cylinder (11.1@80 to 7.1@78), a 2-line improvement in UCVA (CF to 20/100), and a 1-line loss of BSCVA.

Orbscan anterior elevation maps (Figure 5) demonstrate a significant treatment effect centrally and smoothing and regularizing of the elevation maps preoperatively and 3 and 6 months postoperatively. There was no change in preoperative to postoperative BCVA contrast levels. The UCVA was so poor preoperatively that comparison with the postoperative uncorrected contrast level would have been meaningless. The axial radius curvature maps (Figure 6) show a large asymmetric cylinder preoperatively, which was reduced to a lower level of astigmatism at 6 months. The postoperative astigmatism also showed improved symmetry and regularity. The difference map shows substantial flattening inferiorly in the area of greatest steepness preoperatively.

Case 3

A 39-year-old white woman presented with a refraction of −5.75 +4.50 × 90 in February 2002. In March 2002, 2 pairs of 90-degree limbal relaxing incisions (LRIs) were made and in May 2002, PRK was performed. Before treatment with the CustomVis laser, the UCVA was 20/80, the BSCVA 20/30, and the refraction −0.50 +3.25 × 90. The keratometric cylinder was 6.5@78. Treatment with a 6.0 mm optical zone and a 9.0 mm treatment zone was planned, requiring a maximum ablation depth of 90 μm.

At 3 months, the UCVA was $20/20^{-1}$, the BSCVA $20/20^{+2}$, and the refraction −0.50 +1.00 × 120. At 6 months, the UCVA and BSCVA remained 20/20 and the refraction was −0.25 +1.25 × 90. The patient had a 2-line improvement in BSCVA, a 5-line improvement in UCVA (20/80 to 20/20), and a 2.00 D decrease in the refractive cylinder (3.25 D to 1.25 D). Contrast acuity improved significantly and was better with the postoperative UCVA than the preoperative UCVA or BCVA (Figure 7).

The anterior elevation maps are shown in Figure 8. The postoperative map shows a large area with a single color in the center, which should translate into improved visual acuity. The difference map again demonstrates the complexity of these custom treatments. The axial power maps in Figure 9 show a significant

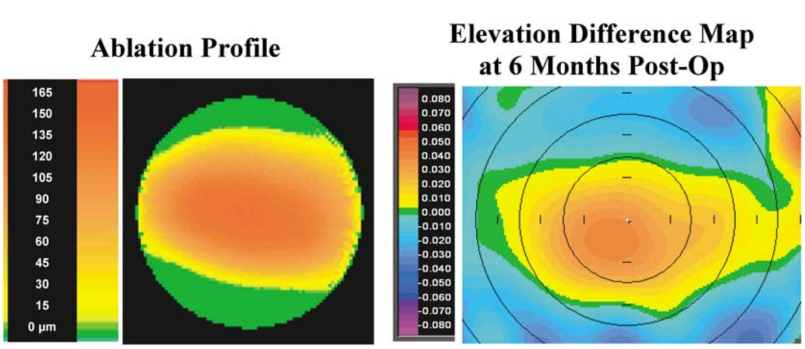


Figure 4. (Anderson) Comparison of the attempted (ablation profile) versus the achieved change in anterior surface elevation in Case 2 measured by Orbscan.

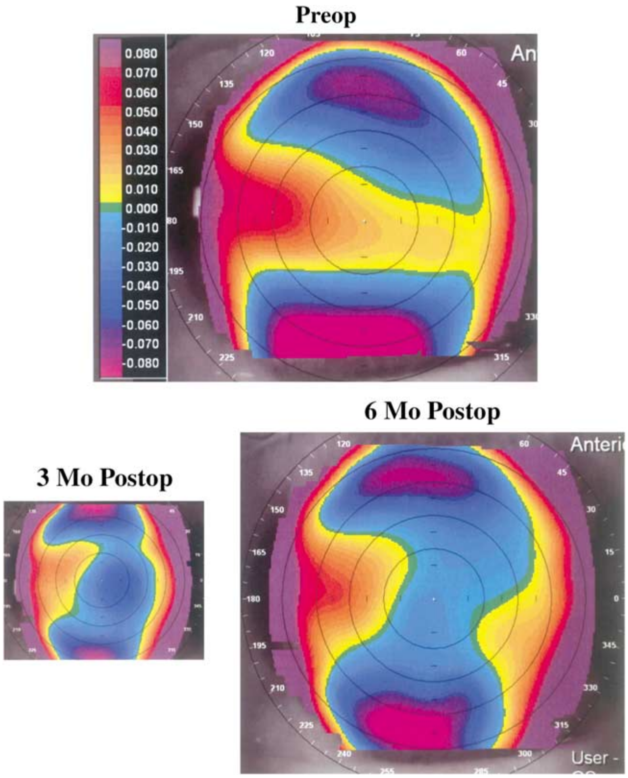


Figure 5. (Anderson) Preoperative and 3- and 6-month Orbscan anterior elevation maps in Case 2.

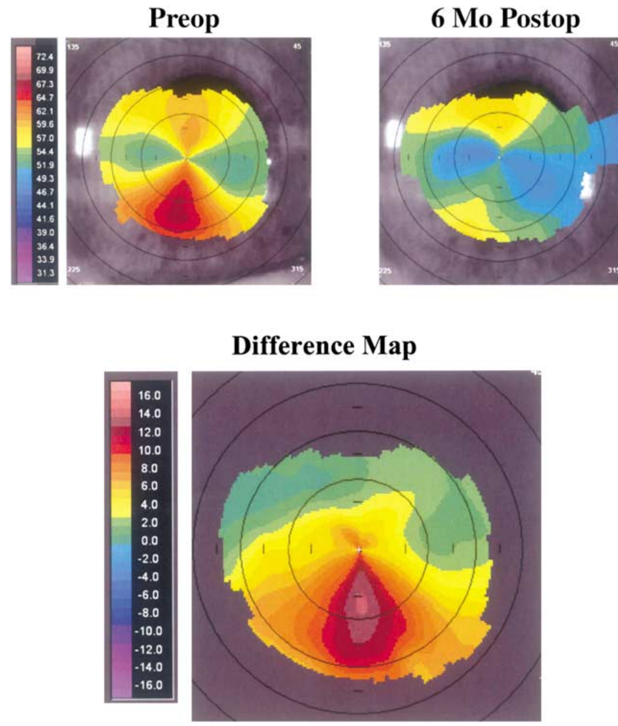


Figure 6. (Anderson) Axial radius of curvature (power) maps comparing the preoperative and the 6-month postoperative examinations in Case 2.

reduction in astigmatism 6 months after CustomVis laser surgery.

Discussion

Three difficult irregular astigmatism cases (2 post-PKP with other refractive procedures and 1 post PRK

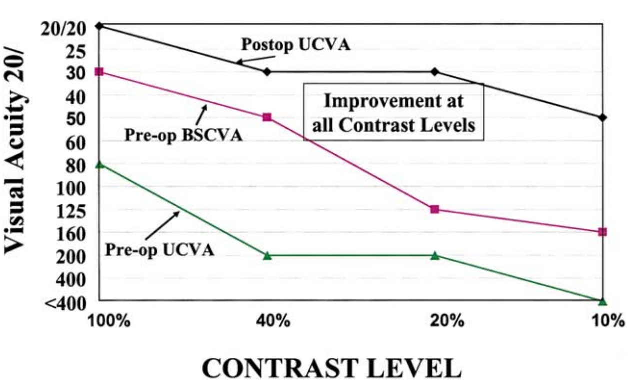


Figure 7. (Anderson) Contrast sensitivity measurements at 4 levels of contrast in Case 3 comparing preoperative measurements with and without correction to postoperative measurements without correction.

with LRIs for high astigmatism) were treated with good results.

The postoperative BSCVA in Case 1 improved to 20/25 (1 line) with an associated improvement in contrast and up to a 50% decrease in keratometric and refractive cylinders. The other post-PKP case (Case 2) demonstrated a 7.00 D refractive decrease in 1 meridian to −4.00 D, a 4.25 D decrease in the opposite meridian to +5.00 D, a 4.00 D decrease in the keratometric cylinder with a 1-line loss of BSCVA, and no loss of contrast sensitivity. In the post-PRK with LRI case (Case 3), the BSCVA improved to 20/20 from 20/30 with more than a 60% decrease in the refractive cylinder to 1.25 D and a marked improvement in contrast acuity.

Several characteristics of this laser, which was designed to perform custom ablation, may explain the observed results. For high resolution of customized ablations, a small spot is required.[11] However, to cover the corneal surface with a small spot, a fast pulse rate is required or the ablation takes too long, leading to corneal dryness. To avoid thermal heating of the corneal

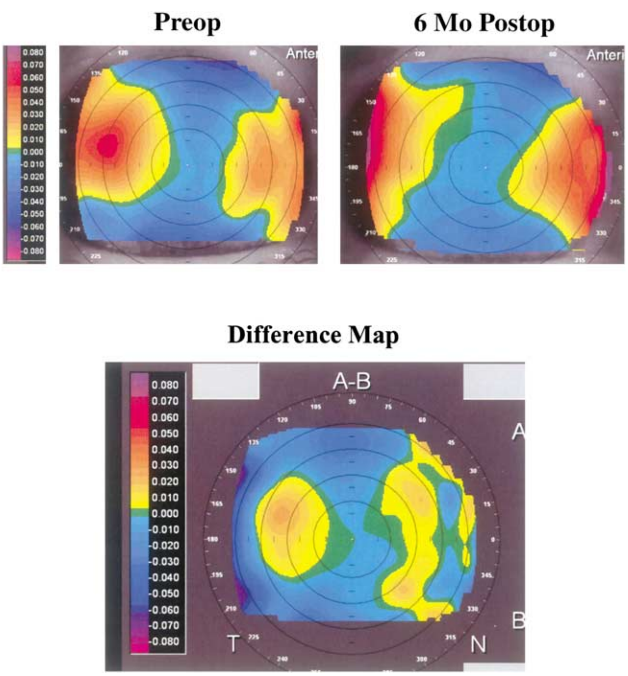


Figure 8. (Anderson) Preoperative and 6-month postoperative anterior elevation maps in Case 3.

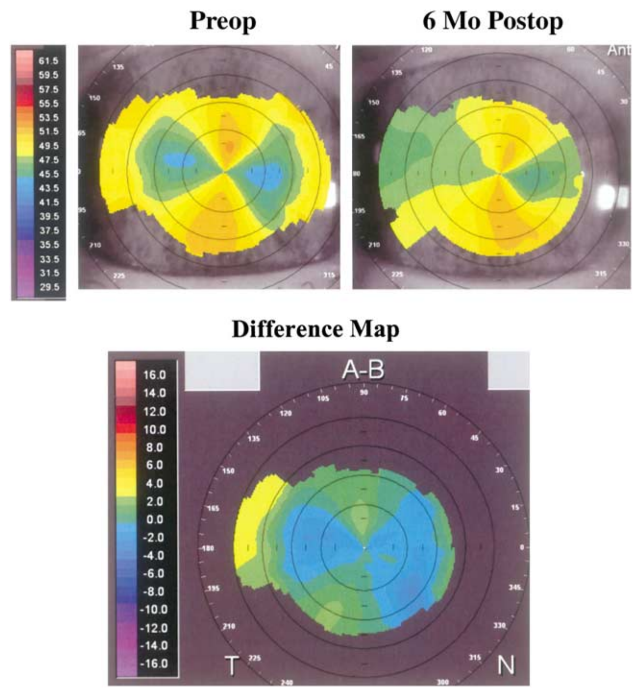


Figure 9. (Anderson) Axial radius of curvature (power) maps comparing the preoperative and 6-month postoperative examinations in Case 3.

surface and to respond to eye movements, fast tracking/scanning is essential.

The combination of an extremely small spot (0.6 mm), a fast pulse rate (currently 300 Hz with capabilities to increase), and ultrafast tracking/scanning for fast response to eye-tracker measurements (scanner is capable of making a 2.0 mm adjustment on the cornea in less than 0.5 milliseconds) resolves many obstacles to achieving excellent custom ablation results in irregular corneas. We believe that preoperative registration of topography data to a fixed point (the limbus) also tends to increase accuracy. If the pupil is used for tracking, the center of the pupil can shift as it changes size, potentially throwing off centration and registration. Although wavefront instrumentation was not used in these earliest cases, it will be used in future cases and be aligned using limbal registration.

The use of the 213 nm wavelength versus 193 nm for excimer lasers also tends to eliminate other potential variability. The sensitivity of achieved refractive correction to the degree of corneal hydration with the 193 nm wavelength excimer laser is well known.[12] Corneas allowed to dehydrate tend to be overcorrected, and overhydration leads to undercorrection. Absorption at the 213 nm wavelength is 1 to 4 orders of magnitude less sensitive to corneal hydration than at 193 nm[13]; thus, the refractive correction should be much less sensitive to changes in corneal hydration.

The use of a solid-state, diode-pumped Nd:YAG system may have some commercial advantages. Preliminary poly(methyl methacrylate) (PMMA) ablation comparing the excimer laser to the solid-state 213 nm laser has shown that with the solid-state laser beam, generation is efficient at producing less heat. Specifically, the maximum temperature generated with the 213 nm solid state was 38.4°C compared with 52.9°C in the excimer-treated PMMA. An Inframetrics thermal imaging camera was used. Thermal imaging testing is being performed on human and pig corneas (CustomVis, unpublished data).

With this solid-state laser, output energy levels are remarkably constant (an energy stability of 3.7 V ± 0.1 [SD] over 30 minutes), producing an excellent beam profile, and the laser requires standard wall current without special wiring. There are no dangerous gases in the laser tube that require replenishment. If properly designed, a solid-state laser should require less maintenance and have lower running costs than a 193 nm excimer laser.

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