Customized ablation algorithm for the treatment of steep central islands after refractive laser surgery

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Steep central island (SCI) formation after photorefractive keratectomy (PRK) and laser in situ keratomileusis (LASIK) represents a major drawback in the visual rehabilitation of patients after refractive laser surgery. Because of the small size of SCIs, current ablation algorithms are unable to properly calculate an ablation pattern for customized retreatment. We present the use of a new ablation algorithm for the treatment of SCIs that occurred after PRK or LASIK surgery. This algorithm uses a smaller zone of approximation and takes into account the spherical shift induced by removal of the SCI. In all 3 eyes treated, best spectacle-corrected visual acuity increased to 20/16 and remained stable at the 1- and 3-month follow-up, with disappearance of the SCI in corneal topography. This new treatment algorithm may be of benefit to patients experiencing visual side effects due to SCI formation after PRK or LASIK surgery.

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Today, refractive laser surgery of the cornea has become a safe and effective procedure. However, some technical advances have been achieved in only the past few years, and many patients who are treated have previous optical complications such as small optical zones, decentered ablation, and the formation of steep central islands (SCIs).[1–6] Whereas a number of strategies and customized treatment techniques have been developed to overcome the first 2 issues,[3,7–11] the latter often remains unresolved with current treatment algorithms.

Recently, attempts were made to treat SCIs by topography-guided customized treatments. However, current ablation algorithms have difficulty properly approximating difference height maps due to the small size of the SCI. We present a new ablation strategy to correct for SCIs after previous photorefractive keratectomy (PRK) and laser in situ keratomileusis (LASIK).

TECHNIQUE

Definition of Steep Central Islands

The definition of diameter and steepening of SCIs varies among authors.[2,12–14] We use the definition established by Krueger et al.[2] in which SCIs are defined as areas of steepening of at least 3 dimensions and 1.5 mm in diameter.

The Ablation Algorithm

The principle of the new algorithm is based on the fact that the surface representation of irregular corneas by means of an aspheric surface is associated with a certain amount of fitting error, especially in case of spatially localized irregularities. Thus, fitting an asphere to a corneal shape with an SCI and subtracting this aspheric fit from

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the original height data, one will be left with a difference height map of the SCI that can be used for an ablation profile. In our study, the data used for deriving a customized profile for central island treatments were based on corneal topography height maps provided by the WaveLight Topolyzer System using the central 3.5 mm only. The height data are fitted to an aspheric shape function and in a second step subtracted from the original data set. The residual height information, which also includes the measured height information of the SCI, was exported to the WaveLight "eye-Q" laser system. The required approximation by means of single laser spots (spot diameter 1.0 mm) was performed using a special adapted version of the WaveLight T-CAT program (topography-guided customized ablation treatment). The proposed ablation pattern was modified adding myopic correction within the SCI area until a homogenous ablation pattern with zero ablation depth at the edges and the height of the SCI as calculated by the Munnerlyn's formula was met (usually −0.5 to −1.0 D). Test ablations were performed on special test targets (WaveLight Laser Technology) before each treatment and visually compared to the planned ablation profile. Treatment was performed using a scanning-spot laser with a 0.8 mm spot size, a Gaussian-like spot profile, and a 400 Hz repetition rate (WaveLight Allegretto). The eye-tracking system had a response time of fewer than 6 milliseconds.

Preoperative Examinations, Treatment, and Postoperative Care

Preoperative examination included uncorrected visual acuity (UCVA) and best spectacle-corrected visual acuity (BSCVA), slitlamp examination of the anterior segment, fundus examination, corneal topography (Topolyzer, WaveLight Laser Technologies), and optical pachymetry (Pentacam). Treatment was performed using the WaveLight Concerto laser system and was performed as LASIK or PRK. In the case of re-LASIK treatment (representative case reported here), the original flap was lifted before ablation. At the end of treatment, a bandage contact lens (BCL) was applied to the eye; the BCL was soaked with antibiotic eye drops (LASIK) or antibiotic ointment was put on the cornea before the BCL was applied (PRK). In LASIK patients, the BCL was removed the next day and the cornea was examined for signs of inflammation. Dexamethasone eyedrops were then applied twice daily for 1 week, followed

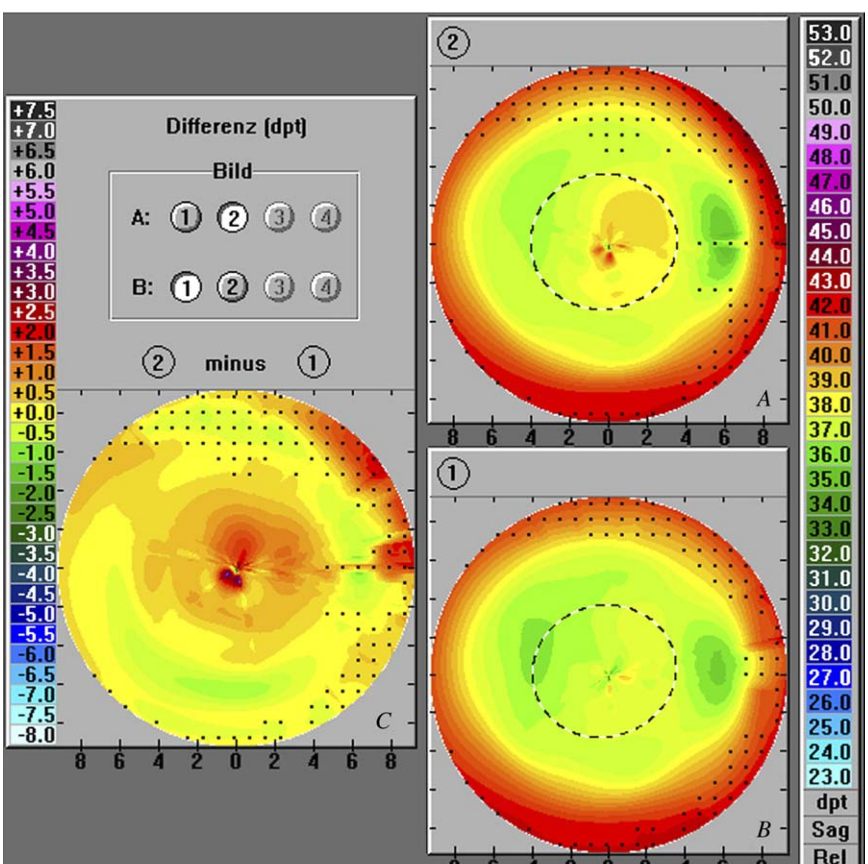

Figure 1. Preoperative and postoperative corneal topographies (axial representation) and the difference map. The preoperative topography shows the SCI (*A*), whereas 1 day after surgery the SCI has disappeared (*B*). The difference power map of preoperative versus postoperative status shows that ablation occurred (*C*).

by a single application daily for another week. Postoperative follow-ups were performed at 1 day, 1 month, and 3 months. Patients who had PRK were examined daily for closure of corneal epithelium, and the BCL was removed 3 days after surgery. After complete closure of the epithelium, dexamethasone eyedrops were applied twice daily for 6 weeks. Additional postoperative follow-ups were performed at 1 month and 3 months.

RESULTS

In the past year, this technique was used in 3 cases. One representative case is presented. The other 2 patients were treated accordingly, and in both cases the UCVA increased from 20/60 to 20/16 in the early and late postoperative period.

Representative Case

A 47-year-old man was examined in November 2004. A history of previous LASIK in 2003 for −5.0 −0.75 × 5 in the right eye was noted. Before the procedure, the BSCVA in the right eye was 20/16. At the first examination, postoperative UCVA and BSCVA was 20/40 with improvement with pinhole to 20/20. Corneal topography showed an SCI (Figure 1, *A*) and a central corneal thicknesses of 500 µm. The patient reported glare and halos at night and inconvenience of vision.

After the flap was relifted, topography-guided LASIK was performed. On the first postoperative day, UCVA was 20/20 and increased to 20/16 at 1 month. At the 1-month and 3-month follow-ups, corneal topography revealed disappearance of the SCI (Figure 1, *B*). Under mesopic conditions, glare and halos were diminished.

DISCUSSION

An SCI represents an area of localized steepening in the central cornea leading to multifocality. Steep central islands can occur after both PRK and LASIK.[1,6] Symptoms include ghost imaging, halos, glare, night-driving disability, reduced BSCVA, reduced contrast sensitivity, and monocular diplopia leading to slow visual rehabilitation.[2,15] Under experimental conditions, SCI formation has been almost exclusively observed after treatment with broad-beam lasers and rarely with scanning-slit and flying-spot systems.[14] In PRK, SCIs occur in up to 70% of cases 1 week after treatment.[2] However, they tend to resolve with time to an incidence of 2% at 6 months.[3,4] Apparently, in PRK, the strong epithelial and stromal healing response levels out irregularities, leading to gradual disappearance of SCIs. In LASIK, in contrast, SCI formation occurs in only 5% to 12% of cases 1 week after treatment.[4,12] However, at 6 months, 3 of 4 SCIs are typically still present.[4] This might be due to the nature

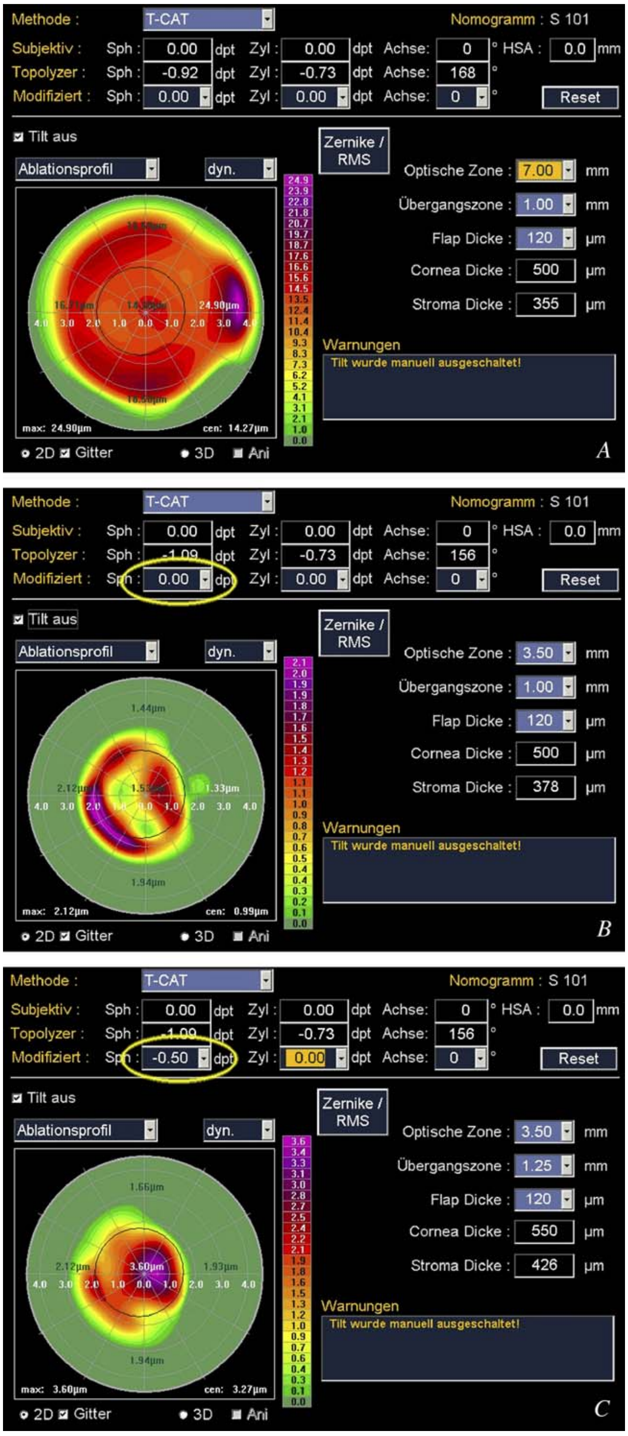

Figure 2. Comparison of different ablation patterns. When using a 7.0 mm approximation zone (*A*), the SCI is significantly undertreated. When using a 3.5 mm approximation zone without spherical correction (*B*), the SCI is again not addressed. When adjusting the spherical correction to −0.5 D within the 3.5 mm approximation zone (*C*), the SCI is fully treated.

of the LASIK procedure, leading to a limited epithelial and stromal wound-healing reaction.

Although the incidence of SCI formation is now significantly reduced by the use of flying-spot laser systems, it should be regarded as important in clinical routine because a large number of patients who have been treated with first- and second-generation laser systems still require retreatment for correction.

The nature of SCI formation remains unclear. In the past, 2 different mechanisms were hypothesized as responsible. Ablation shock waves might induce intrastromal shifts of water, leading to different levels of corneal hydration in the center and the periphery,[16,17] and the laser beam might be blocked centrally by the ejected vortex plume of gaseous and particulate debris generated during surgery.[2,12,18] In support of the latter hypothesis, Cua and Pepose[19] report an increased incidence of SCIs after LASIK in a laser system in which the plume evacuator was accidentally installed improperly. To prevent SCI formation, various laser systems incorporated anti-SCI programs in which a specific overcorrection within the central 25% of the ablation zone should compensate for the undercorrection. However, results were not always satisfactory.[3,14,20–22] Moreover, other attempts were undertaken to correct SCIs by topography-guided retreatments using topography only as a descriptor of the power of the SCI rather than the actual height data, still relying solely on Munnerlyn's formula and a standard phototherapeutic keratectomy (PTK) or PRK formula (Figure 2).[23] However, current algorithms are unable to properly approximate the difference height map because of the small size of the SCIs.

We present a new ablation algorithm based on the following principle: Precise corneal topography allows the generation of a correct height map. The difference to the best-fit conoid may then be calculated and approximated by Zernike polynomials. The key point of the technique lies in the precision of approximation, which is dependent on the ablation area. Figure 3, *A* and *B*, demonstrates the Zernike fit error for different areas of approximation.

When using the standard approximation area with a diameter of 7.0 mm, the Zernike fit error is on the order of microns which is close to the height of the island itself. In consequence, most of the island would be missed using this algorithm (Figure 3, *A*). However, when decreasing the area of approximation to 3.5 mm, the Zernike fit error is in the submicron range (at least in the area of interest) (Figure 3, *B*). Furthermore, the spherical correction must be adjusted because removal of the SCI includes a spherical shift that is not related to the refraction of the eye treated. We adjusted the sphere in a way that no tissue is removed at the edges of the ablation area (Figure 3, *C*) and the height of the SCI as determined by Munnerlyn's formula is removed. In the case presented, the refractive height of the

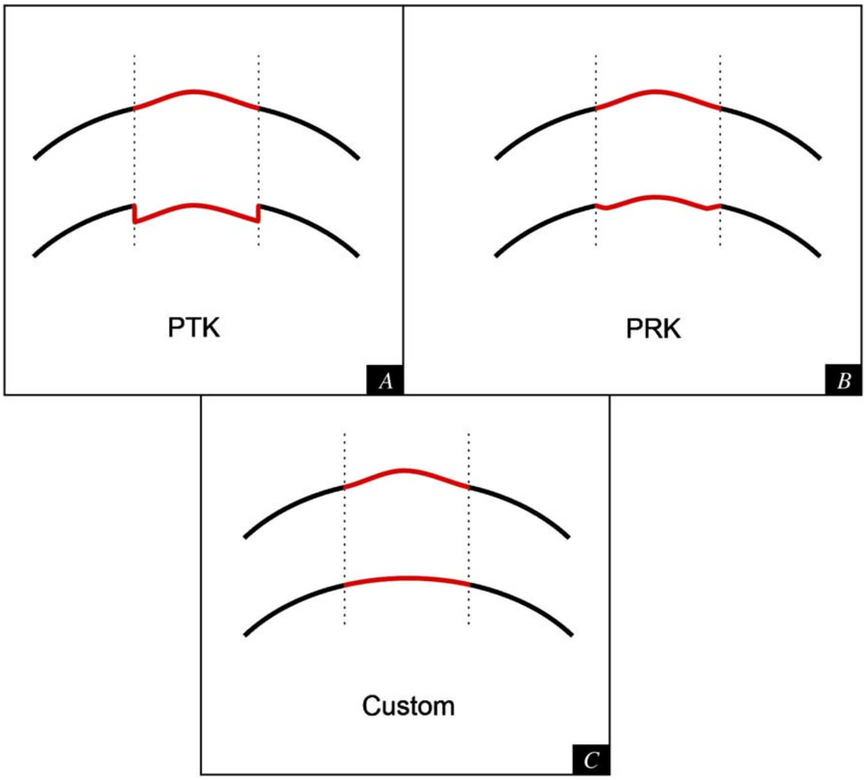

Figure 3. Standard and customized treatment strategies for the correction of SCIs. In previous studies, either PTK (*A*) or PRK (*B*) ablation modes were used in combination to assess a SCI's height by Munnerlyn's formula. Owing to the nature of the ablation algorithms, neither a PTK (*A*, top-hat) nor a PRK (*B*, parabolic) algorithm fully correct for the CSI, whereas the new customized algorithm (*C*) provides full CSI correction.

SCI was 2.0 D and the diameter was 2.0 mm. According to Munnerlyn's formula, the height was $1/3 \times 22 \times 3$ µm = 4 µm.

The peak amount of tissue removed is 3.6 µm, which is close to the height calculated. In 1998, Manche et al.[23] presented cases of SCI removal using a PTK ablation mode and proposed the use of a PRK mode to improve results. However, these approaches do not address the true shape of the SCI but match only the central amount of tissue removed by the height of the SCI (Figure 2, *A*, *B*). Usually, SCIs are not symmetric and have a higher refractive power in the center with variable slopes in different meridians. Therefore, customized ablation algorithms such as the one presented here are needed. The strategy whether to lift the flap or perform a surface ablation clearly depends on the depth of ablation. Scarring of the cornea should occur only if Bowman's membrane is penetrated during ablation. In cases in which the ablation depth is larger than 7.0 or 8.0 µm, we suggest relifting with subsequent ablation in the stromal bed or, alternatively, performing PRK on the flap followed by the application of mitomycin-C (2 sponges soaked with mitomycin-C 0.02%, 1 minute of action each).

Our approach was to decrease the area of approximation to more accurately treat the SCI. An alternative approach would be the use of orders of approximation higher than the 6th order. Because higher-order approximations using Zernike polynomials are inconvenient and slowly converting, the mathematical alternative would be Fourier or Taylor analysis. Although this approach has already been used clinically, we have not found scientific and peer-reviewed reports on this topic.

In summary, the new ablation algorithm represents a promising step toward the visual rehabilitation of patients with visual impairment due to SCI formation after refractive surgery.

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