The future of laser refractive surgery is exciting with the potential for ever-improved postoperative visual performance. In the past, the operative goal has been 20/20 uncorrected visual acuity with zero residual refractive error. Criteria for a successful procedure are no longer 20/40 or better with ±1.00 diopter (D) of residual refractive error, because neither surgeons nor patients are satisfied with such gross measurements of visual performance. Hence, considerable research effort is being devoted to develop customized procedures for each patient. The new goal is 20/10 uncorrected visual acuity with aberration-free postoperative vision. How can these lofty goals be accomplished? First, lasers have been improved with the development of scanning, small spot systems, as opposed to broad-beam systems. Scanning systems have brought customized procedures into the realm of feasibility. Second, more comprehensive and sophisticated input data can be used to guide the laser based on individual patient measurements, as opposed to the simple refractive sphere and cylinder. Two types of approaches are currently being pursued—wavefront-guided and topography-guided procedures. Early results are promising, yet neither approach has demonstrated consistently superior results to non-guided procedures in controlled, scientific studies. Is a piece of the perfect vision puzzle still missing? Is there an additional, complimentary approach to customization that has yet to emerge? Are we leaping into the future ahead of our understanding of how these procedures may be implemented to be optimally successful?

Munnerlyn and colleagues\(^1\) gave us an elegant analysis of how corneal surface shape may be altered to correct both myopia and hyperopia. His geometric approach can be thought of as a “shape-subtraction” model, where tissue of an appropriate profile is simply “subtracted” using an excimer laser to produce the desired surface curvature. Essentially, the cornea is treated like a piece of plastic to be sculpted into the ideal surface shape. The Munnerlyn approach, combined with empirical experience, has been relatively successful in correcting spherical and cylindrical errors for the majority of patients treated to date. However, only 50% to 85% achieve 20/20, despite greater than 90% of patients being “satisfied.” In addition, significant postoperative optical aberrations are produced using conventional algorithms\(^2-4\), encouraging the development of aberration-reducing ablation profiles.

To improve the percentage of patients who achieve postoperative visual acuity of 20/20 or better, as well as to minimize optical aberrations, it is important to examine critically our current conceptual model of laser refractive surgery. There are three assumptions inherent in the shape-subtraction model that are not supported by the data, even though they currently drive algorithm development. These flawed assumptions are: 1) the only portion of the cornea that is changed is within the ablation zone; 2) what you cut is what you get; and 3) even if there are changes outside the ablation zone, they don’t affect central vision. Assumption #1 can be invalidated by anyone who studies critically postoperative topography from photorefractive keratectomy (PRK) or laser in situ keratomileusis (LASIK). Outside the ablation zone, corneal curvature increases significantly\(^5\), with the appearance of the characteristic red ring (high dioptric value) surrounding the central flattened zone.
after a myopic procedure. (Be sure to examine the tangential map, not the axial.) In addition, elevation and pachymetry also increase outside the ablation zone, as measured by Orbscan topography.\(^5\) (Fig 1). This finding of a seemingly paradoxical addition of stromal tissue outside the ablation zone, in the presence of epithelial thinning, has been validated in this issue by Reinstein and coauthors, using high-frequency ultrasound. The stromal difference map calculated between the preoperative and postoperative condition (page 423, Figure 7, map #8) presents a positive ablation depth in the center, indicating decreased thickness of the central stroma, and negative ablation depth outside the ablation zone, indicating increased peripheral stromal thickness. The increase in peripheral thickness is on the order of 10 to 20 \(\mu m\), similar in magnitude to what we have measured with the Orbscan.

Assumption #2 can be invalidated by examining the predicted topographic result with a known ablation profile, and comparing that to the measured result. Summit Technologies agreed to supply their proprietary ablation algorithms for several LASIK patients being treated with a Summit Apex Plus and a Krumeich-Barraquer microkeratome. The actual ablation algorithm was subtracted from the preoperative topography (measured with an Orbscan II) to generate a predicted postoperative topography. The predicted topography was subtracted from the measured postoperative topography to generate an error map, which is given in Figures 2 and 3 for two eyes, along with the measured results. Two important features emerge. First, the red area in the center of the tangential curvature error maps corresponds to the central island treatment. This treatment involves delivery of extra pulses in the center of the cornea, which would cause excessive flattening IF they were not compensating for the central island phenomenon—the genesis of which is not yet understood. Therefore, the curvature error maps appear to have a central island even though the postoperative topographies do not. Second, the red areas outside the ablation zone on the tangential curvature error maps correspond to the unexpected increases in curvature, which are not predicted by the shape-subtraction model.

Assumption #3 raises the question: How can documented changes outside the ablation zone affect central curvature? The answer to this question lies in the biomechanics of the corneal response to laser
refractive surgery\textsuperscript{7-10}, which is unaccounted for in current ablation algorithms. Radial keratotomy (RK) taught us that the cornea is a biomechanical entity, and that by changing its structure, the surface shape would change—even without removal of any tissue. If the cornea were similar to a homogeneous piece of plastic, RK would not have worked, because a biomechanical response to the structure-altering incisions would not have occurred. Yet, with the development of laser refractive surgery, this experience was ignored. Laser refractive surgery, whether PRK or LASIK, changes the corneal structure—in a different manner than RK, but a significant change nonetheless. Corneal lamellae are permanently severed by the laser, which will cause a change of central shape in addition to that imposed by the ablation profile. This is a distinctly different mechanism than the biomechanical decompensation that may occur with less than 250 \( \mu \text{m} \) of intact residual stromal bed. At this depth, another mechanism takes over the response and may produce ectasia.

A conceptual model is presented in Figure 4 that predicts biomechanical central flattening as a direct consequence of severed corneal lamellae. Rather than a piece of plastic, the cornea may be conceived as a series of stacked rubber bands (lamellae) with sponges between each layer (interlamellar spaces.
filled with extracellular matrix). The rubber bands are in tension, since there is a force pushing on them from underneath (intraocular pressure), and the ends are held tightly by the limbus. The amount of water that each sponge can hold is determined by how tautly the rubber bands are pulled. The more they are pulled, the greater the tension each carries, the more water is squeezed out of the interleaving sponges, and the smaller the interlamellar spacing. This is analogous to the preoperative condition in Figure 4A. After laser refractive surgery for myopia, a series of lamellae are severed centrally and removed, as shown in Figure 4B. The remaining peripheral segments relax, just like the taut rubber bands would relax once cut. With the reduction of tension in the lamellae, the squeezing force on the matrix is reduced and the distance between lamellae expands, analogous to the sponges taking up water if the rubber bands are cut. This allows the periphery of the cornea to thicken. Due to the crosslinking between lamellae, the expansion force pulls on the underlying intact lamellae, as indicated by the arrows pointing radially outward. An outward force in the periphery pulls laterally on the center and flattens it. Thus, the cornea will flatten centrally with any procedure that circumferentially severs lamellae. This includes myopic profiles, hyperopic profiles, constant depth phototherapeutic

Figure 3. A) Preoperative elevation (left) and tangential curvature (right). B) One day postoperative elevation (left) and tangential curvature (right) after a -3.82 D LASIK procedure with a Summit Apex Plus laser and a 6.0 mm diameter ablation zone. Black reference circles have diameters of 8.00 mm. C) Elevation error map (left) and tangential curvature error map (right) generated by subtracting known ablation algorithms (supplied by Summit Technologies) from the preoperative topography (A) and generating a predicted postoperative topography, which was subtracted from the measured topography (B) to create the difference maps shown in (C). The red area in the center of the tangential error map represents the central island pretreatment and the outer red area represents the biomechanical response of the cornea. White reference circles have diameters of 5.5 mm, 6.5 mm, and 9.0 mm.
keratectomy (PTK) profiles, as well as the simple cutting of a LASIK flap. The biomechanical flattening enhances a myopic procedure, works against a hyperopic procedure, and will cause flattening with a hyperopic shift in a non-refractive PTK.

Evidence of the biomechanical response has been presented\textsuperscript{7-10}, and will be described in future publications.\textsuperscript{11,12} Most recently, in cooperation with two surgeons, we measured the shape of the LASIK flap using a Keratron Scout, which is a portable, Placido-based topography instrument. It can be used intraoperatively to acquire topography of the flap immediately after it is cut but before it is reflected, and thus prior to ablation. Figure 5 demonstrates that the characteristic red ring on this patient is at least partially a biomechanical phenomenon, since it appears BEFORE any tissue is removed. Cutting the flap alters the corneal structure in the same way described by the model presented (Fig 4). The difference is that the severed lamellae are not ablated, but are put back in place. Therefore, the stability of the greater than 1.00-D average central decrease in curvature shown by the difference map in Figure 6, which is generated simply by cutting the flap, is not known. Investigations are currently underway.

Postoperative corneal shape, and thus visual performance, is a function of at least three factors: the ablation profile, the healing process, and the biomechanical response of the cornea to a change in structure. Only by increasing our knowledge of the interaction of these factors can predictability in PRK and LASIK be improved. This has important implications in the development of new ablation algorithms and wavefront or topography-guided procedures. It points to an optimization approach, rather than a priori defining an ideal corneal shape that is ultimately not achievable. There are only certain shapes a cornea will assume biomechanically. For example, the deeper the peripheral cut in a myopic procedure to generate a potentially desirable postoperative prolate shape, the greater the number of severed lamellae and the greater the biomechanical central flattening response to counter the effect. Both the ablation profile and the biomechanical response need to be taken into account, as well as the healing response—which is less with LASIK than PRK and is difficult to quantify. Therefore, step one is to gain a better understanding of corneal response to standard ablation profiles in well-controlled studies, before moving into the realm of customized procedures. The outcome measures in these controlled studies should be more comprehensive than in the past to allow us to thoroughly interrogate the corneal response. This means we need to
measure and report the outcome error in terms of the predicted topography and/or the predicted wavefront, not just visual acuity and refractive spheres and cylinders.

What is the future of customized laser refractive surgery? Can we better predict postoperative shape and visual performance? Can we reach 20/10 visual acuity with minimal aberrations? These are achievable goals if we unravel the controllable and/or predictable sources that contribute to the final corneal shape and visual outcome. Which instruments will be important to guide the laser ablation? It is likely that both aberrometers for wavefront analysis and videokeratoscopes for corneal topography will be necessary to program the laser profile in order to consistently achieve an optimized result. Wavefront analysis will provide the means necessary to measure and minimize aberrations. Topography will help us measure and predict the biomechanical corneal response in ways that have not been elucidated. The future of customized laser refractive surgery is bright, but we must step into the future with a better understanding of our current procedures, rather than leap without knowing where we will land.
REFERENCES


