Biomechanics of the Cornea

Analyzing how the cornea responds to surface ablation, sub-Bowman's keratomileusis, and LASIK.

BY CYNTHIA ROBERTS, PHD

Refractive surgery manipulates the inherent biomechanical properties of the cornea. To optimize their success, surgeons should have a firm understanding of the cornea's basic structure and its dynamic response to different procedures. In addition, they should be able to detect abnormalities that can adversely affect outcomes. This article describes how my colleagues and I are using the Ocular Response Analyzer (ORA; Reichert Ophthalmic Instruments, Inc., Depew, NY) to quantify the effects of different refractive procedures on corneal biomechanics.

BIOMECHANICAL BASICS

Refractive surgeons know that severing corneal lamellae, whether by placing arcuate incisions, ablating tissue with an excimer laser, or creating a LASIK flap (essentially a circumferential arcuate incision) induces central corneal flattening.

John Marshall, PhD, noted that increasing the size of the ablation zone in PRK decreased the procedure's variability and improved its predictability (oral communication, fall 2003). Four years postoperatively, the patients who underwent PRK with a 5-mm ablation zone had a wider range of refractive outcomes than those who underwent the same procedure with a 6-mm zone. The difference between the groups was likely not optical in nature, but biomechanical. Increasing the size of the ablation zone removed more cross-links between the peripheral lamellar segments and thereby minimized the cornea's biomechanical response to the procedure.

My colleagues and I observed a similar phenomenon

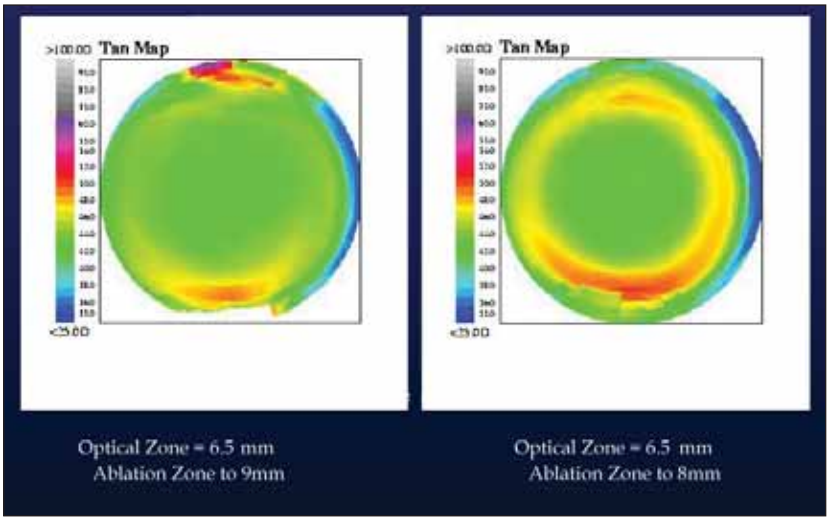


Figure 1. The average of 30 post-LASIK tangential topographical maps of contralateral eyes with matched optical zones showed that the Technolas 217A laser (left) induced less spherical aberration than the Visx Star S3 laser (right). The eyes treated with the Visx laser had greater paracentral steepening due to their smaller ablation zone (optical plus transition zones).

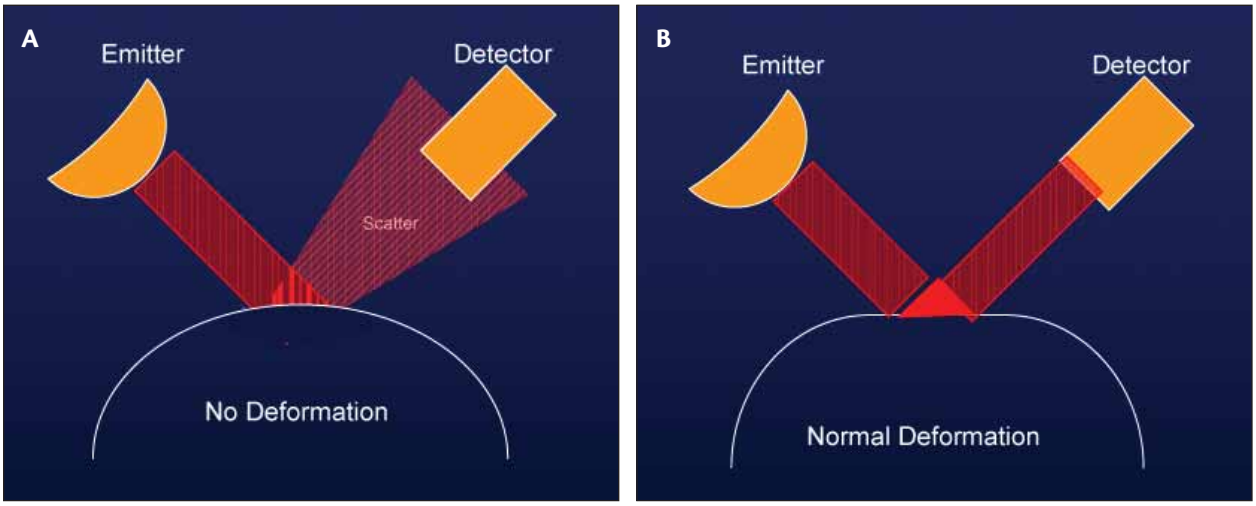


Figure 2. Before the ORA directs a stream of air toward the eye, only a small amount of the light reflected off the convex cornea aligns with the detector (A). During corneal applanation, the light fully aligns with the detector (B) and is recorded as an infrared signal peak on the ORA signal plot.

in a study of 30 patients who underwent treatment for low-to-moderate myopia with the Technolas 217A laser (Bausch & Lomb, Rochester, NY) in one eye and the Visx Star S3 excimer laser (Advanced Medical Optics, Inc., Santa Ana, CA) in the other.[1] Although all eyes received a 6.5-mm optical zone, those treated with the Visx laser had a total ablation zone (including the transition zone) of 8 mm versus 9 mm with the Technolas laser. At 6 months postoperatively, we found a greater degree of induced spherical aberration in the eyes with smaller transition zones. Because the eyes in the Visx group had more intact interlamellar cross-links in the peripheral cornea than those in the Technolas group, they had a greater biomechanical response to ablation (Figure 1). This study also showed that the transition zone, and thus the total ablation zone, is not neutral and should be considered in comparisons of different corneal procedures.

In 2005, Reichert Ophthalmic Instruments, Inc., introduced the ORA, a new instrument that measures the biomechanical properties of corneal tissue. My colleagues and I have used this instrument to compare the effects of different refractive procedures on the cornea. To understand the results of our studies, however, one must first understand how the ORA measures the cornea's viscoelasticity and the significance of the newly defined parameter of corneal hysteresis.

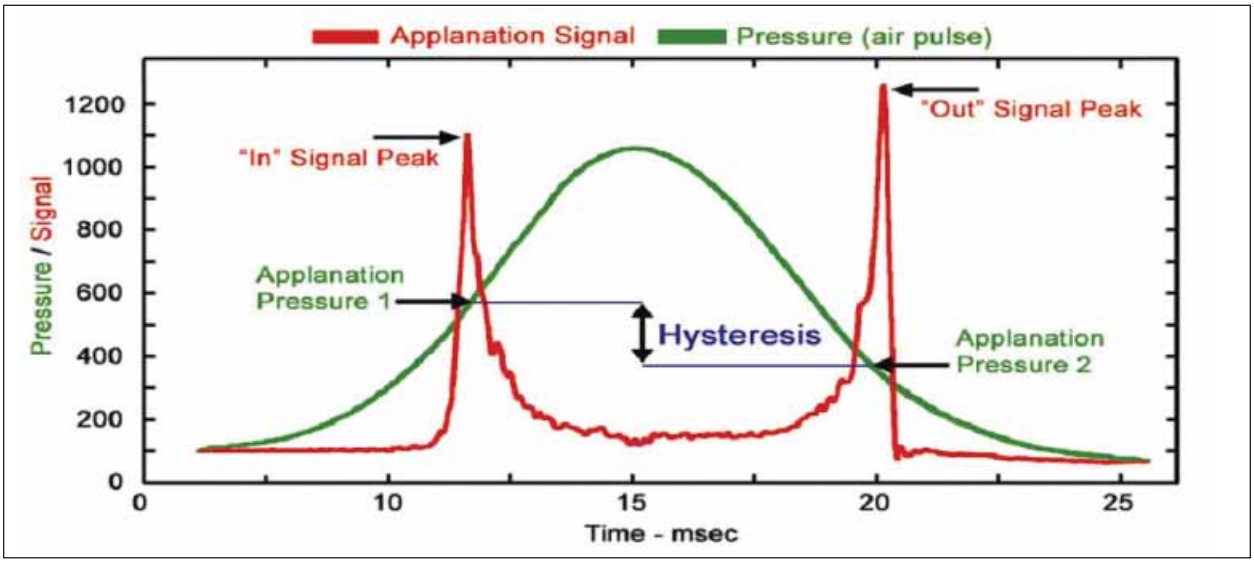
QUANTIFYING CORNEAL BIOMECHANICS

The ORA features an infrared-light emitter, a light detector, and a tube that directs a stream of air toward the cornea. At the beginning of the examination, the light from the emitter is focused on the convex cornea. Figure 2A shows the distribution of light in relation to the instrument's detector. Note how the convex cornea reflects the light in a broad pattern that produces only a small signal on the detector. As pressure from the device's air jet flattens (applanates) the cornea, the reflected light focuses on the infrared detector (Figure 2B).

The ORA records this event (P1) and continues to direct air toward the cornea until it becomes concave, the light disperses, and the applanation signal is reduced. The cornea undergoes a second applanation event (P2) as the air pulse's pressure is reduced, and the structure returns to its baseline convex shape.

Figure 3 shows the information obtained by the ORA. The difference in pressure between P1 and P2 represents hysteresis, a quantification of the cornea's ability to absorb and/or dissipate energy and a measurement of corneal viscoelasticity. In addition, the number of photons that hit the ORA's detector during the applanating events may provide information about corneal stiffness.

Applying pressure to a stiff versus soft cornea produces a wider area of applanation that is registered as a higher peak on the red curve in the ORA signal plot (Figure 3). We can use the peaks' relative heights to differentiate between normal and abnormal corneas, because the former flattens more symmetrically than the latter. Conditions such as keratoconus and ectasia may be detected with the ORA due to a dynamic misalignment of the light reflected off the cornea. Eyes with these conditions tend to produce a lower signal peak during the first applanation event, possibly because of



(Image courtesy of Reichert Ophthalmic Instruments, Inc.)

Figure 3. The green line on the ORA signal plot indicates the pressure exerted on the cornea during the applanating events, and the red line shows the amplitude of the infrared signal. The first and second peaks occur during the inward and outward applanation events, respectively.

the cornea's asymmetric deformation. Recently, my colleagues and I determined that the height of the first infrared peak is negatively correlated with the severity of keratoconus[2] and positively correlated with age,[3] indicating that corneal stiffness decreases and increases with these parameters, respectively.

In addition, other research has shown that creating the LASIK flap and ablating tissue during refractive surgery change the cornea's biomechanical properties.[4]

INTERPRETING CHANGES IN SIGNAL HEIGHT

My colleagues and I collaborated with Jay Pepose, MD, to compare the effect of the flap's creation and subsequent ablation on the IOP and corneal biomechanics after LASIK and surface ablation.[5] All patients were evaluated with the ORA before and after undergoing bilateral LASIK, bilateral LASEK, or monocular LASIK. The flaps were matched by thickness in the two LASIK groups, as was the ablation depth among the patients in the two bilateral treatment groups. The monocular LASIK group underwent a presbyopia-correcting procedure with a very shallow ablation. We determined the relative effects of these procedures within and between groups by comparing the changes in IOP and biomechanic parameters, as well as the heights of two infrared peaks on the ORA signal plot.

Surface ablation did not significantly affect patients' postoperative IOPs (measured with the ORA, the Pascal Dynamic Contour Tonometer [Ziemer USA, Inc., Wood River, IL], and a Goldmann tonometer). The same techniques showed greater changes in measured IOPs in both LASIK groups than in the LASEK group, which suggested that the flap has a greater effect on this parameter than the depth of ablation.

We recorded the highest change in hysteresis (reflected by a greater change in P2 than in P1) in the eyes that received bilateral surface ablation. These eyes also had the least change in measured IOP postoperatively. The eyes that underwent monocular LASIK with the shallowest ablation showed the least alteration in hysteresis, indicating that the change in this biomechanic parameter is driven by ablation depth.

Why does surface ablation cause a greater change in hysteresis than LASIK? Is the difference related to where the ablation occurs in the corneal stroma? Does it mean that eyes that undergo surface ablation are weaker? The answer to the last question is no, which becomes evident if the overall changes in the ORA signal are considered.

We can learn more about the effect of LASIK and LASEK on corneal biomechanics by analyzing the characteristics of the ORA signal plot in more detail. In the LASIK eyes, the height of both infrared signal peaks dropped postoperatively.[5] This change was more symmetric than with surface ablation (in which P2 changed more than P1), which explains the different effects of the two procedures on corneal hysteresis. It is important to remember that hysteresis measures the viscoelasticity of the cornea, not its stiffness. The height

of the first infrared signal peak is greater after surface ablation than after LASIK, which is consistent with a stiffer cornea in the surface ablation group. As previously described, the infrared signal peak increases as the cornea becomes stiffer with age[3] and decreases as the cornea becomes softer with increasingly severe keratoconus.[4]

> "We should not use hysteresis exclusively to evaluate the effects of refractive surgery on the cornea."

LASIK significantly reduces the height of both infrared signal peaks, an indication that although this procedure does not change corneal hysteresis as much as LASEK, it has a greater overall effect on the ORA signal plot. Thus, we should not use hysteresis exclusively to evaluate the effects of refractive surgery on the cornea. To understand how different procedures change corneal biomechanics, we must also take a closer look at the infrared signal peaks.

Based on these results, my colleagues and I concluded that:

- The flap's creation has a greater effect on the measurement of IOP than ablation;
- The depth of the ablation has a greater effect on biomechanic parameters such as corneal hysteresis and corneal resistance factor than the flap's creation; and
- Both the flap's creation and the depth of the ablation act additively to induce changes in IOP and/or corneal biomechanics.

During the Sixth International Congress on Advanced Surface Ablation & SBK in Fort Lauderdale, Florida, Daniel S. Durrie, MD, presented the results of a study in which he performed advanced surface ablation on one eye and sub-Bowman's keratomileusis (SBK) on the contralateral eye of 25 patients.[6] The parameters for the two surgical groups were carefully matched and controlled. All subjects received a 6.5-mm optical zone with a 1.25-mm blend zone. On average, there was no difference between the treatment groups' hysteresis values or other characteristics of their ORA signal plots, indicating that both techniques of flap formation affect corneal biomechanics similarly. Because differences may become apparent with corneal healing, however, Dr. Durrie and I plan to study the long-term effects of advanced surface ablation and SBK on corneal biomechanics.

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CONCLUSION

Although my colleagues and I found a significant difference between the effect of LASIK and surface ablation on corneal biomechanics, we did not observe similar results in the immediate postoperative period between advanced surface ablation and SBK.

Our newfound ability to measure the biomechanic properties of the cornea in vivo has generated interest about how we can use this information to improve the outcomes of refractive surgery. We have only begun to explore this topic, however. Perhaps additional research will produce algorithms that will allow the next generation of refractive surgeons to perform biomechanical customized procedures. ■

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