Corneal Hysteresis, Resistance Factor, Topography, and Pachymetry After Corneal Lamellar Flap

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ABSTRACT

PURPOSE: To measure prospectively the early changes in corneal hysteresis, topography, and pachymetry after the creation of a stromal flap cut without laser photoablation.

METHODS: A 37-year-old man was referred for a bioptic procedure to correct for compound myopic astigmatism in the left eye. A 159-μm-thick 8×8.5-mm superior hinged flap was created with a mechanical microkeratome in the left cornea. Changes in the corneal hysteresis, corneal resistance factor, Goldmann correlated intraocular pressure (IOP), corneal compensated IOP, anterior and posterior topography, and optical and ultrasound pachymetry were monitored prospectively before and at 1 hour, 1 day, 5 days, and 25 days after the flap creation. The right eye served as a control.

RESULTS: In the left eye, corneal hysteresis and corneal resistance factor decreased immediately after the flap cut and remained lower than preoperatively at 1 hour, 1 day, 5 days, and 25 days. Corneal compensated IOP varied significantly less than Goldmann correlated IOP in both eyes. Central flattening of the horizontal meridians was observed on the difference topography maps. The values of the left eye posterior best fit sphere increased after the flap cut. Increased central corneal thickness occurred immediately after the flap cut and decreased over time without returning to its preoperative value.

CONCLUSIONS: The creation of a stromal flap can modify the biomechanical properties of the cornea, including a reduction in corneal hysteresis. The topographic changes were consistent with previously reported cases of flap cut in normal corneas. [*J Refract Surg*. 2007;23:xxx-xxx.]

The characterization of corneal biomechanical properties may become a useful tool for assessing refractive surgery qualification and outcomes. Besides keratectasia prevention, specific knowledge of the biomechanical response of the cornea to lamellar flap cut and photoablation would improve the optical results of LASIK procedures.

Corneal hysteresis is a new measure of corneal biomechanics that can be measured clinically with dynamic bidirectional applanation as used in the Ocular Response Analyzer (Reichert, Buffalo, NY).[1] This device uses a brief air impulse to rapidly deform the cornea and an advanced electro-optical system to monitor the shape of the cornea during deformation. Two different applanation pressure measurements are recorded: one while the cornea is moving inward and one while the cornea is returning and moving outward. The average of these two applanation pressure measurements corresponds to the Goldmann correlated intraocular pressure (IOP). The difference between the two is referred to as corneal hysteresis, which results from viscous damping of the corneal tissue. Using the same bidirectional applanation process, the ORA software also provides two additional parameters: corneal compensated IOP, and corneal resistance factor. Corneal compensated IOP is an intraocular pressure measurement that the manufacturer claims is less affected by the corneal properties. Corneal resistance factor is claimed to be an indicator of the overall corneal "resistance" encountered during the measurement process.

One preliminary study using this instrument has shown that the corneal hysteresis may be reduced after LASIK.[1] We

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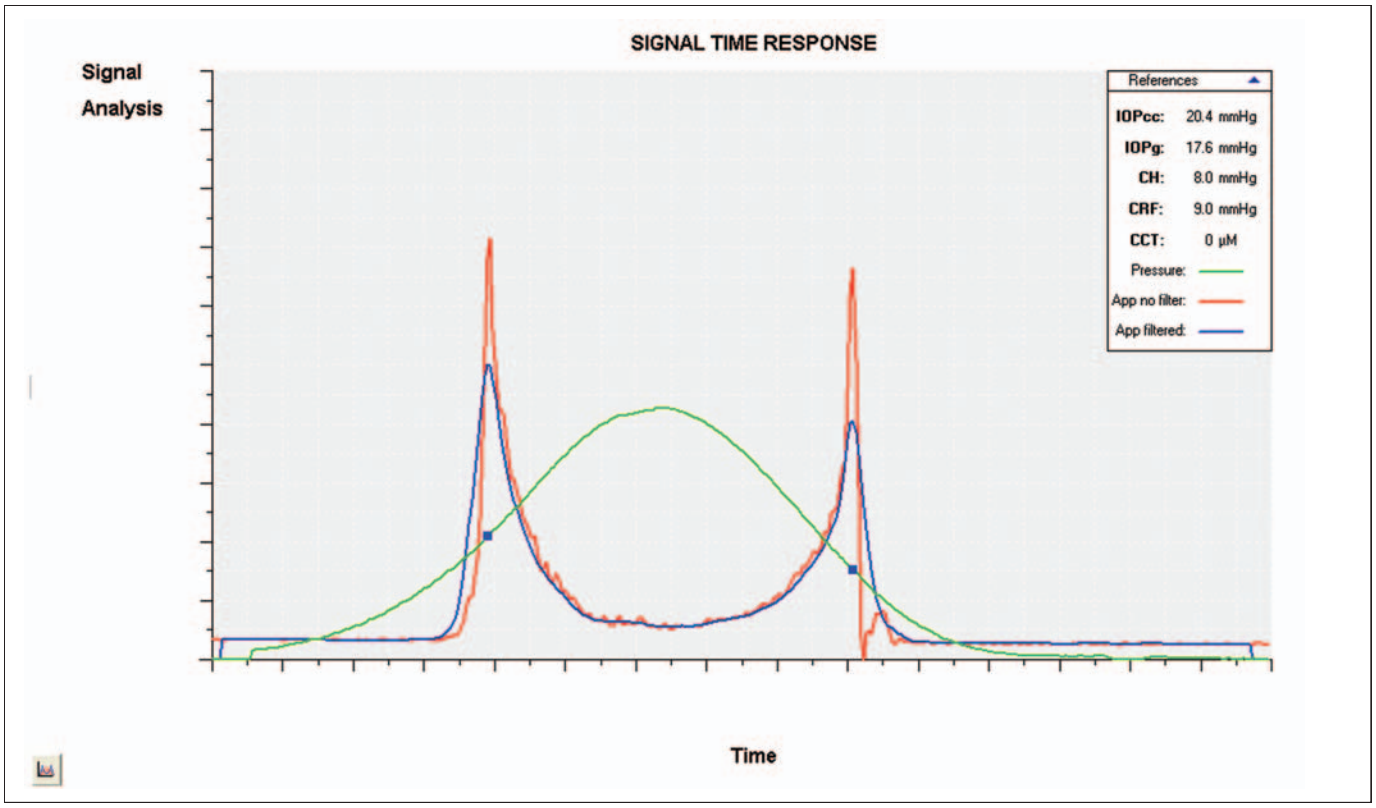


Figure 1. Ocular Response Analyzer measurement signal on the day of surgery. The raw and filtered applanation signals are plotted in red and blue, respectively. The air pulse pressure is plotted in green. IOPcc = corneal compensated intraocular pressure, IOPg = Goldmann correlated intraocular pressure, CH = corneal hysteresis, CRF = corneal resistance factor, CCT = central corneal thickness

report a clinical case in which we attempted to measure the specific effects of the flap cut on the corneal hysteresis and corneal resistance factor over 3 weeks.

PATIENT AND METHODS

A healthy 37-year-old man presented in November 2005 to inquire about refractive surgery to reduce anisometropia and correct for compound myopic astigmatism in his left eye. On examination, best spectacle-corrected visual acuity was 20/20 with −2.25 −2.00 × 180° in the right eye and 20/30 with −12.00 −5.00 × 170° in the left eye. The patient was soft and rigid contact lens intolerant.

Slit-lamp and fundus examination were normal in both eyes; there was no evidence of corneal guttata or Fuchs' endothelial dystrophy. Preoperative IOP was 17 mmHg in the right eye and 18 mmHg in the left eye by applanation tonometry. The preoperative ultrasound mean central corneal thickness was measured with the SP2000 ultrasound pachymeter (Tomey Corp, Nagoya, Japan). The Orbscan IIz (Bausch & Lomb, Rochester, NY) was used to analyze elevation and curvature measurements on both anterior and posterior surfaces of the cornea. The best fit sphere was computed in the float mode using the analyzed points in the 10-mm central area of the corneal surfaces. The preoperative anterior axial map showed anterior corneal steepness and with-the-rule toricity on both eyes. Endothelial cell count revealed a density of 2100 cells/mm^2.

Corneal hysteresis, corneal resistance factor, Goldmann correlated IOP, and corneal compensated IOP were measured with the Ocular Response Analyzer; for each of these examinations, at least six successive measurements were performed on each eye by an experienced technician. The measurements corresponding to the two extreme values of corneal hysteresis were discarded. Figure 1 shows an example of the Ocular Response Analyzer measurement signal. The final values of the corneal hysteresis, corneal resistance factor, Goldmann correlated IOP, and corneal compensated IOP were calculated as the average of the saved measurements. A bioptic procedure including a stromal flap cut as a first step and the insertion of an Artisan lens (Ophtec, Groningen, The Netherlands) as a second step was proposed to reduce the high magnitude of the refractive error in the left eye.

Informed consent was given, and the patient accepted to repeat some of the preoperative examinations on

TABLE

Variation of Subjective Refraction Before and After Flap Creation

	Before Flap Cut		After Flap Cut		
Refraction	D-25	D0	1 day	5 days	25 days
Sphere (D)	−12.00	−12.00	−10.75	−10.75	−11.00
Cylinder magnitude (D) × axis(°)	−5.00 × 170	−5 × 170	−5.25 × 175	−0.25 × 175	−5.50 × 170
Spherical equivalent (D)	−14.50	−14.50	−13.375	−13.375	−13.25

the day of surgery, 1 hour prior to the flap creation in the left eye, and at scheduled postoperative visits at 1 hour, 1 day, 5 days, and 25 days.

Cross-sectional examination of the left anterior segment with a customized version of the OCT3 (Carl Zeiss Meditec, Jena, Germany), in which the exit lens was modified to focus on the cornea, was planned at day 25 to check the regularity and central thickness of the stromal flap. The insertion of the Artisan lens was scheduled to be performed on day 26.

Two weeks after the first visit, uncomplicated flap creation was performed on the left eye using a Hansatome microkeratome (Bausch & Lomb) with an 8.5-mm ring and 180-μm head. Ultrasound pachymetry was performed immediately before and after the flap cut on the stromal bed to estimate the central flap thickness. The flap dimensions were measured with a caliper: the horizontal and vertical diameters were 8.5 mm and 8.0 mm, respectively, and the hinge width was 4 mm. The flap was carefully repositioned using violet gentian marks after short and gentle irrigation of the interface with balanced salt solution. A slit-lamp control examination was performed 20 minutes after surgery and disclosed mild diffuse edema on a well-positioned flap. Postoperative regimen included Ciloxan (Alcon Laboratories Inc, Ft Worth, Tex) 4 drops a day for 5 days and Tobradex (Alcon Laboratories Inc) 2 drops a day for 25 days. The patient complied with the schedule of the planned postoperative examinations.

An Artisan lens was inserted and iris-fixated in the anterior chamber on day 26, and no postoperative complications occurred.

RESULTS

Slit-lamp Examination

Mild diffuse stromal edema was noticed at 1 hour, but was not detectable on slit-lamp examinations at the following visits. No flap folds or epithelial or interface complications were observed in the postoperative course.

Variation of Manifest Refraction Values

The Table shows the manifest refraction values of sphere, cylinder, cylinder axis, and spherical equivalent for the left and right eyes on the day of surgery, and 1, 5, and 25 days postoperatively. The cylinder value increased in comparison to the day of surgery at each of the postoperative visits on the treated (left) eye. The spherical equivalent refraction was reduced from −14.50 diopters (D) on the day of surgery to −13.25 D on day 25 on the treated eye. The refractive parameters of the untreated (right eye) remained stable. The patient did not report halos or glare in the postoperative course.

Variation of Corneal Hysteresis and Corneal Resistance Factor

At first examination on the left eye, corneal hysteresis was 8.2 mmHg. Corneal resistance factor was 9 mmHg. Goldmann correlated IOP and corneal compensated IOP were 17.17 mmHg and 19.17 mmHg, respectively.

In the left eye, corneal hysteresis and corneal resistance factor decreased immediately after the creation of a superior-hinged mechanical flap cut and remained lower than the preoperative value at days 1, 5, and 25 (Fig 2). The left corneal hysteresis, initially measured at 8.2 mmHg, decreased to between 6.42 and 7.22 mmHg after the flap cut. The corneal resistance factor in the left eye, initially measured at 9 mmHg decreased to between 6.85 and 7.67 mmHg. A noticeable reduction was seen in the signal width and amplitude of the applanation signal (Fig 3). The differences between the pre- and postoperative values of the corneal hysteresis and corneal resistance factor in the left eye were statistically significant at follow-up examination (Student *t* test). Corneal hysteresis and corneal resistance factor in the right eye showed no significant fluctuations over the postoperative course.

Variation of Goldman Correlated IOP and Corneal Compensated IOP

Variations in Goldmann correlated IOP and corneal compensated IOP for the right and left eyes are shown

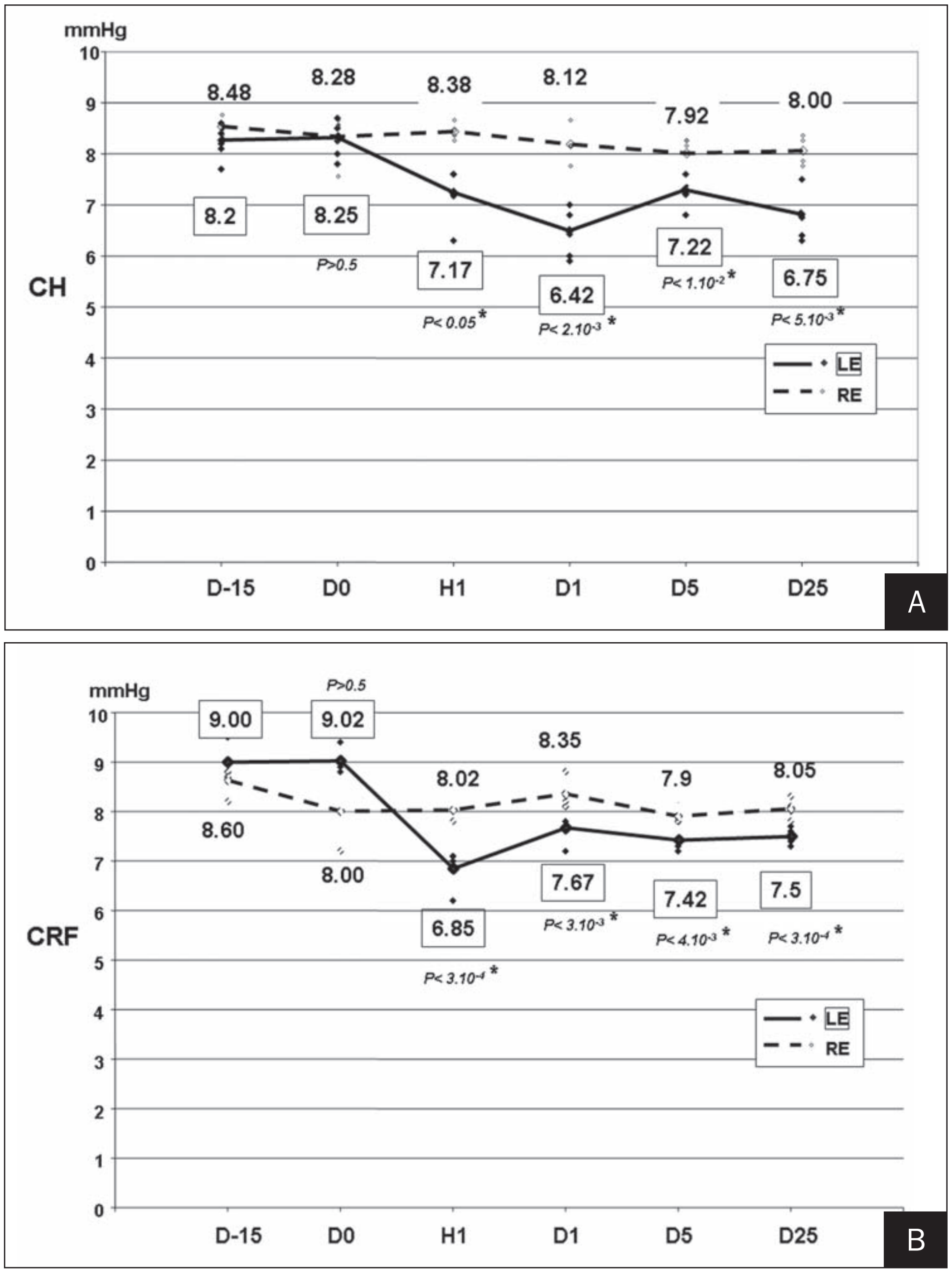


Figure 2. A) Corneal hysteresis (CH) values at the different before and after flap formation time points on the left (LE) and right (RE) eyes. **B)** Corneal resistance factor (CRF) values at the different before and after flap formation time points on the left (LE) and right (RE) eyes. D-15 = 15 days prior to surgery, D0 = day of surgery, H1 = 1 hour postoperatively, D1 = 1 day postoperatively, D5 = 5 days postoperatively, D25 = 25 days postoperatively

Figure 4. A reduction in Goldmann correlated IOP and corneal compensated IOP was observed at 1 hour in both eyes. Corneal compensated IOP decreased less than Goldmann correlated IOP.

Variation of Orbscan Corneal Topography and Optical Pachymetry

Central flattening, peripheral steepening, and increased vertical toricity were revealed on the difference axial curvature maps of the left treated eye at each of the postoperative visits (Fig 5A). Central decrease and midperipheral increase in elevation were noticeable on anterior elevation maps (Fig 5B). Points located in midperipheral horizontal had increased elevation, whereas points located in the midperipheral vertical meridians had decreased elevation. At 1 hour, the difference in elevation of the posterior surface was positive for points located in midperipheral horizontal and negative for points located in midperipheral vertical meridians (Fig 6). This was completely opposite to that of the anterior surface. No significant anterior shift in posterior elevation was observed at the following postoperative visits on the difference maps of the left eye. Variation of the anterior corneal best fit sphere radius was not significant. The posterior corneal best fit sphere increased from 6.12 mm on the day of surgery to 6.22 mm on day 25.

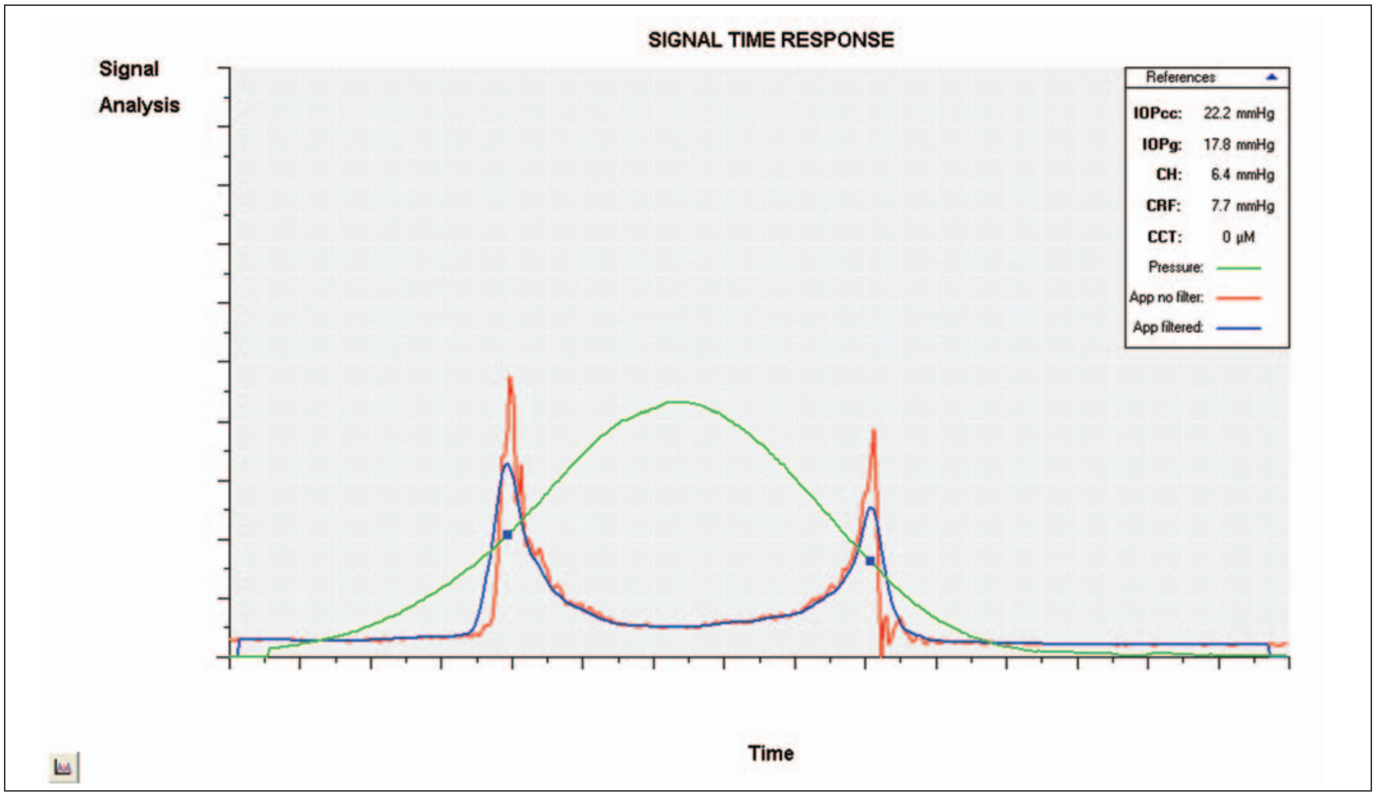


Figure 3. Ocular Response Analyzer measurement signal at day 25. The raw and filtered applanation signals are plotted in red and blue, respectively. The air pulse pressure is plotted in green. IOPcc = corneal compensated intraocular pressure, IOPg = Goldmann correlated intraocular pressure, CH = corneal hysteresis, CRF = corneal resistance factor, CCT = central corneal thickness

Increased global corneal thickness was observed with optical slit scanning topography in the area opposite to the hinge location at 1 hour. This increase was more pronounced in the inferotemporal quadrant of the left cornea. The left corneal pachymetry continuously decreased at days 1, 5, and 25 but did not return to the preoperative values.

Successive Orbscan topographies of the right cornea did not show significant differences in anterior, posterior elevation, or optical pachymetry.

Variation of Corneal Central Thickness Measured With Ultrasound Pachymetry

Preoperative central corneal thickness measured by ultrasound pachymetry was 525 µm in the right eye and 520 µm in the left eye. Handheld ultrasound pachymetry found a central flap thickness of 159 µm. Compared to the preoperative value, there was an increase in corneal thickness following flap formation at day 5 (530 µm) and day 25 (535 µm).

Flap Regularity and Corneal Thickness With Optical Coherence Tomography

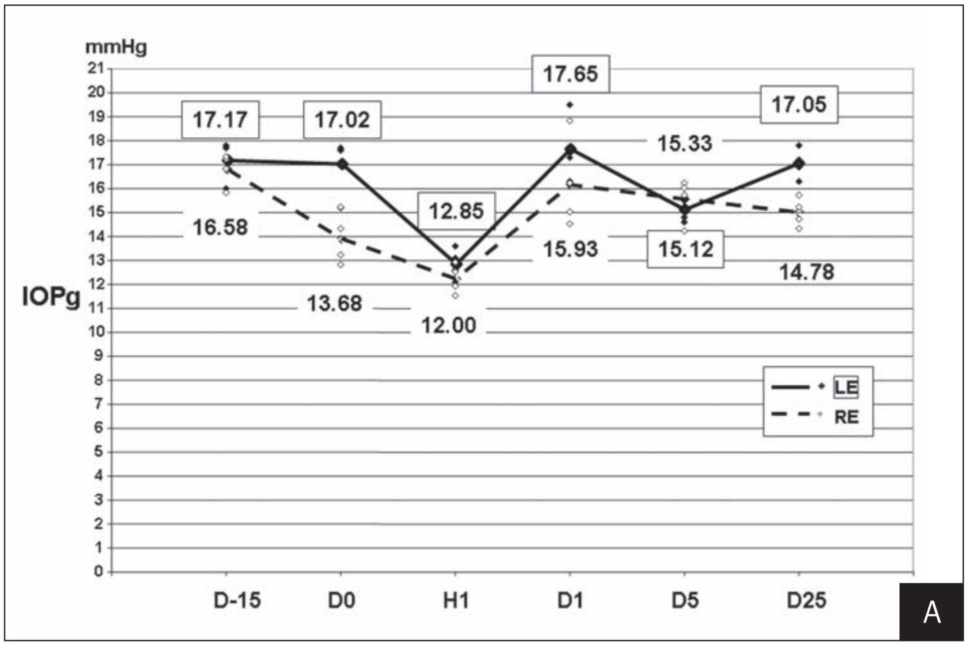
The interface between the flap and underlying stroma was clearly delineated and appeared rectilinear on the cross-sectional images provided with the OCT3. No interface irregularities were seen at day 25 (Fig 7). The central flap thickness was 165 µm for a total central corneal thickness of 539 µm (residual stromal thickness of 374 µm).

DISCUSSION

A reduction in corneal hysteresis and corneal resistance factor was observed after the creation of a stromal LASIK flap. To our knowledge, our report is the first clinical "in vivo" demonstration of the potential reduction in corneal hysteresis and corneal resistance due to uneventful LASIK flap creation.

Previous reports aimed at investigating either directly or indirectly the separate effects of the microkeratome flap cut on the corneal topography or aberrations were limited to the appreciation of factors relating to possible variation of the geometry of the cornea, but could not provide any estimation of possible changes to its biomechanical properties.[2-6]

Corneal hysteresis in the left eye was lower than preoperatively at each of the postoperative measurements. Corneal hysteresis has been shown to have low correlation with corneal thickness.[1] In our case, the corneal hysteresis decreased at 1 hour, despite increased



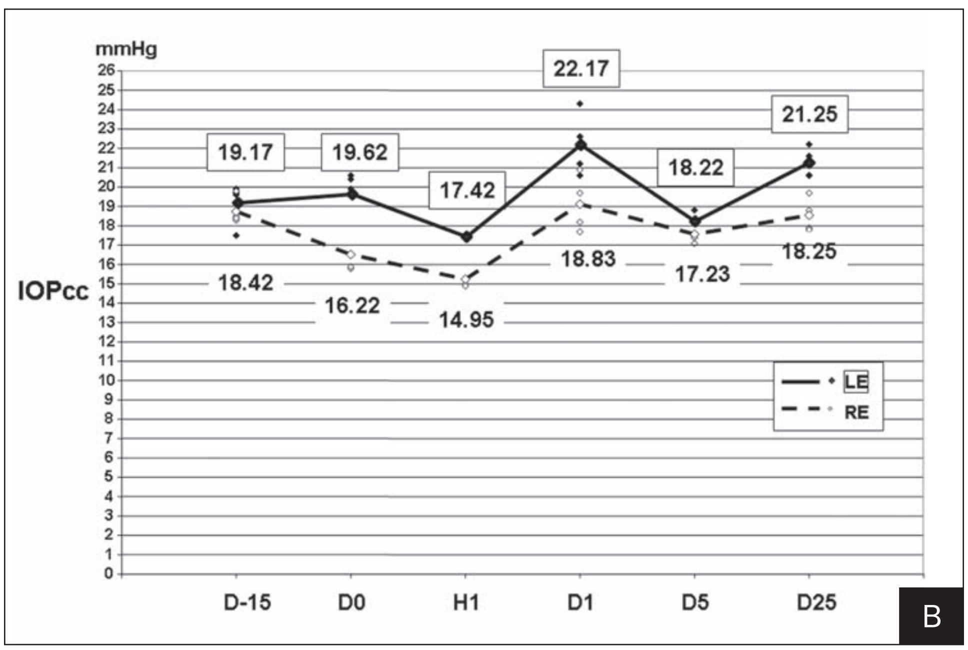


Figure 4. A) Goldmann correlated intraocular pressure (IOPg) values at the different before and after flap formation time points on the left (LE) and right (RE) eyes. **B)** Corneal compensated intraocular pressure (IOPcc) values at the different before and after flap formation time points on the left (LE) and right (RE) eyes. D-15 = 15 days prior to surgery, D0 = day of surgery, H1 = 1 hour postoperatively, D1 = 1 day postoperatively, D5 = 5 days postoperatively, D25 = 25 days postoperatively

corneal thickness. Diurnal fluctuations in the value of corneal hysteresis have been reported,[1] and were presumably attributed to hydration changes. In comparison with the left eye where we observed a decrease in corneal hysteresis and corneal resistance factor values after flap formation, the corneal hysteresis and corneal resistance factor values for the right eye (control eye) did not vary significantly from preoperative values at any of the postoperative visits.

Because both eyes showed a reduction in corneal compensated IOP and Goldmann correlated IOP at 1 hour, it is difficult to separate the respective influences of the flap cut and diurnal fluctuations on the IOP measurements. In addition, no studies specifically address the reproducibility of hysteresis and IOP measurement. The variation of left and right corneal compensated IOP were of less than the variation of left and right Goldmann correlated IOP; this could be explained by the fact that the corneal compensated IOP measurement attempts to compensate for corneal influence. Interestingly, Goldmann correlated IOP and corneal compensated IOP in the left eye were measured lower at 1 hour than H0 while the central corneal thickness was increased due to corneal edema. Pallikaris et al[2] reported significant increase in corneal thickness following flap formation in a series of 15 patients.

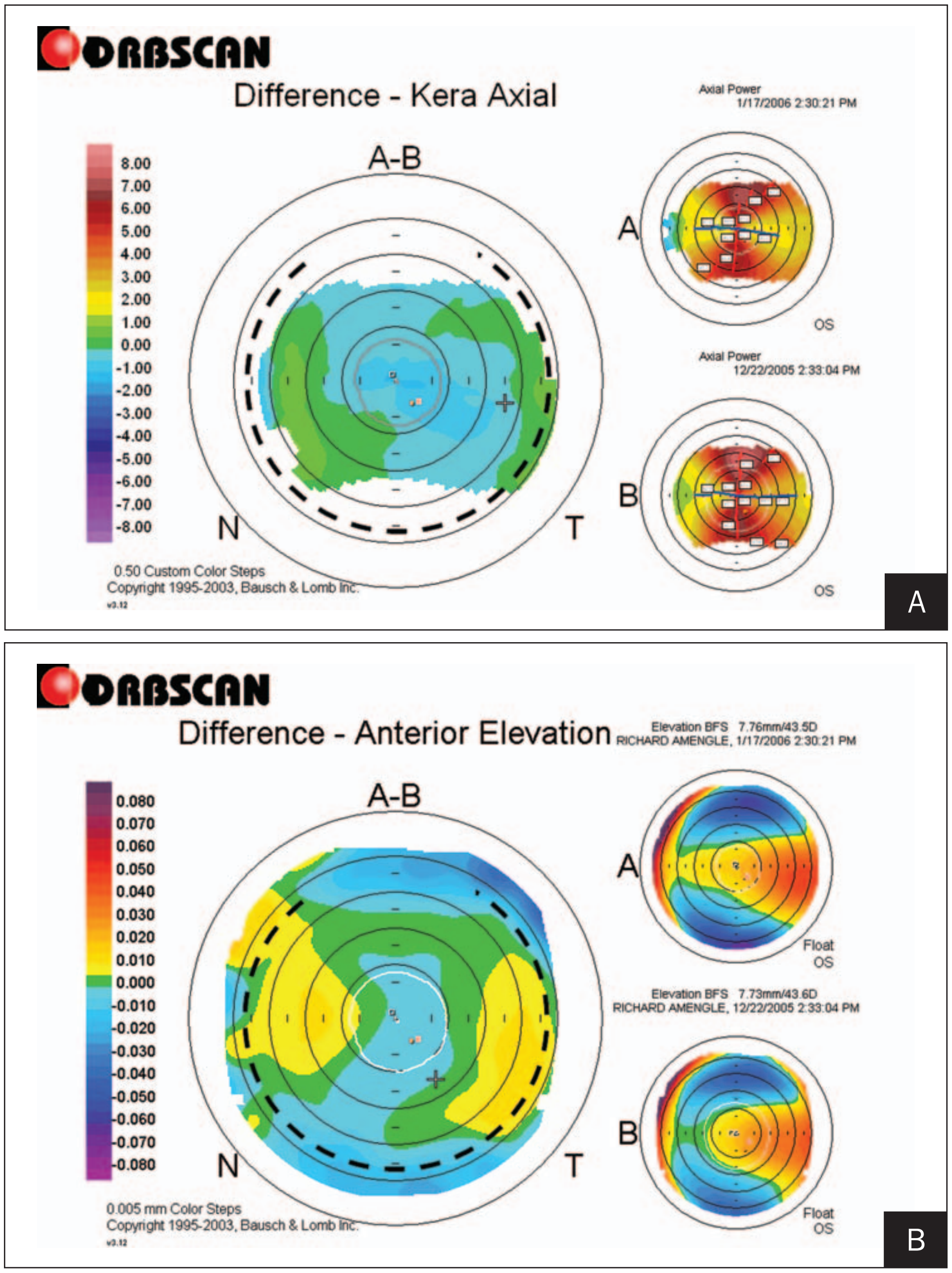


Figure 5. A) Left and **B)** right eye Orbscan difference maps in anterior axial curvature at day 25. The dark dashed line outlines the flap margins.

A reduction in the corneal hysteresis after complete LASIK procedures has been reported by Luce.[1] A consistent reduction, although variable in magnitude, occurs in corneal hysteresis and corneal resistance factor after myopic LASIK (unpublished data). Our case suggests that the reduction in the corneal hysteresis after LASIK surgery is not a function of corneal thinning only, but rather the result of combined thinning and creation of the flap. Further study is required to confirm this finding and determine the significance of the observed change.

Laser in situ keratomileusis is a surgical procedure that involves approximately the anterior one-third of the cornea. However, previous clinical studies have shown that changes in the posterior corneal surface can be detected after LASIK surgery and are correlated with surgical parameters such as residual bed thickness.[7-9]

To better predict the role of biomechanical factors in corneal refractive surgery, a spherical elastic thin shell model has been proposed recently.[10] This model predicts a forward shift in the posterior surface as a result of myopic LASIK. However, the existence of a constant forward shift of the posterior corneal surface after LASIK has been contested by several authors.[11-13] In addition, this model does not account for the visco-

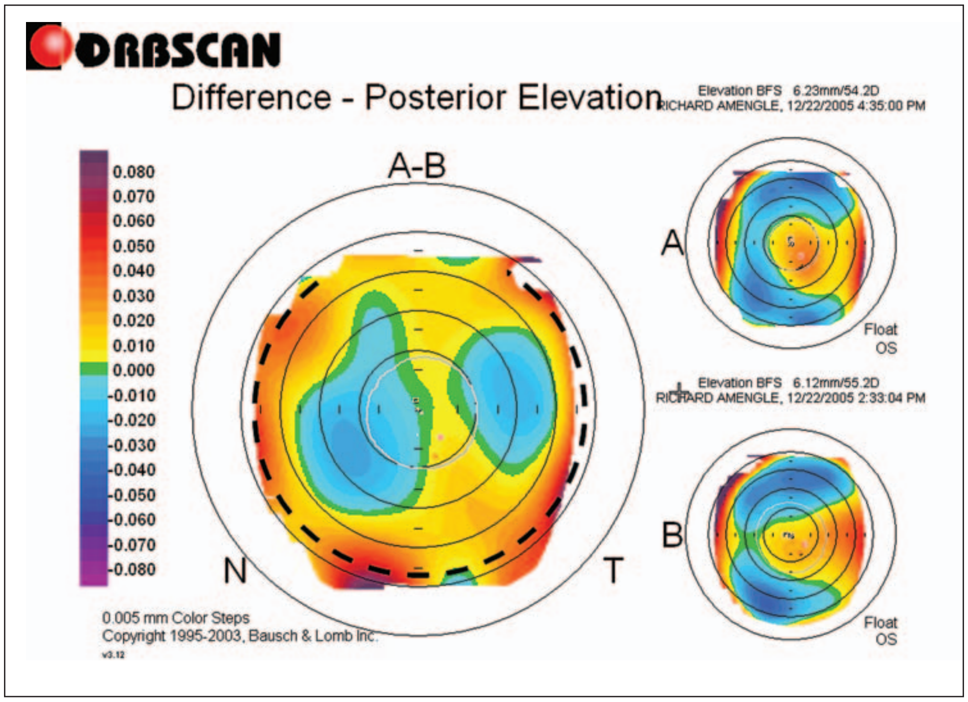


Figure 6. Left eye Orbscan difference map in posterior elevation at 1 hour.

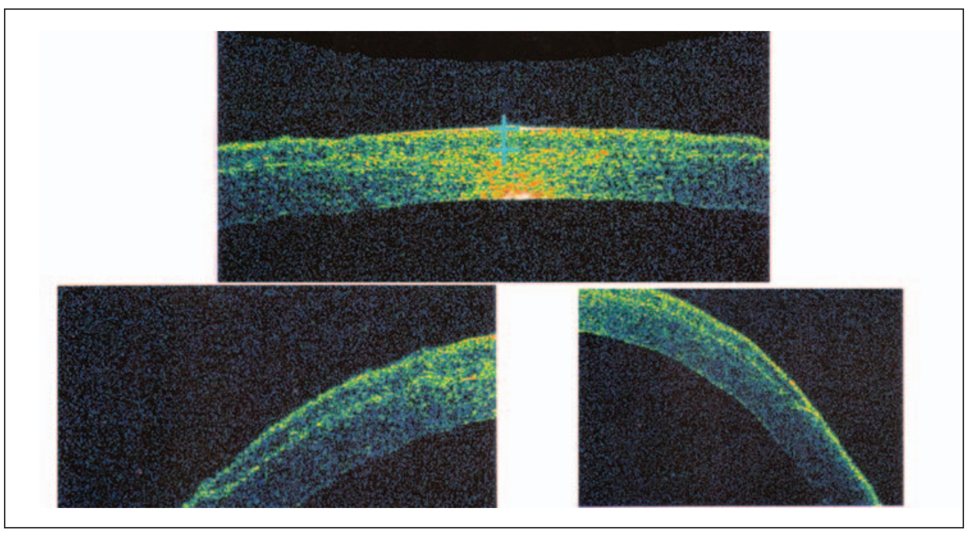


Figure 7. High-resolution cross-sectional imaging of the left cornea with optical coherence tomography.

elastic properties of the cornea, which appear to be of significance based on our findings.

Because laser photoablation was not delivered in our study, no significant change in the posterior cornea should be expected. The immediate variation in the posterior elevation of the cornea after the flap cut did not show significant increase in positive elevation.

The resulting change in anterior corneal toricity may account for the slight increase in with-the-rule astigmatism, which had also been predicted previously from clinical investigations on LASIK procedures with superior-hinged flaps.[14]

We observed an overall central corneal flattening persisting at day 25. Previous experimental work has demonstrated the tendency for the anterior cornea to flatten in response to tissue removal.[15]

Thus, our observations favor the predictions of viscoelastic[16,17] rather than elastic thin shell[10] biomechanical models of the cornea. This case supports the hypothesis that the biomechanical properties of the cornea are a function of more than a variation in corneal thickness. Because the flap had not reached a mature wound-healing state at 3 weeks, we could not measure the effect of the fibroplasia that occurs around the edge of the flap, which may further modify the biomechanical state of the cornea.

In our patient, the cornea was steep and showed marked regular toricity. The initial values of corneal hysteresis and corneal resistance factor were slightly below the average value of 9.6 mmHg in the study by Luce.[1] Further investigations and case series analysis are required to confirm our findings and assess the influence of preoperative corneal characteristics such as curvature, thickness, and hysteresis, and of flap parameters such as diameter , thickness, and hinge location.

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