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Changes in custom biomechanical variables after femtosecond laser in situ keratomileusis and photorefractive keratectomy for myopia

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Abstract

PURPOSE—To analyze changes in new biomechanical descriptors with myopic femtosecond laser–assisted laser in situ keratomileusis (LASIK), compare them with the biomechanical response after photorefractive keratectomy (PRK) with similar levels of myopic ablation, and evaluate correlations between changes in custom variables and biomechanically relevant variables.

SETTING—Cleveland Clinic, Cleveland, Ohio, USA.

DESIGN—Cohort study.

METHODS—Custom biomechanical variables from the Optical Response Analyzer were assessed preoperatively and 1 and 3 months postoperatively. Differences between preoperative values and postoperative values were determined. Intraindividual change (preoperative value minus postoperative value) was calculated and compared with changes after PRK. The correlation of the change in each custom biomechanical variable with the preoperative central corneal thickness, residual stromal bed tissue ablated, and percentage of tissue depth altered was also studied.

RESULTS—The study enrolled 156 eyes of 156 consecutive patients. Fifteen variables changed significantly after femtosecond myopic LASIK and were stable postoperatively because no significant difference was shown between 1-month values and 3-month values. Comparison of the changes in biomechanical variables between LASIK and PRK eyes showed no significant

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FINANCIAL DISCLOSURES
Dr. Ambrosio was a consultant to Reichert Technologies, the manufacturer of the Ocular Response Analyzer, and is currently a consultant to Oculus, Inc., a manufacturer of a competing product not addressed in this paper. Dr. Dupps is a coinventor of intellectual property issued through Cleveland Clinic Innovations for a technique of biomechanical measurement that is not addressed in this paper. No other author has a financial or proprietary interest in any material or method mentioned.

differences. Surgical changes in several custom biomechanical variables correlated with the percentage of tissue depth altered.

CONCLUSIONS—The results provide the first reference values for a more comprehensive panel of indicators of the biomechanical response to myopic LASIK and PRK. Changes in custom variables reflected a consistent decrease in corneal biomechanical resistance to deformation after myopic femtosecond LASIK and PRK. For comparable attempted corrections, biomechanical changes were comparable between femtosecond laser–assisted LASIK and PRK.

Laser in situ keratomileusis (LASIK) flap creation associated with myopic ablation produces profound changes in the corneal structure and biomechanical properties secondary to central thinning and disruption of collagen lamellar continuity.[1] Several forces contributing to the preoperative steady state undergo complex disruptions during corneal refractive surgery.[1,2] Researchers have attempted to develop in vivo methods for measuring corneal biomechanical properties that could be useful in generating reliable biomechanical diagnostic metrics and predicting treatment responses. The goals of such research are to improve outcomes and reduce complications by discerning details of the biomechanical and wound-healing pathways and by more accurately assessing the risk for ectasia in refractive surgery candidates.[1]

The Ocular Response Analyzer (Reichert Ophthalmic Instruments) is a dynamic bidirectional applanation device that records corneal inward and outward applanation events after delivering a metered collimated air pulse and provides an indication of the viscoelastic behavior of the cornea. The change in the shape of the cornea is detected using an infrared light that reflects from the corneal surface to an aligned sensor, as previously described in detail.[3,4] The device currently reports 2 variables—corneal hysteresis (CH) and the corneal resistance factor (CRF)—which are thought to represent, respectively, the viscoelastic damping capabilities and the overall elastic resistance of the cornea and associated structures. However, the clinical utility of these standard variables is limited because of the high degree of overlap between eyes with forme fruste keratoconus and normal eyes[5] or between different stages of keratoconus severity.[6]

The Ocular Response Analyzer signal contains characteristics not captured by CH and the CRF that yield additional information about biomechanical differences between normal corneas and diseased corneas.[7,8] Some authors in the present study presented a panel of custom signal-derived variables[9,A] that describe aspects of the temporal response, applanation signal intensity, and pressure. Some of these variables have shown greater diagnostic value for differentiating keratoconus than the standard Ocular Response Analyzer variables.[9] We hypothesize that they may also be more sensitive indicators of the more subtle corneal biomechanical changes associated with corneal refractive surgery.

To further evaluate this possibility, we initiated a study to obtain multiple measures of the corneal biomechanical response in normal refractive surgery candidates before and after femtosecond laser–assisted myopic LASIK and myopic photorefractive keratectomy (PRK). The purpose of this study was therefore to analyze changes in these new biomechanical descriptors with myopic femtosecond LASIK, to compare that behavior with the biomechanical response after PRK with similar levels of myopic ablation, and to determine whether there is a correlation between changes in custom variables and other biomechanically relevant variables, such as preoperative central corneal thickness (CCT), the residual stromal bed (RSB) tissue ablated, and the percentage of tissue depth altered.

PATIENTS AND METHODS

This prospective study evaluated eyes of consecutive patients screened from November 2009 through November 2011 at the Refractive Surgery Department, Cole Eye Institute, Cleveland, Ohio, USA. The Institutional Review Board, Cleveland Clinic, approved the study, and all patients provided informed consent. The study followed the tenets of the Declaration of Helsinki.

Patients who were considered normal candidates for femtosecond laser–assisted LASIK to correct myopia based on corneal topography and corneal thickness with a comprehensive postsurgical follow-up of at least 1 month and 3 months were eligible for inclusion in the study. Also studied were consecutive patients who were considered normal candidates for PRK to correct myopia and had a postsurgical follow-up of at least 1 month. Exclusion criteria for the study included corneal infection, trauma, and flap dislocation. Laser in situ keratomileusis enhancements were not used as exclusion criteria because all the enhancement procedures occurred beyond 3 months.

Each patient had a comprehensive ophthalmologic examination that included a medical history review, uncorrected (UDVA) and corrected (CDVA) distance visual acuities, slitlamp and fundoscopic evaluations, Placido-disk topography (Humphrey Atlas, Carl Zeiss Meditec AG), ultrasound (US) pachymetry, wavefront aberrometry (Wavescan, Abbott Medical Optics, Inc.), Scheimpflug tomographic evaluation (Oculus, Inc.), and dynamic bidirectional applanation device measurements (Ocular Response Analyzer). Patient age and preoperative manifest refraction spherical equivalent (MRSE) were also recorded.

The same surgeon (S.E.W.) performed all LASIK and PRK procedures. All LASIK flaps were created with the 60 kHz Intralase femtosecond laser (Abbott Medical Optics, Inc.). Femtosecond flap settings were 9.0 to 9.3 mm diameter with a 55-degree superior hinge angle and 55-degree side-cut angle. The attempted flap thickness was 100 to 110 mm. Side-cut energy and bed energy were recorded.

Laser ablation was performed with the Star S4 excimer laser (Visx, Inc.) according to a surgeon-specific nomogram. The optical zone diameter was 6.5 mm. All patients had wavefront-guided treatment to correct myopia or myopic astigmatism. After laser application, the flap and stromal bed were irrigated with a balanced salt solution. This was followed by sweeping the stromal bed and flap with lint-free sponges. The bed and flap were briefly irrigated a final time with filtered balanced salt solution, and the flap was smoothed and put back in position with an iris spatula. The flap was allowed to adhere to the bed while the center of the flap was moistened with a polyvinyl alcohol sponge (Merocel) wetted with a balanced salt solution. Finally, topical moxifloxacin hydrochloride (Vigamox ophthalmic solution) and prednisolone acetate ophthalmologic suspension USP 1.0% eyedrops were applied to the surface.

The femtosecond LASIK flap thickness was obtained by the subtraction method (total corneal thickness stroma after flap lift) using US pachymetry. The total ablation depth was recorded from the computer-generated surgical report for the surrogate approximate corneal volume removed for each treatment. The RSB values were also obtained by the subtraction method [(total corneal thickness) − (total ablation depth + flap thickness)]. The percentages of tissue-altered values were obtained by the sum of total ablation depth and flap thickness divided by preoperative CCT [(flap thickness + ablation depth)/preoperative CCT].

All PRK procedures involved mechanical epithelial scraping, including removal of the epithelial basement membrane and subsequent laser photoablation of the Bowman layer and the anterior stroma. Mitomycin-C 0.02% was applied for treatments greater than −4.0 diopters (D) of myopia, astigmatism of 1.25 D or greater, or tissue removed with a laser ablation of more than 50 μm. Finally, topical moxifloxacin hydrochloride and prednisolone acetate ophthalmologic suspension USP 1.0% eyedrops were applied to the surface.

Dynamic Bidirectional Applanation Device Variables

The method of operation of the dynamic bidirectional applanation device has been described in detail.[3] Briefly, an air jet generates a force directed at the central cornea that causes deformation into a slight concavity. This is followed by a return to its pre-perturbation convex shape. During this sequence of events, which occur over 20 to 30 milliseconds, the plenum pressure of the air jet chamber is measured and an infrared detector system monitors the number of photons reflected from the corneal center. The intensity of the infrared signal is a function of specular reflection from the anterior corneal surface, and it reaches a local maximum when the cornea is most planar (ie, applanated or near-applanated). Maximum planarity occurs at 2 points in the cycle as follows: (1) during the inward phase of the response just before concavity and (2) during the outward phase of the response after concavity. Two device measurements of acceptable quality as defined by the manufacturer's user manual were obtained for each eye, and averaged results were used for analysis.

United States Food and Drug Administration–approved versions of the dynamic bidirectional applanation device software provide 2 measurements of biomechanical behavior based on the pressures obtained at the 2 applanation events. The CH is calculated as the difference between the pressure values at the ingoing (P1) and outgoing (P2) corneal applanation events. The CRF is based on the same pressure values but is a linear combination of the applanation pressure values, $P1 - (k \times P2)$, which biases the CRF toward the pressure associated with the ingoing applanation event. The coefficient, k, was empirically set to 0.7 by the manufacturer to maximize the dependence of the CRF on the CCT.[3]

Custom Variables

The infrared intensity, pressure, and time series data of the Optical Response Analyzer were exported using the device's software and analyzed in Matlab (version 7.0, Mathworks). Fifteen variables suspected of being of biomechanical relevance were derived from signal morphology aspects of the device.[9,A] Table 1 describes all variables, which are illustrated in Figure 1.

The main outcome variables in this study were the standard dynamic bidirectional applanation device and custom biomechanical variables preoperatively and 1 month and 3 months postoperatively. The statistical significance of the change from preoperative values to values obtained 1 and 3 months after myopic LASIK was determined. Subsequently, the intraindividual difference between the same parameter obtained before and after refractive surgery (preoperative value minus postoperative value) was calculated.

The changes in LASIK eyes and the changes in PRK eyes were compared to determine whether there were significant differences in the biomechanical change from preoperatively to 1 month postoperatively between the 2 groups. Also compared were age, spherical equivalent, and percentage of tissue altered in both groups.

The correlations (Spearman ρ and 95% confidence interval) of changes in CH and CRF and preoperative CH and CRF with the CCT, ablation depth, RSB, and percentage of tissue altered were determined. Finally, the correlation between the change in each custom biomechanical variable from preoperatively to 1 month postoperatively and the pre-operative CCT, ablation depth, RSB, and percentage of tissue altered was evaluated.

Statistical analyses were performed using JMP software (version 8.0, SAS Institute, Inc.). Normality of data was evaluated with the Kolmogorov-Smirnov test. Differences between data were evaluated using analysis of variance, the Student *t* test, or the Wilcoxon test. In the LASIK group, for comparisons within the same patient between preoperatively and 1 month postoperatively, preoperatively and 3 months postoperatively, and 1 month postoperatively and 3 months postoperatively, a paired *t* test was used because the samples were not independent. The Pearson or Spearman rank test, depending on normality of the sample, was used to establish correlation coefficients. Data were expressed as the mean ± standard deviation (SD). Based on significant intraclass correlation, only the right eye of each patient was included in the analysis. Bonferroni correction for multiple comparisons was applied and resulted in a *P* value criterion for significance of less than 0.003.

RESULTS

The study enrolled 156 eyes of 156 consecutive patients. The LASIK group comprised 104 eyes of 104 patients (54 women [52.5%]) and the PRK group, 52 eyes of 52 patients (23 women [44%]). Table 2 shows the preoperative data of the eyes included in the study. No patients were excluded. Although comparable in MRSE (P=.4) and age (P=.8), PRK eyes had statistically significantly thinner and steeper corneas (P<.001). The percentage of tissue depth altered was statistically significantly greater in the LASIK group than in the PRK group, as expected (P<.0001).

Table 3 compares the preoperative values of standard and investigator-derived variables from the dynamic bidirectional applanation device measurements in the femtosecond laser–assisted LASIK group and the PRK group. The PRK group had statistically significantly different values of A1, concavity mean, CH, CRF, and hysteresis loop area.

Analysis of the behavior of biomechanical variables after femtosecond LASIK found that only 2 of 17 variables (slope up and slope down) did not change significantly between preoperatively and 1 month and 3 months postoperatively (Table 4). All the other variables changed significantly after LASIK and were stable postoperatively; no statistically significant differences were found between 1-month and 3-month values (Table 4).

Comparison of the changes in biomechanical variables between LASIK eyes and PRK eyes showed no statistically significant difference between the groups (Table 5).

Table 6 shows the significant findings in the correlation between changes in the CH and the preoperative CH and CRF, CCT, ablation depth, RSB, and percentage of tissue depth altered. The CCT and RSB had weak correlations with the change in CH and change in the CRF. Ablation depth and percentage of tissue altered showed stronger correlations with the change in CH and the change in CRF. Changes in CH and changes in the CRF were also correlated with the preoperative CH and CRF values. Table 7 shows the correlations between changes in custom biomechanical variables and the CCT, ablation depth, RSB, and percentage of tissue depth altered.

DISCUSSION

Although empirical modifications to algorithms and major advances in laser delivery platforms have improved the predictability of LASIK, the ability to anticipate confounding biological and biomechanical responses at the level of the individual patient remains limited. The effects of femtosecond laser flap creation, photoablation pattern, and geometry of the residual stroma on biomechanical state and postoperative refractive error are rooted in complex interactions that are unique in each case.[10,11] In the current study, we evaluated the behavior of new biomechanical descriptors after femtosecond laser–assisted LASIK and myopic ablation, calculated the change in the biomechanical response after LASIK and myopic ablation compared with the change in the biomechanical response after PRK with similar levels of ablation, and assessed the correlation between the change in custom biomechanical variables and the CCT, ablation depth, RSB, and percentage of tissue depth altered. By analyzing preoperative biomechanical metrics and observing the effects of femtosecond LASIK on these variables, we are able to identify which variables changed most and determine whether these changes differed as a function of surgical approach.

We found significant changes in all but 2 variables 1 month and 3 months after surgery. As in previous studies,[4,12–14] LASIK and PRK for myopia were both associated with reductions in CH and the CRF. New analyses of custom variables derived with the Optical Response Analyzer found that myopic LASIK resulted in (1) reductions in applanation signal intensity for both applanation events, (2) a lower applanation signal at maximum corneal concavity consistent with a greater amplitude of corneal deformation, (3) lower pressures required for applanation, (4) earlier occurrence of maximum concavity consistent with a more readily deformed cornea, (5) longer duration of corneal concavity consistent with slower recovery of deformation, and (6) reductions in a more comprehensive analog of response hysteresis (hysteresis loop area). Collectively, these changes reflect a consistent decrease in corneal biomechanical resistance to deformation after myopic femtosecond laser–assisted LASIK. Slope up and slope down were the only measured variables not affected by LASIK.

These results also provide the first reference values for a more comprehensive panel of indicators of the biomechanical response to myopic LASIK and PRK. Further study in a large cohort that includes eyes with postoperative topographic instability would be needed to determine whether postoperative values outside the ranges reported here are predictive of regression or ectasia. In previous studies comparing the same custom variables in keratoconic and normal eyes,[9,A] all variables except lag time were significantly different between keratoconic eyes and normal eyes and variables related to the maximum depth of deformation (concavity min, concavity mean) and a comprehensive measure of hysteresis (hysteresis loop area) showed the greatest discriminative value for keratoconus. The hysteresis loop area is a construct of the pressure and applanation intensity signal throughout the loading and unloading cycle, whereas CH reflects behavior at 2 finite time points only. Qualitative comparison of the postoperative values in the present study with native values in keratoconic eyes in a study by Hallahan et al.[9,A] suggest that concavity min and the hysteresis loop area are, as expected, much lower in keratoconus than after myopic LASIK and therefore appear to appropriately reflect the differences between the normal unoperated state, the nonpathological post-refractive surgery state, and the manifest ectatic disease.

Only 1 biomechanical variable shared a correlation between its LASIK-induced change and RSB thickness; however, this relationship was also the strongest single correlation among the custom variables. A thinner RSB was associated with a greater increase in lag time, the delay between peak applied pressure and maximum deformation ($r = -0.329$). Given that the downward slope term (the rate of decrease of applanation signal intensity after the first applanation peak) was unchanged after LASIK or PRK and therefore effectively constant, one might attribute a greater lag time in eyes with a thinner RSB to a larger deformation into concavity. However, there was no correlation between RSB thickness and concavity min or concavity mean. A potential explanation for this phenomenon would be that in eyes with a thin RSB, deformation is both deep and broad, where the breadth of the corneal surface recruited in the deformation response increases the number of reflected photons for a given depth of deformation.

Surgical changes in several custom Optical Response Analyzer variables correlated with the percentage of tissue depth altered and ablation depth, suggesting some degree of sensitivity to the biomechanical impact of a given procedure in a particular patient. Specifically, greater levels of tissue disruption were associated with (1) greater reductions in minimum concavity signal, (2) greater reductions in time to maximum deformation, (3) greater reductions in the time to initial applanation, (4) greater reductions in maximum applied pressure, and (5) greater reductions in the area under the pressure versus time curve. Hallahan et al.[9] showed that the rate of pressure rise is constant with the Optical Response Analyzer; thus, the latter 2 observations depend on the pressure pulse being shut off earlier as a function of a more readily deformed cornea. Although these correlations suggest that the degree of invasiveness is a factor in biomechanical change in LASIK, the amount of variance (calculated as the square of the correlation coefficient) in biomechanical changes explained by even the most strongly correlating variables was less than 11%. Therefore, ablation depth and residual bed thickness fall short as lone predictors of the biomechanical impact of corneal refractive surgery. For RSB thickness, this low predictive value is further confounded by the difficulty of accurately estimating its postoperative value a priori.[15,16] To the extent that biomechanical alterations are predictive of ectasia risk, RSB should be used with caution as an isolated predictor of risk. Taken together, Tables 6 and 7 show that the Optical Response Analyzer variables and percentage of tissue depth altered are much stronger predictors of LASIK-induced biomechanical changes than the CCT, RSB thickness, or ablation depth, at least within the range of values encountered in this relatively large series. This conclusion is similar to that of a smaller study by de Medeiros et al.[14] and emphasizes the importance of intrinsic preoperative biomechanical properties as factors in surgically induced change. This may explain why ectasia can occur even in corneas with a normal preoperative thickness, normal preoperative topography, and normal RSB. These results also suggest the importance of better characterizing the preoperative biomechanical status and incorporating such information into treatment planning.

During LASIK, PRK, or any other procedure involving central ablation, an immediate circumferential severing of corneal lamellae is produced along with a patterned reduction in corneal thickness that is expected to alter corneal biomechanical behavior.[17] However, PRK and LASIK involve different degrees of tissue disruption and invoke distinctive wound-healing responses. To better understand any differential effect on the biomechanical behavior of the cornea, we compared multiple aspects of the corneal response to a high-speed air-driven perturbation after LASIK and PRK. Because PRK candidates had thinner and slightly steeper corneas preoperatively than LASIK candidates and these variables could be covariants of some of the biomechanical variables of interest, we compared the change that occurred in the biomechanical variables rather than absolute postoperative values.

We found no significant differences in surgically induced changes in any measured biomechanical variables, including the standard variables CH and CRF and 15 custom biomechanical variables, between PRK and femtosecond laser–assisted LASIK. This similarity existed despite large differences in the percentage of tissue depth altered between the LASIK group (32%) and the PRK group (11%). Several factors may have contributed to the similarity of the responses. First, much of the biomechanical strength of the cornea is concentrated in the anterior third of the cornea, which has been characterized as having higher interlamellar cohesive force[18] and more extensive collagen interweaving[19] than the deep stroma. With the high repeatability of femtosecond flap geometry and more uniform thickness profiles,[2,20] it is likely that LASIK, at least for the levels of correction compared here, preserved sufficient amounts of anterior stroma to avoid provoking more significant biomechanical changes than in eyes that had surface ablation.

Although it is possible to create very thin flaps with femtosecond lasers, such flaps are not free of complications.[21] The results in this study suggest that for the range of percentage of tissue depth altered in this series, the benefits of an ultrathin flap may be limited from a biomechanical standpoint. With a mean flap thickness of 114.0 µm, corneal responses after LASIK were similar to those after PRK without the increased risks of subepithelial flaps, which include undesirable epithelial–stromal interactions moderated by chemotactic cytokines and growth factors with potential generation and persistence of myofibroblast and consequent haze.[22]

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WHAT WAS KNOWN

- Laser in situ keratomileusis and PRK for myopia have been shown to cause reductions in CH and the CRF.
- Biomechanical interpretation of changes in CH and the CRF is limited by the fact that both variables are combinations of the same 2 pressure measurements. Furthermore, these variables do not explicitly measure temporal and other features of the ocular response that may be relevant to characterization of biomechanical change in corneal refractive surgery.

WHAT THIS PAPER ADDS

- This paper presents a comprehensive analysis of high-speed corneal deformation behavior after myopic keratorefractive surgery.
- Custom dynamic bidirectional applanation device variable analysis showed that LASIK and PRK resulted in a multitude of changes reflecting altered resistance to deformation. These changes included an increased depth of corneal deformation, lower applanation pressures, more rapid onset of maximum deformation, slower recovery of deformation, and reductions in a more comprehensive analog of hysteresis (hysteresis loop area).
- For comparable attempted corrections, biomechanical changes were comparable for femtosecond laser–assisted LASIK and PRK.

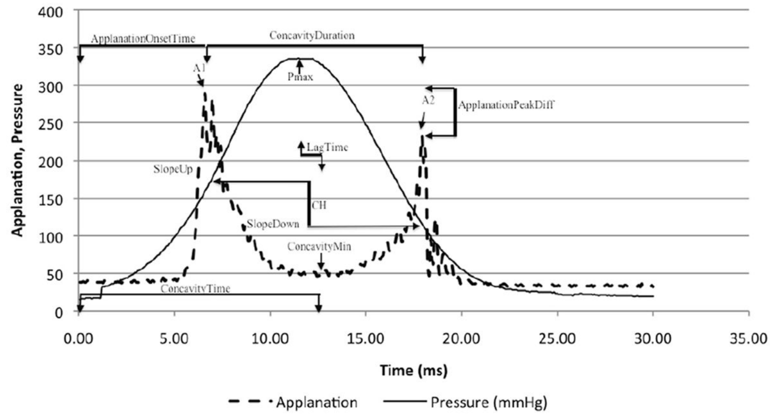

Figure 1.

Several custom variables suspected of being of biomechanical relevance that were derived from aspects of the dynamic bidirectional applanation device signal morphology (*reprinted with permission from* Ophthalmology[9]).

Table 1

Variables derived from the signal of the dynamic bidirectional applanation device (adapted from Hallahan et al.)

Variable	Operational Definition	Interpretation
Applanation signal intensity		
A1	Peak intensity of 1st applanation event	Maximum surface area achieving planarity during inward deformation
A2	Peak intensity of 2nd applanation event	Maximum surface area achieving planarity during recovery
Applanation peak difference	A2 − A1	Difference in maximum planarity between inward and recovery phases
Concavity min	Minimum applanation intensity between A1 and A2	Depth and irregularity (nonplanarity) of deformation
Concavity mean	Mean applanation intensity between A1 and A2	Depth and irregularity of deformation, averaged
Pressure		
CRF (mm Hg)	P1 − 0.7P2	Difference in applanation pressures, weighted toward pressure required to produce the first applanation; maximizes correlation to CCT
CH (mm Hg)	P2 − P1	Difference in pressures between the 2 applanation events (a single cross–section of the pressure–deformation relationship)
P1P2Avg	(P1 + P2)/2	Average of the pressures at the 2 applanation events
P max	Peak value of pressure signal	Force and time required to reach first applanation event
Response time (ms)		
Concavity duration	Time lapse between A1 and A2	Temporal delay of deformation recovery between applanation events
Concavity time	Time from onset of applied pressure to concavity min	Time required to achieve maximum deformation from onset of impulse
Lag time	Time between P max and concavity min	Delay between peak applied pressure and maximum deformation
AOT	Time from onset of applied pressure to A1	Time required to achieve first applanation from onset of impulse
Applanation intensity and response time (ms^{-1})		
Slope Up	Positive slope of the first applanation peak, from inflection point to peak	Rate of achieving peak planarity
Slope Down	Negative slope of the first applanation peak, from peak to inflection point	Rate of loss of peak planarity
Pressure and applanation intensity		
HLA	Area enclosed by pressure vs applanation function	Hysteresis aggregated over entire deformation cycle except concavity
Pressure and time		
Impulse	Area under pressure vs time curve	Air pressure intensity

AOT = applanation onset time; CCT = central corneal thickness; CH = corneal hysteresis; CRF = corneal resistance factor; HLA = hysteresis loop area; ms = millisecond

Table 2

Preoperative and surgical data.

Variable	Femto LASIK	PRK	*P* Value
MRSE (D)			
Mean ± SD	−3.97 ± 1.82	−4.33 ± 2.68	.4
95% CI	−3.58, −4.85	−3.56, −5.71	
Age (y)			
Mean ± SD	36.8 ± 10.8	37.3 ± 11.3	.8
95% CI	35.4, 38.1	33.1, 40.5	
PTA (%)			
Mean ± SD	31 ± 5	13 ± 5	<.0001 *
95% CI	29, 32	11, 14	
CCT (μm)			
Mean ± SD	557.51 ± 36.17	527.22 ± 31.52	<.0001 *
95% CI	550.55, 564.48	517.43, 537.02	
Mean K (D)			
Mean ± SD	43.43 ± 1.31	44.44 ± 1.79	<.0001 *
95% CI	43.26, 43.59	43.91, 44.97	
Flap thickness (μm)			
Mean ± SD	114.77 ± 13.74	NA	NA

CCT =central corneal thickness; CI =confidence interval; Femto LASIK = femtosecond laser–assisted laser in situ keratomileusis; K = keratometry; MRSE = manifest refraction spherical equivalent; NA = not applicable; PRK =photorefractive keratectomy; PTA =percentage of tissue depth altered [(flap thickness + ablation depth)/preoperative CCT]

* Statistically significant

Table 3

Preoperative standard and custom variables derived from the dynamic bidirectional applanation device.

Variable*	Femto LASIK	PRK	*P* Value
A1			
Mean ± SD	724.6 ± 119.1	682.5 ± 123.7	.0002†
95% CI	701.45, 747.76	627.3, 687.2	
A2			
Mean ± SD	572.6 ± 117.7	537.1 ± 117.9	.02
95% CI	549.7, 595.5	508.6, 565.6	
Applanation peak difference			
Mean ± SD	−166.1 ± 104.7	−179.1 ± 145.5	.2
95% CI	−185.0, −147.3	−238.0, −121.4	
Concavity min			
Mean ± SD	42.4 ± 0.5	42.4 ± 0.5	.6
95% CI	42.3, 42.5	42.2, 42.5	
Concavity mean			
Mean ± SD	151.2 ± 23.9	135.7 ± 22.2	<.0001†
95% CI	146.5, 155.9	130.3, 141.1	
CRF (mm Hg)			
Mean ± SD	10.6 ± 1.9	9.9 ± 2.2	.0007†
95% CI	10.2, 10.9	9.3, 10.4	
CH (mm Hg)			
Mean ± SD	10.8 ± 1.7	9.9 ± 1.8	.0003†
95% CI	10.4, 11.1	9.4, 10.4	
P1P2Avg			
Mean ± SD	181.52 ± 26.31	181.9 ± 32.5	.9
95% CI	176.41, 186.64	174.0, 189.8	
P max			
Mean ± SD	426.53 ± 38.95	421.8 ± 48.3	.4
95% CI	418.96, 434.11	410.1, 433.60	
Concavity duration (ms)			
Mean ± SD	10.85 ± 0.60	10.79 ± 0.64	.6
95% CI	10.73, 10.98	10.64, 10.95	
Concavity time (ms)			
Mean ± SD	12.70 ± 0.06	12.70 ± 0.07	.3
95% CI	12.69, 12.72	12.68, 12.71	
Lag time (ms)			
Mean ± SD	0.22 ± 0.21	0.29 ± 0.37	.7
95% CI	0.18, 0.27	0.14, 0.45	
Applanation onset time (ms)			
Mean ± SD	8.10 ± 0.51	8.06 ± 0.62	.5

Variable*	Femto LASIK	PRK	*P* Value
95% CI	8.00, 8.20	7.91, 8.21	
Slope up (ms^{-1})			
Mean ± SD	40.04 ± 10.25	40.15 ± 12.47	.6
95% CI	38.04, 42.03	37.13, 43.17	
Slope down (ms^{-1})			
Mean ± SD	−43.79 ± 20.99	−42.33 ± 26.33	.1
95% CI	−47.87, −39.70	−48.71, −35.96	
HLA × 10^3			
Mean ± SD	116.10 ± 23.03	102.9 ± 21.4	<.0001†
95% CI	111.62, 120.59	97.7, 108.1	
Impulse × 10^3			
Mean ± SD	4.60 ± 3.68	4.56 ± 0.45	.4
95% CI	4.52, 4.67	4.45, 4.67	

CI = confidence interval; Femto LASIK = femtosecond laser–assisted laser in situ keratomileusis; ms = millisecond; PRK = photorefractive keratectomy

*See Table 1 for definitions of variables.

†Statistically significant

Table 4

One-month and 3-month postoperative custom variables derived from the dynamic bidirectional applanation device.*

Variable†	1 Mo Postop	3 Mo Postop	*P* Value		
			Preop† Vs 1 Mo	Preop† Vs 3 Mo	1 Mo Vs 3 Mo
A1					
Mean ± SD	602.53 ± 131.61	608.08 ± 136.72	<.0001‡	.003‡	.3
95% CI	576.94, 628.13	584.01, 722.15			
A2					
Mean ± SD	539.36 ± 128.92	542.58 ± 129.28	.001‡	.002‡	.8
95% CI	514.29, 564.44	518.91, 578.26			
Applanation peak difference					
Mean ± SD	−116.18 ± 91.60	−116.95 ± 9.16	<.0001‡	.003‡	.5
95% CI	134.00, 98.40	135.00, 98.90			
Concavity min					
Mean ± SD	41.83 ± 0.36	42.06 ± 0.43	<.0001‡	.0003‡	.1
95% CI	41.76, 41.90	41.83, 42.28			
Concavity mean					
Mean ± SD	125.79 ± 25.05	126.86 ± 23.89	<.0001‡	<.0001‡	.8
95% CI	12.93, 13.67	121.55, 134.18			
CRF (mm Hg)					
Mean ± SD	8.50 ± 1.89	8.55 ± 1.93	<.0001‡	<.0001‡	.8
95% CI	8.13, 8.87	8.09, 8.91			
CH (mm Hg)					
Mean ± SD	9.68 ± 1.62	9.72 ± 1.79	<.0001‡	<.0001‡	.7
95% CI	9.36, 9.99	9.15, 1.04			
P1P2Avg					
Mean ± SD	152.85 ± 19.92	154.47 ± 25.23	<.0001‡	.0002‡	.1
95% CI	148.98, 156.73	15.82, 162.14			
P max					

Variable[†]	1 Mo Postop	3 Mo Postop	*P* Value		
			Preop[†] Vs 1 Mo	Preop[†] Vs 3 Mo	1 Mo Vs 3 Mo
Mean ± SD	379.77 ± 34.05	385.16 ± 36.26	<.0001[‡]	.0003[‡]	.1
95% CI	373.16, 386.40	375.63, 394.70			
Concavity duration (ms)					
Mean ± SD	11.42 ± 0.46	11.29 ± 0.48	<.0001[‡]	.0003[‡]	.3
95% CI	11.33, 11.51	11.08, 11.49			
Concavity time (ms)					
Mean ± SD	12.62 ± 0.06	12.62 ± 0.06	<.0001[‡]	.0005[‡]	.1
95% CI	12.61, 12.64	12.62, 12.65			
Lag time (ms)					
Mean ± SD	0.35 ± 0.38	0.36 ± 0.37	<.0001[‡]	.001[‡]	.3
95% CI	0.28, 0.42	0.28, 0.45			
Applanation onset time (ms)					
Mean ± SD	7.49 ±0.44	7.58 ± 0.51	<.0001[‡]	.0002[‡]	.9
95% CI	7.40, 7.57	7.42, 7.84			
Slope up (ms^{-1})					
Mean ± SD	39.19 ± 12.89	39.69 ± 1.03	.9	.9	.8
95% CI	36.68, 41.70	36.45, 42.93			
Slope down (ms^{-1})					
Mean ± SD	−47.03 ± 31.93	−48.13 ± 3.53	.9	.2	.3
95% CI	−51.25, −4.83	−53.25, −4.13			
HLA × 10^3					
Mean ± SD	87.01 ± 21.16	89.12 ± 24.57	<.0001[‡]	.009[‡]	.2
95% CI	82.90, 91.13	86.63, 92.43			
Impulse × 10^3					
Mean ± SD	4.18 ± 3.15	4.19 ± 3.28	<.0001[‡]	.001[‡]	.2
95% CI	4.12, 4.24	4.14, 4.31			

CI = confidence interval; ms = millisecond

[*] See Table 3 for the preoperative values.

† See Table 1 for definitions of variables.

‡ Statistically significant

Table 5

Comparison of change (postoperative – preoperative) in variables 1 month postoperatively.

	Mean Change±SD		
Variable*	**Femto LASIK**	**PRK**	***P* Value**
A1	−155.94 ± 110.08	−174.65 ± 125.87	.5
A2	−120.57 ± 96.27	−122.73 ± 82.02	.9
Applanation peak difference	−176.45 ± 126.26	−160.62 ± 113.24	.6
Concavity min	−0.66 ± 0.43	−0.66 ± 0.37	.9
Concavity mean	−29.88 ± 18.92	−27.24 ± 20.15	.5
CRF (mm Hg)	−2.57 ± 1.44	−2.86 ± 1.27	.4
CH (mm Hg)	−1.69 ± 1.08	−1.93 ± 1.06	.3
P1P2Avg	−32.86 ± 22.04	−29.65 ± 17.63	.5
P max	−53.92 ± 34.73	−53.11 ± 29.30	.9
Concavity duration (ms)	+0.75 ± 0.64	+0.56 ± 0.33	.1
Concavity time (ms)	−0.09 ± 0.07	−0.10 ± 0.09	.6
Lag time (ms)	+0.43 ± 0.37	+0.40 ± 0.36	.7
Applanation onset time (ms)	−0.72 ± 0.45	−0.72 ± 0.37	.9
Slope up (ms^{-1})	−11.93 ± 8.42	−9.36 ± 7.68	.2
Slope down (ms^{-1})	−26.67 ± 35.28	−24.28 ± 38.28	.8
HLA × 10^3	−30.78 ± 1.85	−29.95 ± 1.92	.8
Impulse × 10^3	−489.38 ± 313.75	−474.80 ± 281.90	.8

Femto LASIK = femtosecond laser–assisted laser in situ keratomileusis; ms = millisecond; PRK = photorefractive keratectomy

*See Table 1 for definitions of variables.

Table 6

Spearman ρ and confidence interval of correlation of change in CH, change in CRF, preoperative CH, and preoperative CRF with CCT, ablation depth, RSB, and percentage of tissue altered.

Variable	Preop CH	Preop CRF	Δ CH	Δ CRF	CCT	Ablation Depth	RSB	PTA
Δ CH								
ρ value	−0.474*	−0.390*	NA	0.692*	−0.185	0.379*	−0.046	0.271*
95% CI	−0.619, −0.299	−0.551, −0.201	NA	0.567, 0.785	−0.416, −0.027	0.189, 0.542	−0.248, 0.160	0.071, 0.451
Δ CRF								
ρ value	−0.344*	−0.544*	0.692*	NA	−0.186	0.452*	−0.106	0.384*
95% CI	−0.512, −0.149	−0.674, −0.382	0.567, 0.785	NA	−0.427, −0.041	0.273, 0.601	−0.307, 0.097	0.194, 0.546

Δ = change; CCT = central corneal thickness; CH = corneal hysteresis; CI = confidence interval; CRF = corneal resistance factor; NA = not applicable; PTA = percentage of tissue depth altered [(flap thickness + ablation depth)/ preoperative CCT]; RSB = residual stromal bed

*Statistically significant (*P* value of correlation <.0001).

Table 7

Spearman ρ and CI of correlation of biomechanical variable change Δ with CCT, ablation depth, RSB, and percentage of tissue depth altered.

Variable*	CCT		Ablation Depth		RSB		PTA	
	Spearman ρ Value	95% CI	Spearman ρ Value	95% CI	Spearman ρ Value	95% CI	Spearman ρ Value	95% CI
Δ A1	−0.156	−0.350, 0.049	0.103	0.104, 0.301	−0.058	−0.260, 0.148	0.039	−0.167, 0.242
Δ applanation peak difference	−0.139	−0.334, 0.067	0.020	−0.186, 0.223	−0.158	−0.351, 0.048	0.082	−0.124, 0.282
Δ concavity min	−0.194	−0.383, 0.011	0.251†	−0.055, 0.451	−0.022	−0.226, 0.183	0.235†	0.006, 0.398
Δ concavity mean	−0.223	−0.401, −0.166	0.024	−0.182, 0.227	−0.158	−0.352, 0.048	0.037	−0.168, 0.240
Δ P1P2Avg	−0.041	−0.244, 0.165	0.158	−0.048, 0.351	−0.104	−0.303, 0.102	0.207†	0.007, 0.389
Δ P max	−0.125	−0.322, 0.081	0.198†	0.010, 0.389	−0.057	−0.258, 0.149	0.214†	0.007, 0.392
Δ concavity duration	−0.035	−0.238, 0.170	0.012	−0.192, 0.217	−0.043	−0.245, 0.163	0.092	0.114, 0.291
Δ concavity time	−0.218†	−0.404, −0.013	0.205†	0.010, 0.391	−0.005	−0.205, 0.204	0.199†	0.006, 0.387
Δ lag time	−0.226	−0.412, −0.023	0.070	0.137, 0.270	−0.329†	−0.500, −0.133	0.287†	0.070, 0.450
Δ applanation onset time	−0.074	−0.275, −0.132	0.225†	0.021, 0.411	−0.133	−0.328, 0.074	0.270†	0.059, 0.450
Δ hysteresis loop area	−0.019	−0.223, 0.185	0.220†	0.002, 0.401	−0.096	−0.295, 0.111	0.156	0.005, 0.351
Δ impulse	−0.121	−0.320, −0.085	0.203†	0.002, 0.395	−0.046	−0.250, 0.160	0.188†	0.017, 0.381

Δ = change; CCT = central corneal thickness; CI = confidence interval; PTA = percentage of tissue depth altered [(flap thickness + ablation depth)/preoperative CCT]; RSB = residual stromal bed thickness

* See Table 1 for definitions of variables.

† Statistically significant *P* value of correlation <.0001