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Factors that Influence Intraocular Pressure Changes after Myopic and Hyperopic LASIK and Photorefractive Keratectomy

A Large Population Study

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Purpose: To describe the factors that influence the measured intraocular pressure (IOP) change and to develop a predictive model after myopic and hyperopic LASIK and photorefractive keratectomy (PRK) in a large population.

Design: Retrospective, observational case series.

Participants: Patients undergoing primary PRK or LASIK with a refractive target of emmetropia between January 1, 2008, and October 5, 2011.

Methods: The Optical Express database was queried for all subjects. Data were extracted on procedure specifics, preoperative central corneal thickness (CCT), IOP (using noncontact tonometry), manifest refraction, average keratometry, age, gender, and postoperative IOP at 1 week, 1 month, and 3 months. A linear mixed methods model was used for data analysis.

Main Outcome Measures: Change in IOP from preoperatively to 1 month postoperatively.

Results: A total of 174 666 eyes of 91 204 patients were analyzed. Hyperopic corrections experienced a smaller IOP decrease than myopic corrections for both PRK and LASIK ($P < 0.0001$). Patients who underwent LASIK had a 0.94 mmHg (95% confidence interval [CI], 0.89–0.98) greater IOP decrease than patients who underwent PRK ($P < 0.0001$), reflecting the effect of the lamellar flap. The decrease in IOP was linearly related to preoperative manifest spherical equivalent (MSE) for myopic PRK and LASIK ($P < 0.0001$), weakly correlated with preoperative MSE after hyperopic LASIK, and not related to preoperative MSE after hyperopic PRK. The single greatest predictor of IOP change was preoperative IOP across all corrections. By using the available data, a model was constructed to predict postoperative IOP change at 1 month; this was able to explain 42% of the IOP change after myopic LASIK, 34% of the change after myopic PRK, 25% of the change after hyperopic LASIK, and 16% of the change after hyperopic PRK.

Conclusions: Myopic procedures lower measured IOP more than hyperopic procedures; this decrease was proportional to the amount of refractive error corrected. Independent of the refractive correction, the creation of the lamellar LASIK flap decreased measured IOP by 0.94 mmHg. A best-fit model for IOP change was developed that may allow better interpretation of post-laser vision correction IOP values. *Ophthalmology 2015;122:471-479 © 2015 by the American Academy of Ophthalmology.*

Laser vision correction (LVC), including LASIK and photorefractive keratectomy (PRK), uses an excimer laser to flatten or steepen the central cornea and change the refractive error of the eye. Tissue removed during this photoablative process can alter the biomechanical properties of the cornea.[1] The majority of current methods for measuring intraocular pressure (IOP) make assumptions about corneal biomechanical parameters[2] that can be altered after LVC.[1]

Previous studies have examined the relationship between IOP and LVC. Some studies have looked solely at an individual type of LVC, including myopic LASIK,[1,3–12] myopic PRK,[13–17] hyperopic LASIK,[18–21] and hyperopic PRK.[22,23] Other authors have compared the influence of different types of LVC on postoperative IOP, including studies on myopic LASIK and PRK,[24] myopic and hyperopic LASIK,[24–29] and myopic PRK with hyperopic and myopic LASIK.[30] Overall, these studies have found a postoperative decrease in measured IOP by applanation. The largest study to this subject to date by Chang and Stulting,[3] with 4240 patients, provided illumination on the effect of the lamellar flap on IOP change, but was limited to myopic LASIK and did not account for central corneal thickness (CCT), which has been shown to have a substantial effect on IOP measurement.[31] The rest of these reports, although useful, have been hampered by small sample sizes and were limited in their ability to fully analyze factors related to the IOP change, such as the baseline patient characteristics, surgical parameters, and type of surgery.

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In this study, we examined the relationship between preoperative and postoperative IOP changes after LASIK and PRK in a large population representing the spectrum of those who seek refractive surgery. By using this data, we developed a predictive model for measured IOP change after refractive surgery and analyzed the effect of a variety of preoperative factors on IOP change.

Methods

This study used only de-identified patient data, and thus received an exemption from full review by the Committee on Human Research at the University of California, San Francisco. This work is compliant with the Health Insurance Portability and Accountability Act of 1996 and adhered to the tenets of the Declaration of Helsinki.

The database of patients receiving refractive surgery at Optical Express (Glasgow, Scotland) was searched for patients undergoing LVC between January 1, 2008, and October 5, 2011, using the following criteria: (1) primary LASIK or PRK, (2) refractive target was emmetropia, (3) attended the preoperative and 1-month postoperative examination, and (4) had IOP measured at each visit. All patients who met these criteria were analyzed. Additional data included the patient's age, gender, preoperative keratometry, preoperative CCT, mean preoperative manifest spherical equivalent (MSE), data from the 1-week and 3-month postoperative visits, and procedure details.

All IOP measurements were taken with the Nidek Tonoref II or the Nidek NCT2000 (Nidek Co, Gamagori, Japan), both noncontact tonometers. For the purpose of this article, IOP will refer to the measurement of IOP by this tonometer, not the actual pressure inside the eye. Central corneal pachymetry was performed using a handheld digital ultrasound pachymeter according to the manufacturer's recommendations (Pachymate; DGH Technology Inc, Exton, PA). For patients with more than 1 reading, the available readings were averaged and the average value was used. The majority of patients (77%) had 3 independent preoperative IOP measurements; 13% had 2 measurements, and 9% had a single measurement. A total of 55% of patients had 1 CCT measurement, 2% of patients had 2 CCT measurements, and 43% of patients had 3 CCT measurements. At 1 month, 67% of patients had 3 IOP measurements, 17% of patients had 2 IOP measurements, and 16% of patients had 1 IOP measurement. The IOP and CCT measurements were averaged, and the average value used in this study if more than 1 value was available. Keratometry was performed by an automated keratometer made by Nidek (Nidek Co) or Topcon (Tokyo, Japan). Manifest refraction was performed by experienced optometrists using a resolution-based technique in which the end point is the least amount of minus sphere that results in the best visual acuity ("push plus"). All patients underwent a full preoperative ocular examination including dilated fundus examination.

All patients desired improved vision without optical aids and met the indications for LVC as specified by the excimer laser user manual (VISX Star S4; Abbott Medical Optics, Inc, Santa Ana, CA) with the exception that patients with autoimmune disease could undergo surgery if their condition was stable and well controlled. Patients were only considered for refractive surgery if they had a minimum CCT of 450 μm (PRK) and 480 μm (LASIK). All patients with the diagnosis of glaucoma and any other vision-limiting pathology were excluded; patients with ocular hypertension were included only if they had no evidence of glaucoma on evaluation by their comprehensive ophthalmologist and were not taking antihypertensive medications.

The Intralase iFS laser (Abbott Medical Optics Inc) femtosecond with a flap thickness of 100 to 120 μm was used for laser-cut flaps, and the Moria M2 mechanical microkeratome (Moria, Antony, France) was used for the mechanical flaps with an estimated flap thickness of 130 μm. All femtosecond flaps were created with the hinge positioned superiorly, whereas the mechanical keratome flaps had nasal hinges. For PRK procedures, the epithelium was removed using an alcohol solution, some surgeons discarding the epithelium and some repositioning it after ablation. The Visx Star S4 excimer laser (Abbott Medical Optics Inc) was used for all ablations. For wavefront-guided myopic corrections, a 6-mm optical zone with a total ablation zone of 8 mm was used, and for standard myopic corrections, an optical zone of 6.5 mm with a total ablation zone of 8 mm was used. For both standard and wavefront-guided hyperopic ablations, an optical zone of 6 mm and total ablation zone of 9 mm were used.

After LASIK, patients were prescribed a third-generation fluoroquinolone and 1% prednisolone acetate, each 4 times per day for 1 week, and instructed to use an artificial tear solution 4 times per day for 1 month. After PRK, patients received a third-generation fluoroquinolone 4 times per day for 1 week (or until the epithelial defect was healed), as well as fluorometholone 0.1% 4 times per day for the first week followed by a weekly taper to off over the course of the next 3 weeks. Patients also received tetracaine 1% eyedrops, and were instructed to use them sparingly as needed for pain during the first 3 postoperative days, and artificial tears 4 times per day for 1 week.

Patient and surgeon preference were the primary drivers of the procedure choice. However, the following groups of patients were selected only for PRK: patients with a CCT <480 μm, patients who would have a residual stromal bed <250 μm with LASIK, patients who had epithelial basement membrane disease, and patients with corneal shape anomalies as assessed by Scheimpflug-based topography. Patients with CCT <500 μm and those with an average keratometry <40 or >46 diopters (D) were required to have the femtosecond microkeratome for flap creation if they were undergoing LASIK.

Statistical analysis and visualization were performed by Accelerated Vision Statistical Consulting (Overland Park, KS). A generalized linear mixed methods multivariate regression analysis and an associative memory analysis were performed to account for the interrelatedness between 2 eyes of the same patient. From the model constructed using this method, the goodness-of-fit statistic R^2 was calculated using a least-squares method by comparing the calculated postoperative IOP change with the actual postoperative IOP change. Descriptive statistics were performed to describe the data using the STATA software package (StataCorp LP, College Station, TX). A significance level of 0.001 was chosen using the Bonferroni correction for multiple comparisons.

Results

A total of 91 204 patients (174 666 eyes) met the inclusion criteria. The patients were divided into 4 subgroups for analysis: myopic LASIK, myopic PRK, hyperopic LASIK, and hyperopic PRK.

Table 1. Preoperative Characteristics for the Myopic and Hyperopic LASIK and Photorefractive Keratectomy Subgroups

	Myopic LASIK	Hyperopic LASIK	Myopic PRK	Hyperopic PRK
n eyes/N patients	133 752/69 742	27 095/14 182	12 164/6402	1655/878
Age (yrs)				
Mean ± SD	35.8±10.2	52.9±8.9	34.9±10.5	52.7±9.01
Range	18−72	18−71	18−72	18−72
Female	55.4%	52.3%	50.1%	50.1%
MSE (D)				
Mean ± SD	−3.22±1.88	+1.92±0.84	−3.21±2.00	+1.79±0.81
Range	−12.65 to −0.125	0 to +7.25	−12.125 to −0.125	0 to +6.125
IOP (mmHg)				
Mean ±SD	15.25±2.86	15.34±2.92	13.73±2.87	14.07±3.01
Range	6−34	6−32	6−27	7−30
Average K (D)				
Mean ± SD	43.7±1.5	43.2±1.5	43.8±1.6	43.2±1.9
Range	32.5−52.9	34.8−48.3	34.8−50.1	35.3−47.4
CCT (μm)				
Mean ± SD	548.9±30.8	550.0±31.1	513.2±38.3	515.3±41.3
Range	435−700	410−680	410−680	437−655
Keratome				
Femtosecond (n/N)	39 680/20 610	19 703/10 339	−	−
Mechanical (n/N)	94 066/49 129	7390/3842		

CCT = central corneal thickness; D = diopters; IOP = intraocular pressure; K = keratometry; MSE = manifest spherical equivalent; PRK = photorefractive keratectomy; SD = standard deviation.
Shown are MSE, IOP, CCT, and average keratometry; also included is the number of patients undergoing LASIK with flaps cut by a mechanical versus femtosecond microkeratome.

There were 69 742 patients (133 752 eyes) in the myopic LASIK group, 6402 patients. (12 164 eyes) in the myopic PRK group, 14 182 patients (27 095 eyes) in the hyperopic LASIK group, and 878 patients (1655 eyes) patients in the hyperopic PRK group. There were 330 eyes (178 patients) that had mixed astigmatism with an MSE of zero; these were analyzed in the hyperopic groups. Table 1 shows the complete preoperative summary statistics for all 4 refractive groups. Of note, hyperopic patients were significantly older than myopic patients at the time of surgery and PRK cases had a thinner initial CCT than LASIK cases ($P < 0.0001$). The preoperative IOP of LASIK cases was slightly higher than that of PRK cases (0.38 mmHg, 95% confidence interval [CI], 0.32−0.44) when controlling for preoperative MSE, CCT, age, gender, and average K using a linear mixed-methods model ($P < 0.0001$).

Preoperatively, the biggest single predictor of measured IOP was CCT, with a strongly linear relationship between CCT and IOP. For every 10 μm change in CCT, the IOP change was 0.3 mmHg (95% CI, 0.30−0.31). The preoperative relationship between IOP and CCT is shown in Figure 1.

After refractive surgery, all 4 patient groups experienced a decline in IOP (Fig 2). The decline was greatest for eyes undergoing myopic LASIK, with a mean decrease of 4.57±2.42 mmHg (mean ± standard deviation) at 1 month, followed by myopic PRK, with a mean decrease of 3.16±2.53 mmHg at 1 month. Patients undergoing hyperopic procedures also experienced a decline in IOP at 1 month, with a mean decrease of 2.28±2.31 mmHg for LASIK and a mean decrease of 0.83±2.48 mmHg for PRK.

Between 1 week, 1 month, and 3 months, the IOP change was stable for the hyperopic PRK subgroup ($P = 0.4$). For the myopic PRK group, there was a small but nearly statistically significant IOP increase between 1 week and 1 month (0.15 mmHg, $P = 0.007$) and an additional small but statistically significant decrease between 1 month and 3 months (0.28 mmHg, $P < 0.001$). The LASIK groups experienced a larger change in IOP between 1 week and 1 month. For hyperopic LASIK, the IOP decreased by an additional 1.1 mmHg between 1 week and 1 month ($P < 0.001$), but was stable between 1 month and 3 months ($P = 0.06$). For myopic LASIK, the IOP decreased by an additional 1.3 mmHg between 1 week and 1 month ($P < 0.0001$) and was essentially stable between 1 month and 3 months, with a small but statistically significant additional decrease of 0.07 mmHg ($P < 0.0001$).

A linear mixed-methods regression model was constructed to explore factors influencing IOP decrease in each of the 4 groups at 1 month (Table 2). For all groups, the largest factor influencing the IOP change was the preoperative IOP (Fig 3). Eyes with higher preoperative IOP experienced a greater IOP decrease. There was a strong correlation between preoperative MSE and IOP change for myopic corrections, and a smaller but still significant correlation for hyperopic LASIK corrections ($P < 0.0001$); there was no correlation between preoperative MSE and IOP change after hyperopic PRK ($P = 0.01$) (Table 2, Fig 4). This model is based on preoperative MSE, not actual change between preoperative and postoperative MSE because all patients were targeted for emmetropia. For myopic LASIK and PRK, a 1 D increase in the amount of myopia corrected lowered the postoperative IOP by 0.4 mmHg ($P < 0.0001$). For hyperopic LASIK, a 1 D increase in the amount of hyperopia lowered IOP by 0.063 mmHg ($P < 0.0001$). Age was associated with IOP change for all corrections except for hyperopic PRK, with a decrease of 0.022 to 0.024 mmHg per year of life ($P < 0.0001$).

Both flat and steep K were associated with IOP change in all correction groups, with the relative influence of keratometry being greater in hyperopic PRK corrections than in the other groups. Flat K had a smaller, positive influence on IOP change than steep K,

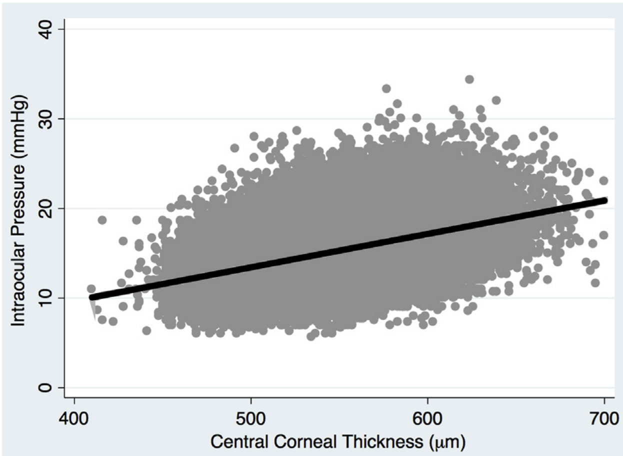

Figure 1. Preoperative relationship between intraocular pressure (IOP) and central corneal thickness (CCT) with the regression line in *black*. There is a linear relationship across all values of CCT. The 95% confidence interval (CI) for the regression line is contained within the width of the *black line* because the sample size is large and the CI is small, and the slope is 0.3 mmHg/10 μm.

which had a larger negative influence, for all corrections. This indicates that eyes with more corneal astigmatism and a greater difference between flat and steep K would experience a larger IOP change from their ablation than eyes with similar flat K/steep K values. Gender was not associated with IOP change after surgery except in female patients undergoing myopic LASIK, in whom it was weakly significant.

To analyze the effect of the lamellar flap, a linear mixed-methods regression of all available data using procedure type as a covariant was performed. Across all patients, LASIK lowered IOP by an additional 0.94 mmHg (95% CI, 0.89−0.98; $P < 0.0001$) over PRK. This relationship held true for both myopic and hyperopic corrections (Fig 5). A subanalysis was conducted by flap type. Overall, patients treated with the femtosecond laser had a 0.048 mmHg (95% CI, 0.009−0.08, $P = 0.01$) greater decrease in IOP than those who had been treated with the mechanical microkeratome. However, patients treated with the femtosecond microkeratome were significantly more myopic than those treated with the mechanical microkeratome (mean MSE femtosecond = −3.39, mean MSE mechanical = −2.77, $P < 0.001$), even when accounting for the selection criteria for the femtosecond laser. Therefore, the analysis was restricted to a subset of patients who had a matched mean amount of preoperative myopia, those with ≤2.5 D. In this population, there was no significant difference between flap creation with the femtosecond or mechanical microkeratome ($P = 0.07$).

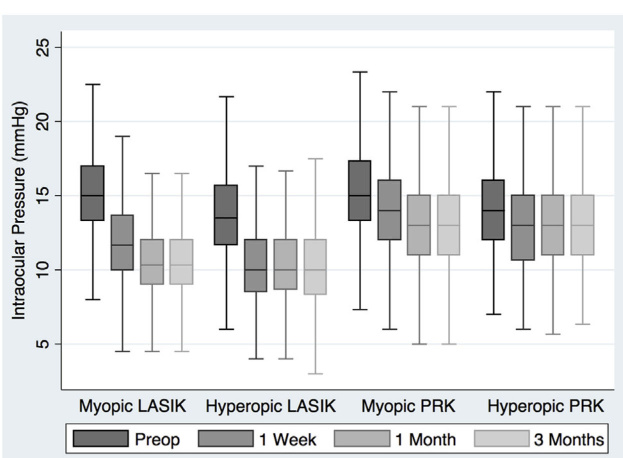

Figure 2. Box plots of intraocular pressure (IOP) for hyperopic and myopic LASIK and photorefractive keratectomy (PRK) subgroups are shown at the preoperative visit and at 1 week, 1 month, and 3 months postoperatively. The boxes represent the 25th to 75th interquartile range, and the bars represent the range of data that are within 1.5 times the interquartile range; outliers are excluded. The IOP decreased from preoperatively to after refractive surgery for all procedures, but the greatest decrease was for myopic LASIK, followed by myopic PRK. The IOP stabilized after 1 week for the PRK subgroups but continued to decrease up to 1 month for the LASIK subgroups.

By using the multivariate linear-mixed model in Table 2 and the influence of the lamellar flap in LASIK procedures, a predictive model for IOP change after refractive surgery was developed (Table 3). To assess the predictive value of this model, a least-squares regression of predicted postoperative IOP using the model versus actual postoperative IOP was performed. A goodness-of-fit R^2 correlation coefficient was then calculated. For each group, the R^2 values were as follows: myopic LASIK, 0.45; myopic PRK, 0.34; hyperopic LASIK, 0.25; hyperopic PRK, 0.16.

A simplified model was developed for day-to-day use in the clinic to estimate a corrected IOP using preoperative MSE for myopic LASIK and PRK and preoperative IOP (Table 3). Because the single greatest predictor of IOP change after LVC was preoperative IOP, this is included in the simplified model. However, preoperative IOP may not be readily available for most patients seen in clinic who have previously had LVC. Therefore, the simplified equation was solved using the average preoperative IOP seen in this study, 15 mmHg, for ease in clinical application (Table 3). Although this may underestimate the IOP change for some patients, it will give an approximate estimate of IOP change that the clinician can perform in a busy clinical setting.

Discussion

There are significant differences in the way IOP changes after myopic and hyperopic treatments, and after PRK and LASIK. Simple differences in the ablation profile for myopic and hyperopic corrections and between LASIK and PRK could affect corneal biomechanics and thus account for this difference we see in the measured IOP after refractive surgery. The myopic ablation profile removes a lenticule of tissue from the cornea that is thickest in the center and thin on the edges, thereby flattening the cornea and reducing its refractive power. The hyperopic ablation profile removes an annulus of tissue from the peripheral cornea while leaving the central corneal unablated, thereby steepening the central cornea and increasing the overall refractive power of the central cornea. The amount of tissue removed in both profiles is related to the intended refractive correction.

Measured IOP after myopic LASIK[1,3−12,24−27] and myopic PRK[13−17,24] has been shown to decrease using a wide array of tonometry devices. The IOP reduction after

Table 2. Multivariate Linear-Mixed Methods Model of the Influence of Preoperative Intraocular Pressure, Preoperative Central Corneal Thickness, Preoperative Manifest Spherical Equivalent, Gender, Age, and Preoperative Average Keratometry on Intraocular Pressure Decrease after Undergoing Myopic and Hyperopic LASIK and Photorefractive Keratectomy

Variable	Group	Correlation Coefficient	95% CI	*P* Value
Preoperative IOP	Myopic LASIK	−0.51	−0.51 to −0.52	**<0.0001**
	Myopic PRK	−0.46	−0.47 to −0.45	**<0.0001**
	Hyperopic LASIK	−0.42	−0.43 to −0.41	**<0.0001**
	Hyperopic PRK	−0.35	−0.39 to −0.32	**<0.0001**
Preoperative CCT	Myopic LASIK	0.0097	0.0093−0.010	**<0.0001**
	Myopic PRK	0.0096	0.0086−0.011	**<0.0001**
	Hyperopic LASIK	0.011	0.010−0.012	**<0.0001**
	Hyperopic PRK	0.0073	0.0046−0.0098	**<0.0001**
MSE	Myopic LASIK	0.40	0.39−0.41	**<0.0001**
	Myopic PRK	0.40	0.38−0.41	**<0.0001**
	Hyperopic LASIK	−0.06	−0.088 to −0.038	**<0.0001**
	Hyperopic PRK	−0.12	−0.23 to 0.0051	0.01
Flat K	Myopic LASIK	0.12	0.11−0.13	**<0.0001**
	Myopic PRK	0.15	0.10−0.18	**<0.0001**
	Hyperopic LASIK	0.13	0.10−0.16	**<0.0001**
	Hyperopic PRK	0.27	0.14−0.41	**0.0008**
Steep K	Myopic LASIK	−0.14	−0.15 to −0.13	**<0.0001**
	Myopic PRK	−0.19	−0.22 to −0.15	**<0.0001**
	Hyperopic LASIK	−0.15	−0.18 to −0.12	**<0.0001**
	Hyperopic PRK	−0.37	−0.49 to −0.24	**<0.0001**
Male gender	Myopic LASIK	0.094	-9.2×10^{-6} to 0.19	0.1
	Myopic PRK	0.054	−0.37 to 0.49	0.8
	Hyperopic LASIK	0.10	−0.23 to 0.42	0.6
	Hyperopic PRK	1.39	0.13−2.67	0.07
Female gender	Myopic LASIK	0.12	0.029−0.219	0.03
	Myopic PRK	0.061	−0.36 to 0.49	0.8
	Hyperopic LASIK	0.12	−0.23 to 0.43	0.6
	Hyperopic PRK	1.46	0.18−2.73	0.06
Age (at time of surgery)	Myopic LASIK	0.024	0.034−0.025	**<0.0001**
	Myopic PRK	0.023	0.020−0.026	**<0.0001**
	Hyperopic LASIK	0.022	0.019−0.024	**<0.0001**
	Hyperopic PRK	0.0097	−0.0013 to 0.021	0.1

CCT = central corneal thickness; CI = confidence interval; IOP = intraocular pressure; MSE = manifest spherical equivalent; PRK = photorefractive keratectomy.
The correlation coefficient is the numeric correlation between the variable and the parameter. Values were considered statistically significant if they had a *P* value <0.001, which accounts for the multiple comparisons made, these values appear in boldface.

myopic LASIK has been estimated to range from 0.027 mmHg/μm of ablated tissue[7] to 0.041 mmHg/μm[5] of ablated tissue and has been estimated at 0.021 mmHg/μm ablated tissue after myopic PRK.[17] Chang and Stulting[3] analyzed 8113 eyes undergoing myopic LASIK with IOP measurements by the Tono-Pen (Medtronic Electronics, Jacksonville, FL) and found a decrease of 0.12 mmHg per D of refractive correction.

In this study, we found a reduction in IOP after myopic procedures that was strongly linked to the amount of myopia corrected, 0.40 mmHg (95% CI, 0.39−0.41) per D of myopic correction for both PRK and LASIK. For a conventional ablation profile, this equates to 0.32 mmHg per 10 μm of tissue removal, which is similar to the correlation between CCT and measured IOP that we and others have found in unoperated eyes.[31] This is similar to what has been described for both myopic LASIK and myopic PRK, confirming the previous estimates.

We found that IOP decreased after hyperopic LASIK and PRK. The correlation with MSE was weak for hyperopic LASIK (−0.06 mmHg per D of hyperopia; 95% CI, −0.04 to −0.08), and there was no correlation between MSE and IOP change for hyperopic PRK. This is in contrast to the strong correlation between MSE and IOP change seen with myopic procedures and indicates that the IOP change after hyperopic LVC is not due to the quantity of peripheral tissue removed, but rather some effect obtained by ablating the peripheral cornea. An IOP decrease after hyperopic LASIK[18,19,25,26] and hyperopic PRK[22,23] has been described before, and 2 articles have reported a finding of no correlation between IOP and preoperative MSE.[18,22]

Overall, the IOP decrease was greater for myopic patients than for hyperopic patients for both LASIK and PRK procedures (Fig 4). This is probably a combined effect of the removal of central corneal tissue plus the peripheral corneal ablation in myopic ablations versus the effect of only peripheral corneal tissue ablation in hyperopic ablations on the IOP measurement. Our findings of a discrepancy in IOP decrease between the myopic and hyperopic ablation profiles are similar to those of Sanchez-Naves et al,[26] who

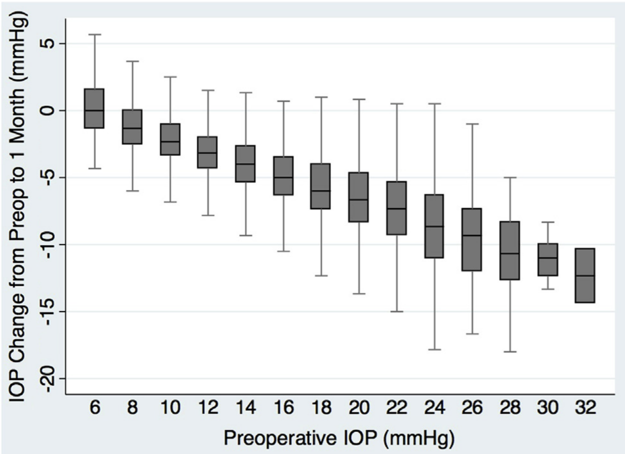

Figure 3. The intraocular pressure (IOP) change at 1 month including all eyes plotted against preoperative IOP. The boxes represent the 25th to 75th interquartile range, and the bars represent the range of data that are within 1.5 times the interquartile range; outliers beyond this are excluded. The IOP decrease at 1 month postoperatively is proportional to preoperative IOP. The greater the preoperative IOP, the larger the IOP change at 1 month.

found an average decrease of 4.46 mmHg for myopic LASIK cases and 2.09 mmHg for hyperopic LASIK cases.

Preoperative IOP was the single strongest predictor of postoperative IOP change, with eyes with a higher preoperative IOP having a greater IOP decrease (Fig 3). Some of this phenomenon may be due to regression to the mean, that is, higher than normal values tend to be closer to normal when measured a second time, although this was mitigated in part by averaging the available preoperative values for patients with more than 1 measurement. It also may be due to innate differences in the elastic properties of the cornea between eyes with lower preoperative IOP and higher preoperative IOP. Chihara et al[8] observed a similar phenomenon in their study of 100 patients undergoing myopic LASIK, which they attributed to a greater reduction in the modulus of elasticity in eyes with higher IOP than in those with lower IOP. A similar phenomenon was noted by Munger et al[22] in a study of hyperopic PRK, with the main predictor of postoperative IOP decrease being preoperative IOP.

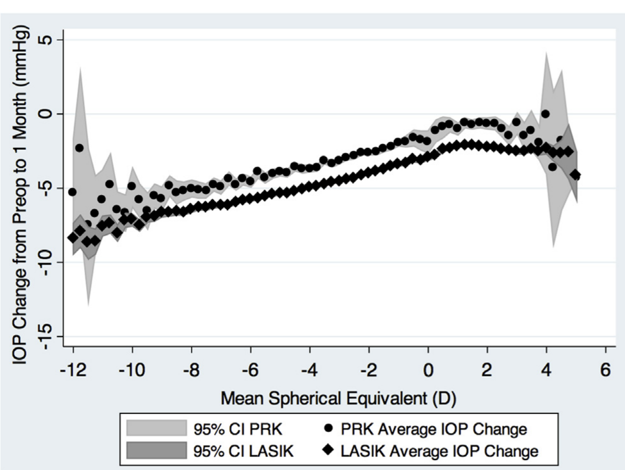

Figure 4. Aggregate intraocular pressure (IOP) change and 95% confidence interval (CI) at 1 month versus preoperative mean manifest spherical equivalent (MSE) in diopters for LASIK (*circle markers*) and photorefractive keratectomy (PRK) (*triangle markers*) with the 95% CI shaded. Each point is the binned IOP change data for all eyes with that MSE, and each represents from 10 to 1000s of eyes (points with <10 eyes were excluded). There is a strongly linear correlation between myopic corrections and MSE, and a weaker one between MSE and hyperopic corrections. The LASIK curve mirrors the PRK but with approximately a 1-mmHg difference.

Preoperative CCT was independently related to the amount of IOP decrease after LVC. This is an interesting finding. We were not looking at the magnitude of the postoperative IOP, which CCT has been clearly shown to be related,[27] but at the magnitude of the change between preoperative and postoperative IOP. Thicker CCTs experienced less change in IOP from preoperative to postoperative than thinner CCTs, and this was true across all 4 groups. This would suggest that thicker corneas are more resilient to ablation and experience less biomechanical alterations after ablation than thinner corneas.

Two previous studies have attempted to quantify the effect of the cutting of a lamellar flap on measured IOP reduction after LASIK. By using a regression analysis, Chang and Stulting[3] estimated that the cutting of the lamellar flap independently reduces measured IOP by an average of 1.36 mmHg. Another study estimated the lamellar flap reduced measured IOP by 1.6±1.8 mmHg.[26] We estimate that the lamellar flap lowers IOP by 0.94 mmHg (95% CI, 0.89−0.98) for both myopic and hyperopic procedures. This is slightly lower than both previous estimates, but the larger number of variables analyzed, the different tonometer, or the larger sample size may explain the difference.

Although it is theoretically possible that the use of different microkeratomes might affect postoperative IOP, this was unclear in our study. In the entire population of patients undergoing LASIK, those treated with the femtosecond microkeratome had a slightly lower IOP than those treated with the mechanical microkeratome. However, this was not borne out in a subanalysis of patients with a matched amount of myopia. It is likely that the method of flap creation plays an insignificant, if any, role in IOP change after refractive surgery.

Corneal astigmatism and corneal steepness played a role in measured IOP as evidenced by the differential effects of flat and steep keratometry on IOP decrease across all groups. Flat K had a smaller effect on IOP decrease, and steep K had a larger effect. The magnitude of this effect was greatest for hyperopic PRK corrections. This indicates 2 interesting conclusions. The first is that the steeper a patient's cornea is, the more the IOP will decrease after LVC. The second is that patients with a larger differential between flat and steep K, or more corneal astigmatism, will experience a larger decrease in IOP. This is in contrast to previous findings, which found no influence of preoperative K on IOP change.[3,8,27,32]

From the available data, it is possible to construct a model for IOP change after refractive surgery. The models we constructed are not able to explain the entire variance in

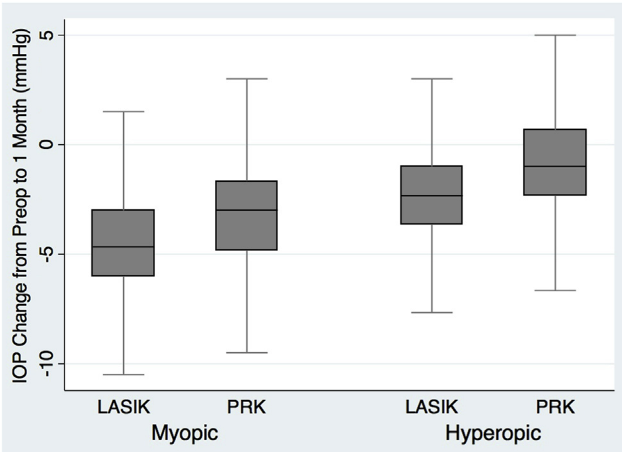

Figure 5. Box plot of intraocular pressure (IOP) change from preoperatively to 1 month for the 4 groups. The box encompasses the 25th to 75th percentiles, the straight line in the box is the average value, and the bars represent data within 1.5 times the interquartile range; outliers beyond this are excluded. After accounting for other factors using a linear mixed-methods regression analysis, there is a difference of 0.94 mmHg between the LASIK and photorefractive keratectomy (PRK) groups ($P < 0.0001$), which can be attributed to the effect of the lamellar flap.

the postoperative IOP. The best-fit model, for myopic LASIK, is able to explain only 45% of the variance, and the worst-fit model, hyperopic PRK, is able to explain only 15%. This may be due to a number of factors, including day-to-day and diurnal variability in IOP, as well as unmeasured factors affected by refractive surgery. At this time, modeling may give us a ballpark idea of the amount of reduction in IOP, but it by no means is able to account for the full clinical IOP change. In addition, for a model to be useful in clinical practice, it must be simple, accurate, and easy to apply. It also needs to use information that is readily available to the clinician. Because most patients undergoing refractive surgery are young and have healthy eyes, the need to consider IOP in context of their ocular health is most likely many years away from the time that they underwent refractive surgery, and the availability of preoperative data may be scarce. Therefore, the utility of IOP correction in clinical practice using this model may be limited by the scarcity of preoperative data.

Some authors have developed statistical models to predict measured IOP change after myopic refractive surgery. Yang et al[27] developed a linear mixed methods model for myopic LASIK from 229 patients that accounts for preoperative IOP, CCT, and MSE, as well as ablation depth and gender. They reported a higher R^2 value than we report in the current study (0.91 vs. 0.45 for the myopic LASIK model). This difference may be explained by the relatively smaller and homogenous population in that study versus the current one, as well as the less robust modeling methods used. Kohlhaas et al[12] developed a model for IOP correction for myopic LASIK from 101 eyes of 59 patients that accounted for changes in CCT and corneal curvature after surgery and added a correction factor of 0.75 mmHg. Cheng

Table 3. Predictive Equations for Corrected Intraocular Pressure after Hyperopic and Myopic LASIK and Photorefractive Keratectomy Using the Measured Intraocular Pressure

Procedure	Full Equation	R^2
Myopic LASIK	$IOP_c = IOP_m + 0.9 + 0.5$ (preoperative IOP) $- 0.4$ (MSE) $- 0.01$ (preoperative CCT) $- 0.1$ (flat K) $+ 0.1$ (steep K) $- 0.02$ (age)	0.45
Hyperopic LASIK	$IOP_c = IOP_m + 0.9 + 0.4$ (preoperative IOP) $+ 0.06$ (MSE) $- 0.01$ (preoperative CCT) $- 0.1$ (flat K) $+ 0.15$ (steep K) $- 0.02$ (age)	0.25
Myopic PRK	$IOP_c = IOP_m + 0.5$ (preoperative IOP) $- 0.4$ (MSE) $- 0.01$ (preoperative CCT) $- 0.15$ (flat K) $+ 0.19$ (steep K) $- 0.02$ (age)	0.34
Hyperopic PRK	$IOP_c = IOP_m + 0.4$ (preoperative IOP) $- 0.007$ (preoperative CCT) $- 0.27$ (flat K) $+ 0.37$ (steep K)	0.16
Procedure	**Simplified Equation with Available Preoperative IOP**	**R^2**
Myopic LASIK	$IOP_c = IOP_m - 3.9 - 0.4$ (preoperative MSE) $+ 0.5$ (preoperative IOP)	0.43
Hyperopic LASIK	$IOP_c = IOP_m - 3.4 + 0.4$ (preoperative IOP)	0.21
Myopic PRK	$IOP_c = IOP_m - 3.5 - 0.4$ (preoperative MSE) $+ 0.4$ (preoperative IOP)	0.32
Hyperopic PRK	$IOP_c = IOP_m - 3.4 + 0.3$ (preoperative IOP)	0.13
Procedure	**Equation without Available Preoperative IOP**	
Myopic LASIK	$IOP_c = IOP_m + 3.6 - 0.4$ (preoperative MSE)	
Hyperopic LASIK	$IOP_c = IOP_m + 2.15$	
Myopic PRK	$IOP_c = IOP_m + 2.5 - 0.4$ (preoperative MSE)	
Hyperopic PRK	$IOP_c = IOP_m + 1$	

CCT = central corneal thickness; IOP = intraocular pressure; IOP_c = corrected intraocular pressure; IOP_m = measured IOP; K = preoperative keratometry; MSE = preoperative manifest spherical equivalent; PRK = photorefractive keratectomy.
The first box contains the full equations, the second box contains simplified predictive equations, and the third box contains the equations for when preoperative IOP is not available and are calculated using the average IOP seen in all patients in the study, 15 mmHg. The equations shown predict the IOP change in millimeters of mercury. The following units are used: preoperative MSE is in diopters, the preoperative CCT is in microns, the flat and steep preoperative keratometry are in diopters, and the age is in years.

et al[33] described a similar model using postoperative corneal curvature, postoperative CCT, and ablation depth. The models described in this article are unique in that they encompass both myopic and hyperopic refractive errors and both LASIK and PRK.

Study Limitations

The IOP was recorded at only 1 preoperative visit, which does not account for day-to-day or diurnal variations in IOP. Accumulating more preoperative IOP data over several visits might have decreased some of the influence of preoperative IOP on IOP change by reducing the effect of regression to the mean, although multiple baseline measures were taken for the majority of patients in the study. This study measured IOP using noncontact tonometry. Noncontact tonometry has been shown to have good agreement with Goldmann applanation tonometry in a large meta-analysis;[34] however, it has been shown to be dependent on CCT, and at least 1 report indicates that it may be more sensitive to changes in CCT than Goldmann tonometry.[35] It would have been interesting to have other types of tonometry against which to evaluate the noncontact results, particularly dynamic contour tonometry, which may be less influenced by CCT.[36] Another possible limitation is the relatively short follow-up of 3 months post-LVC. However, IOP was essentially stable between the 1- and 3-month visits across all groups. Last, only 1 type of laser system (the VISX Star S4) was used in this study, so the results may not be generalizable to ablations performed by other laser systems.

In conclusion, this study compared IOP change after both PRK and LASIK in myopic and hyperopic correction profiles in a substantial number of patients, and is by far the largest number of patients and eyes studied in this subject. Overall, measured IOP can decrease after LVC. For patients undergoing highly myopic corrections, the IOP decrease can be dramatic. For instance, LASIK to treat 10 D of myopia can reduce measured IOP by as much as 9 mmHg. Any LASIK correction will lower IOP by approximately 1 mmHg because of the effect of the lamellar flap. This is important when evaluating suspicious optic nerves and visual field losses in potential glaucoma suspects who have undergone refractive surgery. There are reports that dynamic contour tonometry is relatively unaffected by corneal biomechanics and remains unchanged after refractive surgery.[37,38] However, until or if there is widespread use of a tonometry device that is independent of corneal biomechanics, refractive surgical history should be included in the evaluation of a patient's IOP.

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Abbreviations and Acronyms:
CCT = central corneal thickness; **CI** = confidence interval; **D** = diopters; **IOP** = intraocular pressure; **LVC** = laser vision correction; **MSE** = manifest spherical equivalent; **PRK** = photorefractive keratectomy.

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