Intraocular Pressure Measurements Using Dynamic Contour Tonometry after Laser In Situ Keratomileusis

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Purpose. Thinning of the corneal stroma by laser in situ keratomileusis (LASIK) results in inaccurate low intraocular pressure (IOP) readings by Goldmann applanation tonometry (GAT). Dynamic contour tonometry (DCT) is a novel measuring technique, designed to measure IOP largely independent of corneal thickness and curvature. The purpose of this study was to compare IOP measurements using GAT and DCT in eyes undergoing LASIK for correction of myopia.

Methods. In a prospective, single-center study, central corneal thickness (CCT) and IOP were measured in patients undergoing first-time LASIK for myopia. IOP was measured before and after surgery using GAT and DCT. The untreated contralateral eyes served as paired controls.

Results. There was good concordance between the two tonometers in 62 normal eyes before LASIK. Corneal ablation of 90.0 $\pm$ 49.18 μm (median $\pm$ SD) reduced IOP readings as measured by GAT by 3.0 $\pm$ 1.9 mm Hg ($P < 0.001$). In contrast, no significant change in IOP readings was recorded by DCT (-0.2 mm Hg $\pm$ 1.5 mm Hg, $P = 0.30$). There was no change in IOP in the untreated control eyes as measured by GAT and DCT.

Conclusions. Significant decreases in IOP were recorded by GAT after LASIK for myopia. Measurements by DCT, however, did not reveal any significant changes in IOP. (*Invest Ophthalmol Vis Sci.* 2003;44:3790–3794) DOI:10.1167/iovs.02-0946

Goldmann applanation tonometry (GAT) is the standard for routine measurements of intraocular pressure (IOP) in ophthalmology. Its accuracy depends on many factors, including corneal thickness and structure,[1] which are all altered by corneal refractive surgery. Therefore, the validity of IOP readings using Goldmann type applanation tonometers after corneal refractive procedures has been questioned. There are numerous reports stating reduced IOP readings after corneal refractive surgery,[2–16] a circumstance that is generally considered to be due to false low IOP reading by GAT rather than a real decrease in IOP.[17] This postulate has been supported by various studies that demonstrated that GAT is more affected by refractive surgery than other types of applanation tonometers, such as the handheld (Tonopen; Medtronic-Xomed-Solan, Jacksonville, FL) or air tonometers.[9,10,14,16] So far, there have not been any reports on true IOP after corneal refractive surgery, because tonometry techniques that work without applanation, such as manometric measurements, are not applicable in routine clinical settings. False low IOP readings pose the risk of delaying the diagnosis of future glaucoma in the rapidly growing population of patients who undergo refractive surgery.

A possible solution to the problem of inaccurate IOP measurements after corneal refractive surgery is the dynamic contour tonometer, a novel, nonapplanation contact tonometer designed to be largely independent of structural properties of the cornea. Its tip reflects the surface contour of a resting human cornea when intraocular and extraocular pressures are equal (e.g., as if the eye were submerged in a pressurized water bath). When in contact with the cornea, the tonometer tip creates a tight-fitting shell on the corneal surface without applanation of the tissue, thereby compensating for all forces exerted on the cornea. This allows an integrated pressure sensor inside the contacting surface to measure IOP, largely independent of corneal properties.

The purpose of this study was to evaluate dynamic contour tonometry (DCT) for IOP measurement in eyes undergoing LASIK for correction of myopia and to compare these IOP measurements with readings obtained by a Goldmann applanation tonometer.

Methods

Patients with normal corneas and no history of previous ocular trauma or surgery about to undergo first-time LASIK for myopia were evaluated in a prospective single-center study. Informed consent according to the tenets of the Declaration of Helsinki was obtained from each patient. Contralateral eyes served as paired controls. Pachymetry and IOP measurements by GAT and DCT were performed as a part of the routine clinical examination before and 2 weeks after LASIK on both the treated eye and the control eye. A 130 $\pm$ 30-μm-thick corneal flap was created by a keratome (Supratome; Schwind Eye-Tech Solutions GmbH, Kleinostheim, Germany), and the corneal stroma was ablated with a 193 nm excimer laser (Allegretto; WaveLight Laser Technologie AG, Erlangen, Germany) using the manufacturers' standard algorithm. Corticosteroid eye drops (FML, fluorometholone 0.1%; Allergan AG, Lachen, Switzerland) were prescribed to all patients three times daily for the first week and tapered to once daily over the first month.

Central corneal thickness (CCT) was measured with an ultrasonic pachymeter (SP-2000, Tomey Corp., Cambridge, MA). A drop of oxybuprocaine anesthetic 0.4% (Ciba Vision, Buelach, Switzerland) was placed on each eye. The patient was asked to blink before measurement to avoid any bias due to corneal drying. The pachymeter probe was smoothly placed on the center of the cornea over an undilated pupil, according to the discretion of the investigator. The mean of three readings within a range of $\pm$5 μm was used for each eye.

Particular attention was paid to standardizing the technique of IOP measurement. The patient was asked to keep both eyes open, breathe quietly, and fixate into the distance behind the examiner. GAT was performed on a slit lamp (Haag-Streit, Koeniz, Switzerland), with a tonometer calibrated according to the manufacturer's guidelines. Paper strips impregnated with fluorescein were used to stain the precorneal tear film. When eyelid support was necessary, compression of the globe was avoided. The mean of three consecutive readings was recorded. Before each reading, the measuring drum was reset to

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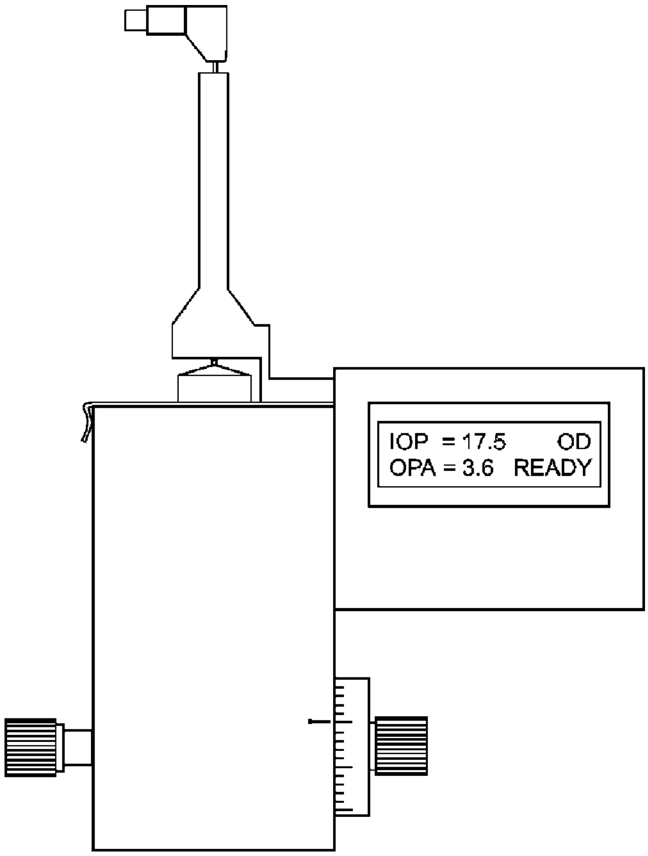

FIGURE 1. DCT mounted on standard slit lamp. IOP and ocular pulse amplitude (OPA) are indicated on a digital readout.

approximately 2 mm Hg. The reading was not masked to the investigator. If IOP fluctuated during the cardiac pulse cycle, the measurement was taken in the middle of the pulsation amplitude.

The dynamic contour tonometer (ODC; Ophthalmic Development Company AG, Zurich, Switzerland) is a further development of the contact lens tonometer[18,19] and is described in detail elsewhere (Kanngiesser H, et al. *IOVS* 2002;43:ARVO E-Abstract 301; Kanngiesser H, Robert YCA. manuscript in preparation). Briefly, it is a contact tonometer with a tip that fits into a standard GAT stand (Fig. 1). The surface of the tip is concave, with a radius of 10.5 mm. An electronic pressure sensor is integrated into the center of the contacting tip surface. The tonometer tip contacts the corneal surface in a manner similar to that of the GAT, except that correct positioning on the cornea is indicated by an audible signal that changes in pitch with changes in the pressure detected. When the tonometer tip contacts the cornea the tissue takes the contour as if the pressure on both sides of the cornea were the same, allowing the pressure sensor to measure IOP independent of corneal properties. IOP is calculated and displayed by the instrument without the examiner being able to change the result, thereby reducing possible observer bias.

The same examiner took all measurements in immediate succession as follows: CCT, GAT, and DCT. The right eye was always measured first.

The differences between the pressure measurements before and after treatment were calculated for both GAT and DCT (Δpressure = $\text{pressure}_{\text{posttreatment}} - \text{pressure}_{\text{pretreatment}}$). To compensate for diurnal IOP fluctuations, an absolute pressure change was calculated by deducting the pressure change found in the contralateral control eye from the change found in the treatment eye after LASIK surgery ($\Delta\text{pressure}_{\text{absolute}} = \Delta\text{pressure}_{\text{treatment eye}} - \Delta\text{pressure}_{\text{control eye}}$).[3] Data are presented as the median ± SD and analyzed using the nonparametric Wilcoxon signed-ranks test to account for the skewed and nonsymmetrical distribution of data points. $P < 0.05$ was considered significant. Statistical analysis was performed on computer (SPSS statistical software, ver. 10; SPSS Science, Inc., Chicago, IL).

RESULTS

Between January and March 2002, 39 consecutive patients underwent first-time LASIK surgery for the correction of myopia at our institution. Eight patients were not included into the study because of a history of ocular trauma or surgery ($n = 5$), preexisting corneal disease ($n = 2$), or suspected glaucoma ($n = 1$). Of the 31 patients who initially enrolled in the study, 6 had to be excluded during the protocol because of unwillingness to defer LASIK in the contralateral control eye for the study period of 2 weeks. Preoperative data obtained from these six patients were included only for the initial evaluation of concordance between the two different tonometers. Twenty-five patients completed the entire study, each contributing data from the treated eye and the contralateral control eye. Ten patients were women and 15 patients were men. The average age was 39 years, ranging from 22 to 58 years. LASIK surgery reduced the CCT by 90.0 ± 49.18 μm (median ± SD), corresponding to a change in spherical equivalent of −5.25 ± 2.76 D.

The concordance between the two different tonometers was evaluated by comparing IOP readings obtained by DCT and GAT in the 62 untreated eyes before surgery. The results are displayed in Figure 2 demonstrating a high concordance between the two techniques. IOP readings obtained by DCT were consistently higher (median difference: +1.6 mm Hg, interquartile range [IQR] = 0.8–2.3 mm Hg, $P < 0.001$) than readings obtained by GAT. This phenomenon may be explained by the fact that the dynamic contour tonometer was calibrated against a manometrically controlled pressure standard rather than a GAT pressure reading.

LASIK surgery reduced IOP readings in the treatment eyes as measured by GAT from a preoperative median of 15.0 mm Hg (IQR = 14.0–17.5 mm Hg) to 12.0 mm Hg (IQR = 10.0–14.0 mm Hg, $P < 0.001$) after surgery (Fig. 3). In the paired contralateral control eyes, median GAT pressures did not differ significantly before and after surgery (15.0 mm Hg, IQR = 14.0–18.0; 16.0 mm Hg, IQR = 12.0–16.5, respectively, $P = 0.08$). To account for a possible effect of individual IOP fluc-

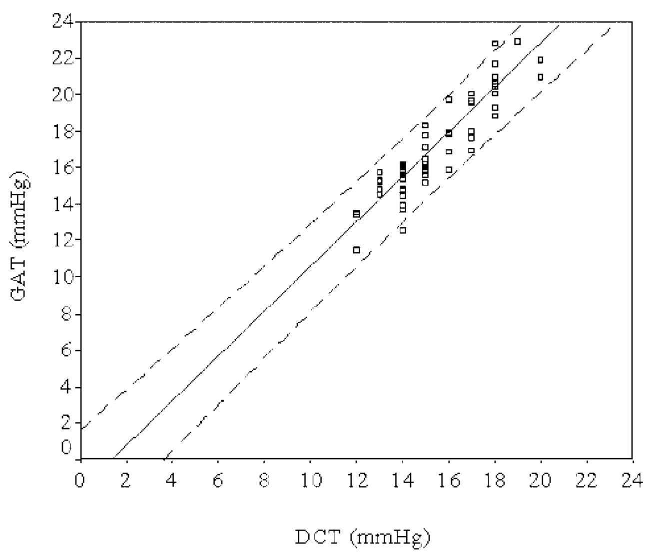

FIGURE 2. Concordance of IOP measurements obtained by GAT readings and DCT. *Solid line*: represents the linear function of the data; *dashed line*: 95% confidence boundaries.

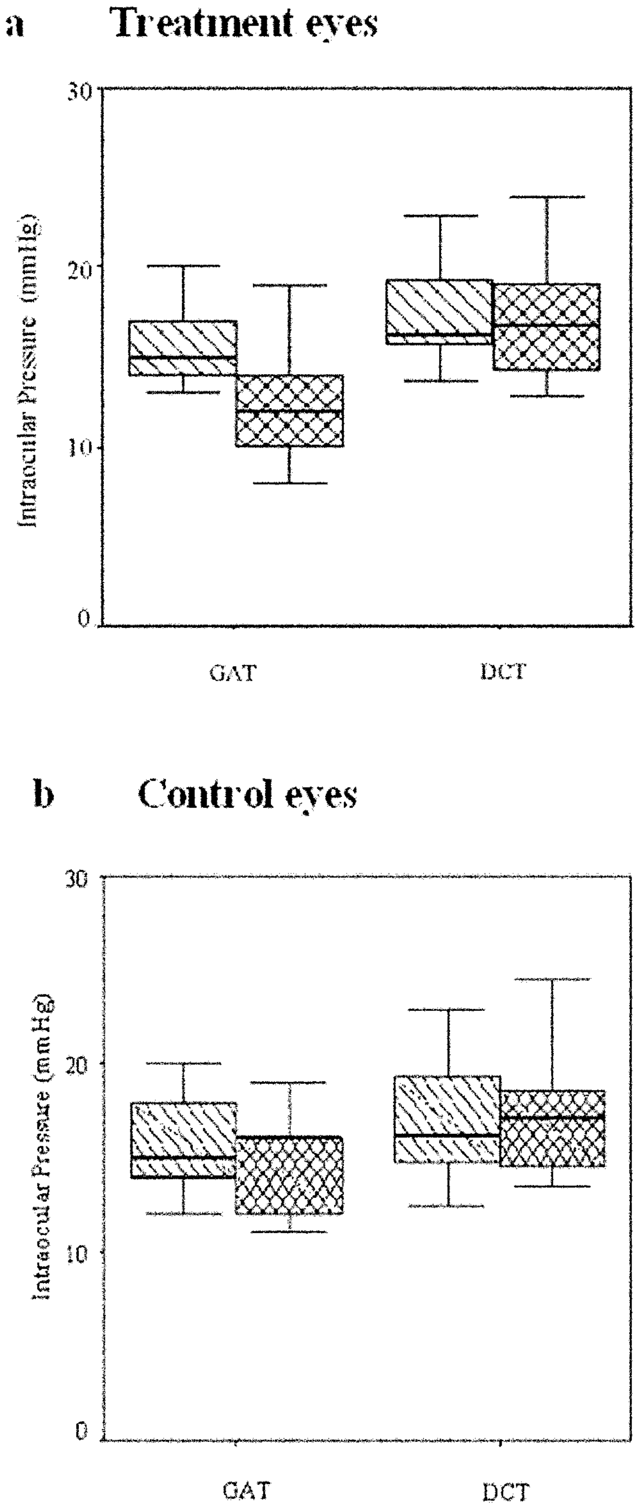

FIGURE 3. Distribution of GAT readings and DCT readings obtained from the treatment eyes (**A**) and the control eyes (**B**). (▧) Before surgery; (▩) after surgery. Box plots of median (*center line*), 25th and 75th percentile values (*bottom* and *top lines*) and range of values (*brackets*).

tuations, an absolute difference in IOP reading in the treated eyes was calculated by deducting the pressure fluctuation found in the paired control eyes from the pressure difference found in the treatment eye. GAT readings in the treated eye remained significantly lower after LASIK surgery, even when using the calculated absolute IOP differences (3.0 ± 1.9 mm Hg, $P < 0.001$).

Using dynamic contour tonometry IOP readings in the treated eyes did not differ significantly before and after LASIK treatment (16.2 mm Hg, IQR = 15.6–19.5 mm Hg before LASIK and 16.8 mm Hg, IQR = 14.2–19.2 mm Hg after LASIK, $P = 0.33$, Fig. 3). In the contralateral eye, median DCT pressure readings were 16.2 mm Hg (IQR = 14.8–19.7 mm Hg) before surgery and 17.1 mm Hg (IQR = 14.5 - 18.7 mm Hg) after surgery ($P = 0.90$). Even when deducting the diurnal pressure fluctuations found in the untreated control eye LASIK surgery had no significant effect on IOP measurements by DCT (-0.2 mm Hg ± 1.5 mm Hg; $P = 0.30$).

To visualize the effect of corneal thinning by LASIK surgery on IOP readings by the two different tonometers, we plotted the changes in IOP readings against the reduction in corneal thickness after LASIK (Fig. 4). Univariate linear regression using the absolute ΔGAT measure as the dependent variable and ΔCCT as the independent variable indicates a decrease of 0.02 mm Hg/μm reduction in CCT (95% confidence interval [CI] 0.005–0.034; $P = 0.01$). We found no significant correlation between the absolute ΔDCT and the decrease in CCT ($P = 0.10$).

DISCUSSION

There are several well-known sources of error in applanation tonometry, including central thickness and structural rigidity of the cornea.[1] In healthy corneas, central thickness is related to the rigidity of the cornea having an impact on the force required to flatten the area that is used to estimate IOP in applanation tonometry. CCT has therefore been widely accepted as an important and confounding variable when it comes to estimating the IOP by means of applanation tonometry.[20–22] Goldmann himself calibrated his applanation tonometer for an average corneal thickness of 520 μm.[23] Subsequently, several reports have shown that GAT overestimates IOP in patients with thicker corneas and underestimates it in those with thinner corneas.[24–26]

In an analogous way, the general tendency toward reduction the IOP measured by GAT after LASIK has been attributed to the iatrogenic thinning of the central cornea.[8,15,16,27,28] Still, the relationship between reduction in CCT and IOP after LASIK is controversial. Together with other reports,[15,16] the present findings are opposed to those in articles reporting no such association[7,11,29] or describing nonsignificant tendencies only.[13] Moreover, the correlation between the absolute ΔGAT and the decrease in CCT in our study does not automatically imply a causal relationship. Even if indicative of a cause, stromal thinning after refractive surgery may represent one possible factor among others. The peripheral cut in Bowman's layer may leave the residual cornea with different applanation properties compared with a cornea that is congenitally of the same thickness[8,30] and the size of the ablation zone may influence the change in IOP measurements by GAT even further.[13] Clinically undetectable fluid accumulations within the lamellar interface[31] and softening of the tissue due to epithelial and stromal edematization[11,13] or to topical steroids[14] have been proposed to account for the reduction of applanation IOP readings.

The present study demonstrates a mean decrease in IOP reading by GAT of 3.0 mm Hg after LASIK surgery. Based on a linear regression model, this decrease would equal approximately 0.2 mm Hg/10 μm of stromal ablation. How can the clinician be advised to account for this error? Nomograms have been published for adjusting GAT readings both in normal eyes with varying CCT[20,21,32] and in eyes after refractive surgery.[3,33,34]

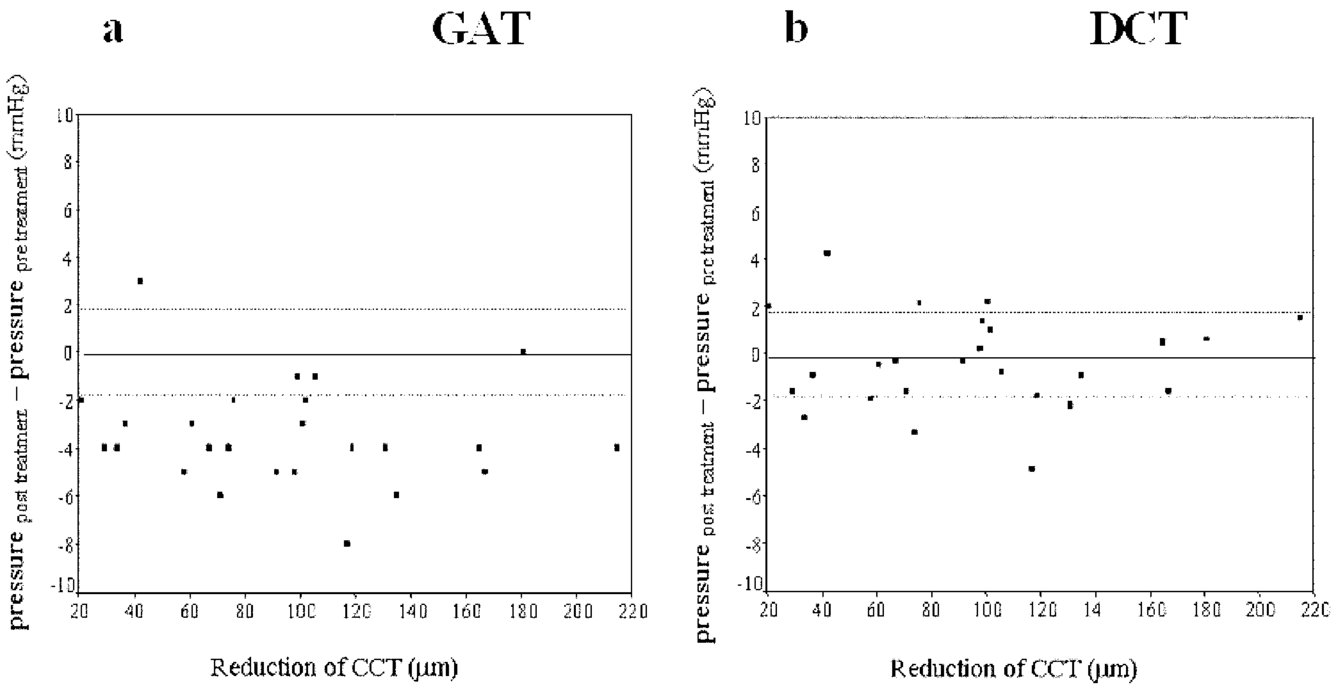

FIGURE 4. Correlation between changes in IOP readings and reduction of CCT after LASIK as measured by GAT (**A**) and DCT (**B**). Most of the DCT values lay within ±2 mm Hg from the preoperative baseline values, whereas most ΔGAT lay below this boundary, indicating an underestimation of IOP in the treated eye.

If the nomogram found in the present study (true IOP = GAT +0.02 mm Hg/μm of stromal ablation) with its minimal slope was used to correct the GAT readings, 12 of the 25 study patients would still have had a potentially hazardous underestimation of IOP of 2 mm Hg or more. Only 6 of 25 patients would have had a calculated IOP within ±1 mm Hg of the IOP individually compensated for by the corresponding values. Possible reasons for the inaccuracy of such nomograms may be due to the exclusion of other factors possibly influencing corneal rigidity, nonlinearity of the correlation between the variables,[35] or the magnitude of individual variation with regard to the effect of CCT on IOP.[36]

Constant correction factors are an alternative to nomograms.[15] The present data suggest assessing IOP after LASIK by adding 3 mm Hg to the GAT reading (Fig. 4). This rule of thumb harbors less potential for clinical misjudgment, because it would have reduced the number of false low-pressure estimations to 7 in 25 patients. However, the pressure in eyes of four patients would have been overestimated by 2 mm Hg or more.

These examples show that the use of nomograms as well as the use of constant correction factors to calculate true IOP after refractive corneal surgery is problematic. With the rapidly gaining popularity of corneal refractive surgery the need for a tonometer that allows for accurate routine IOP measurements independently of corneal properties becomes obvious.[15,37]

In contrast to GAT, IOP measurements performed by DCT seem not to be associated with a decrease in IOP after LASIK. The variations in IOP readings found before and after LASIK were minimal, and similar changes in IOP readings were observed in the paired nontreated fellow eye, findings that suggest that these minor changes reflect individual IOP fluctuations.

In normal eyes before surgery the novel dynamic contour tonometer showed a high concordance with the IOP readings obtained by GAT. The individual DCT readings tended to be 1.6 mm Hg higher than GAT readings. This is in good agreement with a recently published study that states that IOP readings made by applanation tonometry were 1.2 mm Hg lower than true IOP measured manometrically in human eyes in vivo.[38] We acknowledge that GAT was not performed in a masked manner. However, performing the more objective DCT last in the measurement sequence prevented any investigator bias, because the investigator was not influenced by the DCT reading when aligning and interpreting the semicircular images of GAT.

The DCT tip has the same dimensions as a GAT tip and fits into any Goldmann type applanation tonometer stand without the need to modify existing slit lamp rigs. In this study, DCT was found to be a suitable method for routine clinical use in normal and treated eyes.

In summary, this study shows that applanation tonometry falsifies IOP after LASIK in a manner that may interfere with the detection and management of glaucoma in a rapidly growing population of patients who undergo refractive surgery. The dynamic contour tonometer may be a valuable alternative to GAT, because its pressure reading does not seem to be affected by LASIK surgery for myopia.

References

1. Whitacre MM, Stein R. Sources of error with use of Goldmann-type tonometers. *Surv Ophthalmol.* 1993;38:1–30.
2. Schipper I, Senn P, Thomann U, Suppiger M. Intraocular pressure after excimer laser photorefractive keratectomy for myopia. *J Refract Surg.* 1995;11:366–370.
3. Chatterjee A, Shah S, Bessant DA, Naroo SA, Doyle SJ. Reduction in intraocular pressure after excimer laser photorefractive keratectomy: correlation with pretreatment myopia. *Ophthalmology.* 1997;104:355–359.
4. Mardelli PG, Piebenga LW, Whitacre MM, Siegmund KD. The effect of excimer laser photorefractive keratectomy on intraocular pressure measurements using the Goldmann applanation tonometer. *Ophthalmology.* 1997;104:945–948; discussion 949.

5. Faucher A, Gregoire J, Blondeau P. Accuracy of Goldmann tonometry after refractive surgery. *J Cataract Refract Surg.* 1997;23:832–838.
6. Rosa N, Cennamo G, Breve MA, La Rana A. Goldmann applanation tonometry after myopic photorefractive keratectomy. *Acta Ophthalmol Scand.* 1998;76:550–554.
7. Fournier AV, Podtetenev M, Lemire J, et al. Intraocular pressure change measured by Goldmann tonometry after laser in situ keratomileusis. *J Cataract Refract Surg.* 1998;24:905–910.
8. Emara B, Probst LE, Tingey DP, Kennedy DW, Willms LJ, Machat J. Correlation of intraocular pressure and central corneal thickness in normal myopic eyes and after laser in situ keratomileusis. *J Cataract Refract Surg.* 1998;24:1320–1325.
9. Levy Y, Zadok D, Glovinsky Y, Krakowski D, Nemet P. Tono-Pen versus Goldmann tonometry after excimer laser photorefractive keratectomy. *J Cataract Refract Surg.* 1999;25:486–491.
10. Zadok D, Tran DB, Twa M, Carpenter M, Schanzlin DJ. Pneumotonometry versus Goldmann tonometry after laser in situ keratomileusis for myopia. *J Cataract Refract Surg.* 1999;25:1344–1348.
11. Gimeno JA, Munoz LA, Valenzuela LA, Molto FJ, Rahhal MS. Influence of refraction on tonometric readings after photorefractive keratectomy and laser assisted in situ keratomileusis. *Cornea.* 2000;19:512–516.
12. Park HJ, Uhm KB, Hong C. Reduction in intraocular pressure after laser in situ keratomileusis. *J Cataract Refract Surg.* 2001;27:303–309.
13. Montes-Mico R, Charman WN. Intraocular pressure after excimer laser myopic refractive surgery. *Ophthalmic Physiol Opt.* 2001;21:228–235.
14. Garzozi HJ, Chung HS, Lang Y, Kagemann L, Harris A. Intraocular pressure and photorefractive keratectomy: a comparison of three different tonometers. *Cornea.* 2001;20:33–36.
15. Rashad KM, Bahnassy AA. Changes in intraocular pressure after laser in situ keratomileusis. *J Refract Surg.* 2001;17:420–427.
16. Duch S, Serra A, Castanera J, Abos R, Quintana M. Tonometry after laser in situ keratomileusis treatment. *J Glaucoma.* 2001;10:261–265.
17. Reinhard T, Sundmacher R. Determining real IOP values. *J Cataract Refract Surg.* 1999;25:157–158.
18. Entenmann B, Robert YC, Pirani P, Kanngiesser H, Dekker PW. Contact lens tonometry: application in humans. *Invest Ophthalmol Vis Sci.* 1997;38:2447–2451.
19. Dekker PW, Robert YC, Kanngiesser H, Pirani P, Entenmann B. Principles of contact lens tonometry. *Int Ophthalmol.* 1998;22:105–111.
20. Ehlers N, Bramsen T, Sperling S. Applanation tonometry and central corneal thickness. *Acta Ophthalmol* (*Copenh*)*.* 1975;53:34–43.
21. Whitacre MM, Stein RA, Hassanein K. The effect of corneal thickness on applanation tonometry. *Am J Ophthalmol.* 1993;115:592–596.
22. Bhan A, Browning AC, Shah S, Hamilton R, Dave D, Dua HS. Effect of corneal thickness on intraocular pressure measurements with the pneumotonometer, Goldmann applanation tonometer, and Tono-Pen. *Invest Ophthalmol Vis Sci.* 2002;43:1389–1392.
23. Goldmann H, Schmidt T. Der Rigiditätskoeffizient (Friedenwald). *Ophthalmologica.* 1957;133:330–336.
24. Johnson M, Kass MA, Moses RA, Grodzki WJ. Increased corneal thickness simulating elevated intraocular pressure. *Arch Ophthalmol.* 1978;96:664–665.
25. Bron AM, Creuzot-Garcher C, Goudeau-Boutillon S, d'Athis P. Falsely elevated intraocular pressure due to increased central corneal thickness. *Graefes Arch Clin Exp Ophthalmol.* 1999;237:220–224.
26. Brandt JD, Beiser JA, Kass MA, Gordon MO. Central corneal thickness in the Ocular Hypertension Treatment Study (OHTS). *Ophthalmology.* 2001;108:1779–1788.
27. Stahl J, Vold S. Effect of corneal thickness on the accuracy of intraocular pressure measurement in rabbits after excimer laser photoablation. *J Cataract Refract Surg.* 2000;26:736–743.
28. Patel S, Aslanides IM. Main causes of reduced intraocular pressure after excimer laser photorefractive keratectomy. *J Refract Surg.* 1996;12:673–674.
29. Agudelo LM, Molina CA, Alvarez DL. Changes in intraocular pressure after laser in situ keratomileusis for myopia, hyperopia, and astigmatism. *J Refract Surg.* 2002;18:472–474.
30. Mills RP. If intraocular pressure measurement is only an estimate-then what? *Ophthalmology.* 2000;107:1807–1808.
31. Rosa N, Cennamo G. Goldmann applanation tonometry after PRK and LASIK. *Cornea.* 2001;20:905–906.
32. Stodtmeister R. Applanation tonometry and correction according to corneal thickness. *Acta Ophthalmol Scand.* 1998;76:319–324.
33. Munger R, Hodge WG, Mintsioulis G, Agapitos PJ, Jackson WB, Damji KF. Correction of intraocular pressure for changes in central corneal thickness following photorefractive keratectomy. *Can J Ophthalmol.* 1998;33:159–165.
34. Cennamo G, Rosa N, La Rana A, Bianco S, Sebastiani A. Non-contact tonometry in patients that underwent photorefractive keratectomy. *Ophthalmologica.* 1997;211:341–343.
35. Shah S. Accurate intraocular pressure measurement-the myth of modern ophthalmology? *Ophthalmology.* 2000;107:1805–1807.
36. Lee GA, Khaw PT, Ficker LA, Shah P. The corneal thickness and intraocular pressure story: where are we now? *Clin Exp Ophthalmol.* 2002;30:334–337.
37. Lewis RA. Refractive surgery and the glaucoma patient: customized corneas under pressure. *Ophthalmology.* 2000;107:1621–1622.
38. Feltgen N, Leifert D, Funk J. Correlation between central corneal thickness, applanation tonometry, and direct intracameral IOP readings. *Br J Ophthalmol.* 2001;85:85–87.