Clinical Comparison of Contour and Applanation Tonometry and Their Relationship to Pachymetry

Christoph Kniestedt, MD; Shan Lin, MD; Joyce Choe, MD; Alan Bostrom, PhD; Michelle Nee, MD; Robert L. Stamper, MD

Objectives: To compare intraocular pressure readings of recently introduced dynamic contour tonometry (DCT) with pneumatonometry (PTG) and Goldmann applanation tonometry (GAT) and to correlate central corneal thickness (CCT) with these readings.

Design: Prospective, cross-sectional observation and instrument validation study. We included 258 independent eyes with normal anterior segment examinations results, irrespective of glaucoma diagnosis or glaucoma suspect. After pachymetry, DCT, PTG, and GAT were performed in a randomized order. Intraocular pressures as measured by DCT, PTG, and GAT were compared with each other and with CCT.

Results: Eyes with thinner CCTs tended to yield lower intraocular pressure measurements by GAT. A significant correlation (Pearson product moment correlation, P<.001) between CCT and GAT was found with a regression of 0.25 mm Hg per 10 µm (r²=0.060). Variation of CCT had no significant effect on intraocular pressure measurements by PTG (P=.10; r²=0.01) and DCT (P=.80; r²<0.01). A piecewise regression model showed that GAT readings are not linearly correlated with CCT. Comparison of the slopes below and above 535 µm showed the highest significance (P<.001).

Conclusions: Goldmann applanation tonometry readings are potentially influenced by CCT, whereas PTG and DCT seem to be less dependent on CCT. Correlation between CCT and GAT is not linear. A simple correction formula suggesting a linear relationship might not be correct.


IN 1955, GOLDMANN1 WAS THE FIRST to successfully apply the principle of corneal applanation for tonometry. Goldmann applanation tonometry (GAT) has since become the gold standard for noninvasive tonometry and is still the most popular method of measuring intraocular pressure (IOP). All types of applanation tonometers are governed by the Imbert-Fick law.2,3 This law states that when a thin, perfectly elastic sphere is flattened, the force per unit area applied to flatten the sphere and the force per unit area of the internal pressure should equalize each other. The flattened area and the subsequently displaced volume are supposed to be small in relation to the total area and volume of the sphere. The latter might be true in a human eye, but human sclera and cornea are neither perfectly elastic nor thin and flexible. Goldmann and Schmidt4 were well aware that corneal rigidity and, therefore, corneal thickness must oppose the effect of indentation and applanation. The inventors of GAT calculated that the surface tension drawing the tonometer tip onto the cornea would be counterbalanced by the resistance to applanation offered by the cornea at a diameter of exactly 3.06 mm. Goldmann and Schmidt4,5 performed all of their measurements on corneal thicknesses ranging from 500 to 520 µm, which they assumed to be normal and representative of almost all eyes with healthy corneas.

Recently, comprehensive multicenter studies have demonstrated that corneal thickness varies considerably within healthy subjects. Because of this, IOP may be incorrectly assessed and, thus, management of glaucoma may be adversely affected.

It would be helpful to have a tonometer that measures IOP directly (ie, determining the pressure rather than a force) and is not biased by individual characteristics of the cornea and the observer. Kanngiesser et al8 developed a method for transcorneal and continuous IOP measurement. They call it dynamic contour tonometry (DCT) because the pressure-sensitive tip is not planar but closely resembles the curvature of the cornea.

The detailed physical hypothesis and theoretical considerations about DCT are described elsewhere.9 Briefly summarized, the DCT tip has a radius that is slightly larger than that of an average human cornea. Kanngiesser et al9 determined empirically that the radius of curvature needed to be 10.5 mm to get accurate results and to fit on most corneas. A pressure sensor (diameter, 1.7 mm) is embedded in the shell-shaped tonometer tip (Figure 1). Forcing the central disc...
The examination is performed with the patient in a sitting position at the slitlamp. A, Dynamic contour tonometer tip inserted into a Goldmann applanation tonometer tip holder. B, Drum is set at 1 g (appositional force = 0.81 mN [milliNewton]).

area of the cornea into the contour of the DCT tip allows the examiner to measure the pressure of the eye directly on the external surface of the cornea because, in the condition of matched contours, the pressure on both sides of the cornea is theoretically equal. The IOP recorded by DCT is defined as the mean diastolic IOP during the period when the tonometer was in contact with the eye.

Proper investigation with the novel DCT on human cadaver eyes showed better absolute and relative accuracy than GAT and pneumatonometry (PTG).9,10 The dependence of central corneal thickness (CCT) could not have been investigated in vitro. However, Kaufmann et al11,12 and Siganos et al13 reported that DCT seems to be less dependent on CCT than GAT or noncontact air-puff tonometry on normal eyes and on eyes after the laser-assisted in situ keratomileusis procedure, respectively.

This study was performed to collect the early clinical experience using DCT in a glaucoma-based single-center patient population and to compare its dependence on CCT with that of PTG and GAT.

METHODS

The present prospective study included a random sample of consecutive patients with glaucoma and suspected glaucoma who consented to the study protocol. All participants were seen at the Department of Ophthalmology, University of California–San Francisco between November 1, 2002, and April 30, 2003, and gave written informed consent before enrollment. Eyes were excluded if they had any corneal disease or acquired irregularity. The study protocol was approved by the Committee on Human Research at the University of California–San Francisco (H10262-22264-01). We examined 309 eyes of 258 consecutive patients and 258 independent eyes were included in the study. To reduce variability, only the right eyes were chosen. Ten right eyes had to be excluded owing to corneal edema, penetrating keratoplasty, prosthesis, and phthisis bulbi. In these cases, the 10 left eyes met study criteria and were included in place of the right eyes.

Visual acuity measurement, pachymetry, GAT, and PTG were performed by a technician certified for the Ocular Hypertension Treatment Study who was masked to DCT readings. Goldmann applanation tonometry, PTG, and DCT were performed in a randomized order. One measurement of at least 10 heartbeats was taken for further analysis for DCT and PTG. To reduce variability, the mean of 2 readings was applicable for GAT analysis. The 2 GAT readings were acquired by the technician and by 1 of us (C.K., S.L., J.C., or R.L.S.). Goldmann applanation tonometry was calibrated weekly and performed in the manner originally described by Goldmann1 and Goldmann and Schmidt14 using a BQ 900 slitlamp (Haag Streit, Bern, Switzerland). If pulsating hemirings were noticeable, an average setting was chosen with horizontally symmetric oscillation to both sides. The model 30 classic pneumatonometer (Medtronic Inc, Minneapolis, Minn) was used for all PTG readings throughout the study. The standard deviation cutoff was set according to the manufacturer’s manual to get sufficiently reproducible readings. To avoid possible interobserver variability, which is assumed to be minimal but not yet determined for DCT, 1 observer was selected to perform DCT (C.K.). Dynamic contour tonometry and GAT were performed with the patient sitting in an upright position at the slitlamp (Figure 1). For DCT, the pressure-sensitive tip was inserted into a GAT tip holder in a manner similar to that for the GAT tip (Figure 1A). The GAT drum was set to 1 g following the inventors’ protocol (Figure 1B). Observation through the slitlamp microscope reveals a fluorescein ring rather than 2 hemicircles. The purpose of the fluorescein ring is to visualize and confirm that the DCT is appropriately centered on the corneal surface. The ring should be located in the midperiphery, evenly distributed in a concentric manner around the pressure sensor (Figure 2), indicating the area of contour matching.

The CCT was assessed as an average of 5 consecutive measurements using an ultrasound pachymeter (Humphrey Instruments, San Leandro, Calif). The speed of sound was adjusted at 1640 m/s according to the internationally accepted standard velocity for human corneas.

Statistical analysis was performed with a mixed-effects regression model using SAS software (SAS Institute Inc, Cary, NC). The model treated patients and their eyes as random effects and did not assume equal variability in the 3 devices. Associations between continuous and other ordered variables were examined using the Spearman nonparametric correlation (Spearman ρ). Nonparametric Kruskal-Wallis and Mann-Whitney tests were also used to examine associations between categorical vari-
ables and continuous or ordered outcomes. Analysis of variance was used to compare IOP readings in the 3 devices. A p value (Spearman, Kruskal-Wallis, and Mann-Whitney) of <.05 was defined as statistically significant.

The possibility of different linear relationships between IOP and CCT for different ranges of CCT was investigated using piecewise regression methods.14 The slope of the IOP on CCT is assumed to be $b_1$ for $CCT \leq X_0$ and $b_2$ for $CCT > X_0$. We also

Figure 3. Central corneal thickness (CCT) in correlation to intraocular pressure (IOP) readings obtained by using Goldmann applanation tonometry (GAT) (A), pneumatonometry (PTG) (B), and dynamic contour tonometry (DCT) (C). The GAT shows the steepest slope (0.025), indicating a statistically significant correlation with CCT. Pneumatonometry shows less correlation, and DCT shows no correlation at all.
assume that the 2 lines intersect at CCT = X_0. Mathematically, this model can be written as follows:

\[ \text{IOP} = a + [b_1(X - X_0)(1 - I[X])] + [b_2I(X)(X - X_0)], \]

where X = CCT, a is estimated CCT value when X = X_0, and I(X) = 0 if X < X_0 and I(X) = 1 if X ≥ X_0.

This model was fit using multiple regression, and the F statistic for testing H_0: (b_1 = b_2) was computed. Large values of this statistic are evidence against the null hypothesis of equal slopes in the 2 CCT regions. To find the optimal cutoff, the value of X_0 was systematically varied from 500 to 600 µm in steps of 1 µm.

RESULTS

A total of 258 eyes underwent evaluation. Sixty-six eyes were diagnosed as being glaucoma suspect, including 23 eyes with ocular hypertension. One hundred seventy eyes were diagnosed as being glaucoma. The population consisted of 95 male and 163 female patients with a mean age of 69 years (median, 71 years; range, 14 - 97 years). The ethnic distribution was 181 white, 39 Asian, and 16 African American patients, 18 patients of Hispanic descent, and 4 patients of Arab (n = 2) or native East Indian (n = 2) extraction. The mean ± SD CCT of the entire group was 545 ± 38 µm.

Intraocular pressure was recorded using GAT, PTG, and DCT in a randomized order. Mean ± SD IOP as measured by GAT was 16.0 ± 3.0 mm Hg (range, 3.2 - 27.1 mm Hg); by PTG, 17.1 ± 4.1 mm Hg (range, 5.0 - 28.5 mm Hg); and by DCT, 18.3 ± 4.2 mm Hg (range, 5.0 - 31.1 mm Hg).

There was no significant intradevice IOP difference detected among the 6 measurement orders (ADP [n = 41], APD [n = 54], DAP [n = 36], DPA [n = 40], PAD [n = 53], and PDA [n = 34], where A indicates GAT; D, DCT; and P, PTG). The Kruskal-Wallis P value was .21 for DCT, .27 for GAT, and .59 for PTG. A strong correlation between all 3 devices was found (r = .86 for DCT vs GAT; r = .87 for DCT vs PTG; and r = .87 for GAT vs PTG; P < .001 for any device comparison).

With analysis of variance, the overall test of equality of IOP in the 3 devices was very strongly rejected (F = 147.12; P < .001). Tukey tests of pairwise differences showed all 3 devices to be significantly different (at P < .05) from each other.

Intraocular pressure measured with GAT was significantly correlated with CCT (γ = 0.025x + 2.70; R^2 = 0.06; P < .001) with a 0.25-µm Hg change per 10-µm variation in CCT based on linear regression analysis (Figure 3A). With a P value of .10, PTG in contrast did not reach enough significance to be correlated with CCT (γ = 0.011x + 11.07; R^2 = 0.01) (Figure 3B). Intraocular pressure measured with DCT showed no significant correlation to CCT (P = .80; γ = 0.002x + 17.34; R^2 < .01) (Figure 3C). Linear regression analysis of each of the diagnostically subgroups showed similar results with comparable significance levels for each tonometric device.

The possibility of different linear relationships between IOP and CCT for different ranges of CCT was investigated using a piecewise regression model.14 The value of the CCT cutoff that maximized the F statistic was found to be 535 µm for all 3 IOP measures (GAT, F = 6.24; DCT, F = 3.15; PTG, F = 3.39). However, the slope −0.040 is not significant owing to higher measurement errors above 535 µm. Both DCT (P = .19) and PTG (P = .08) showed no significant change in the slopes at any cutoff point. Models across the entire CCT range with higher-order terms showed no significant nonlinear effects.

Central corneal thickness has become an important biometric factor and is an essential part of the evaluation of glaucoma. The quality of pachymeters has changed considerably during the past few decades. At present, ultrasonic pachymeters have replaced the older optical pachymeters, which have been shown to be less accurate and measure consistently lower than ultrasonic pachymeters.15-17 In their meta-analysis, Doughty and Zaman18 found a chronological upward trend in the reported averages for CCT during a 30-year period that is thought to be due to the change from optical to ultrasonic measuring methods. The group-averaged value for CCT using optical pachymetry was 525 µm (median), and for ultrasonic pachymetry, 544 µm (median). Thus, Goldmann and Schmidt’s4-7 value for CCT of 500 to 520 µm, which is based on optical means, might be, in fact, approximately 520 to 540 µm.

Therefore, recently published data are based on ultrasound pachymetry. These data showed mean CCTs of 532 µm,19 518 µm,20 554 µm,21 536 µm (a primary open-angle glaucoma sample), and 592 µm (an ocular hypertension sample).22 The Ocular Hypertension Treatment Study re-
Table. Relationship Between CCT and GAT

<table>
<thead>
<tr>
<th>CCT, Mean ± SD, µm</th>
<th>GAT, mm Hg per 10 µm</th>
<th>NTG</th>
<th>Control</th>
<th>POAG</th>
<th>OHT</th>
<th>Mixed</th>
<th>Notes</th>
<th>Source</th>
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<tr>
<td>0.23</td>
<td>552 ± 49</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td>0.28 (PTG); 0.10 (TPN)</td>
<td>Bhan et al., 2002</td>
</tr>
<tr>
<td>0.27</td>
<td>518*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>n = 334; 0.48 (POBF)</td>
<td>Gurvint et al., 2004</td>
</tr>
<tr>
<td>0.19</td>
<td>537 ± 14</td>
<td>518*</td>
<td>553 ± 19</td>
<td>536 ± 3</td>
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<td></td>
<td>n = 395; CCT, mean (95% CI)</td>
<td>Wolfs et al., 1997</td>
</tr>
<tr>
<td>0.32</td>
<td>545 ± 33</td>
<td>536 ± 3</td>
<td>610 ± 33</td>
<td>552 ± 49</td>
<td></td>
<td></td>
<td>n = 60</td>
<td>Argus, 1994</td>
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<tr>
<td>0.35</td>
<td>521 ± 37</td>
<td>555 ± 34</td>
<td>556 ± 35</td>
<td>573 ± 39</td>
<td></td>
<td></td>
<td>n = 1301; 554 ± 40 and 579 ± 37</td>
<td>Brandt et al., 2001</td>
</tr>
<tr>
<td>0.11</td>
<td>514 ± 10</td>
<td>550 ± 13</td>
<td>580 ± 5</td>
<td></td>
<td></td>
<td></td>
<td>n = 273; 550 ± 31§</td>
<td>Bron et al., 1999</td>
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<tr>
<td>0.7</td>
<td>578 ± 48</td>
<td>596 ± 41</td>
<td>584 ± 41</td>
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<td></td>
<td>n = 579</td>
<td>Stodtmann, 1998</td>
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<tr>
<td>0.7</td>
<td>521 ± 31</td>
<td>552 ± 35</td>
<td>543 ± 35</td>
<td>583 ± 34</td>
<td></td>
<td></td>
<td>(n = 133)</td>
<td>Copt et al., 1999</td>
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<td>0.19</td>
<td>461/466</td>
<td>520/524</td>
<td>543/557</td>
<td>566/575</td>
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<td></td>
<td>n = 332 using TPN</td>
<td>Dohadwala et al., 1998</td>
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<tr>
<td>0.71‡</td>
<td>547.3</td>
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<td></td>
<td></td>
<td>(n = 209) in 3 studies</td>
<td>Whitacre and Stein, 1993</td>
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<td>0.18–0.49</td>
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<td></td>
<td></td>
<td>Corneal thinning by PRK</td>
<td>Shah et al., 2000</td>
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<td>0.71</td>
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<td>0.5</td>
<td>500</td>
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<td>Review article, 300 data sets</td>
<td>Johnson et al., 1978</td>
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<td>0.3–0.6</td>
<td>504</td>
<td>534</td>
<td>542</td>
<td>563</td>
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<td></td>
<td>Manometric case report</td>
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<td>0.6</td>
<td>500</td>
<td>900</td>
<td></td>
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</table>

Abbreviations: CCT, central corneal thickness; CI, confidence interval; GAT, Goldmann applanation tonometry; Mixed, study design without subgroups; NTG, normal-tension glaucoma; OAG, open-angle glaucoma; OHT, ocular hypertension; POBF, pulsatile ocular blood flow tonograph; PRK, photorefractive keratectomy; PTG, pneumotonometer; TPN, Tono-Pen.

*Includes mostly rural Indians.
†Ocular Hypertension Treatment Study.
‡Indicates CCT of African American/CCT of white subjects.
§Includes patients with diabetes mellitus and no glaucoma.
‖For white subjects, 552 ± 2 µm; for black, 530 ± 5 µm; and for Asian, 533 ± 7 µm.
¶Manometric study including 29 subjects. Data are expressed as numbers of right eyes/left eyes.
#Study used a Perkins tonometer.

ported a mean CCT of 573 µm, and the Rotterdam Study described 537 µm with a very wide range of 193 µm. Central corneal thickness appears to be thicker in patients with ocular hypertension, which may be explained, in part at least, by the fact that some of these eyes are misclassified owing to IOP overestimation. Argus described 537 µm with a very wide range of 193 µm. Cen-

numerous studies have been conducted to determine a correlation factor to define real IOP in eyes with unusually thin or thick corneas. Argus introduced a correction formula assuming 578 µm as normal. Stodtmann published correction nomograms for applanation tonometry performed on corneas of a thickness different from 580 µm. Unfortunately, only a few studies are based on manometric measurements. Even if IOP was checked manometrically, caution in analyzing the results is necessary; for instance, Ehlers et al have compared CCT to a correction factor, derived from manometric IOP and applanating IOP, whereas Wolfs et al have plotted CCT to manometric values directly. Orssengo and Pye recently proposed a new nonlinear correlation formula. To our knowledge, its accuracy has not yet been proved with an independent manometric study. Furthermore, the fact that normal corneal thickness is assumed to vary widely from 450 to 600 µm makes it unclear at what CCT level to start using any nomogram.

Our study results emphasize the general suggestion that IOP as measured by GAT is dependent on CCT. Using a piecewise regression model, we found a significant correlation between GAT and CCT with a 0.25–mm Hg change per 10-µm variation in CCT. The average ±SD CCT of our glaucoma sample (545 ± 38 µm) and the correlation between CCT and IOP are clearly within the range indicated in most other studies (Table). Dynamic contour tonometry and PTG are not significantly correlated with CCT, although PTG is closer to a significant correlation (IOP variation of 0.11 mm Hg for every 10 µm). This may be clinically negligible in the CCT range obtained in this study. Dynamic contour tonometry showed the least correlation with CCT, with readings that were subject to change only 0.02 mm Hg for each 10 µm. However, the chosen study design has its limitations and its possible bias. Our population sample is based on patients with glaucoma, many of whom have far advanced disease, and we did not include a control group. For the comparison of the 3 devices, this might be irrelevant. The range of IOPs found in this population is somewhat limited because all of the patients with glaucoma were receiving pressure-lowering treatment.

A review of the literature shows variations from 0.11 mm Hg to 0.71 mm Hg for every 10 µm of CCT change. These studies applied different study designs to different race and diagnosis groups; therefore, it is not surprising that they showed different mean CCTs. The fact that patient samples with different CCTs result in a wide range of correlation factors leads to the possibility that a linear correlation between IOP and the entire range of possible CCTs might not exist. We addressed this assumption with a piecewise regression model and have found that with thin
Dynamic contour tonometry is a promising technology that may provide more accurate IOP measurements and, thus, allow better management of ocular hypertension and glaucoma. Further work is warranted to determine whether DCT keeps its reliability on abnormally thin corneas (eg, after a laser-assisted in situ keratomileusis procedure), differently hydrated corneas (eg, in the case of stromal edema), and corneas with irregular surfaces. Clinical studies that include manometric reference pressures would be necessary to address these questions appropriately.

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Correspondence: Christoph Kniestedt, MD, Department of Ophthalmology, Cantonal Hospital Winterthur, Brauerstrasse 15, 8400 Winterthur, Switzerland (research@kniestedt.ch).

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CONCLUSIONS

Dynamic contour tonometry is not significantly influenced by CCT and, therefore, the application of correction factors for unusually thin or thick corneas is unnecessary. Also, PTG appears not to be affected by CCT, whereas GAT is significantly influenced by CCT within the range investigated in this study. Goldmann tonometry did not show a linear relationship to CCT.

Dynamic contour tonometry is a promising technology that may provide more accurate IOP measurements and, thus, allow better management of ocular hypertension and glaucoma. Further work is warranted to determine whether DCT keeps its reliability on abnormally thin corneas (eg, after a laser-assisted in situ keratomileusis procedure), differently hydrated corneas (eg, in the case of stromal edema), and corneas with irregular surfaces. Clinical studies that include manometric reference pressures would be necessary to address these questions appropriately.

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