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

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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=.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.


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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 cor-
nea is theoretically equal. The IOP recorded by DCT is de-
fined 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 accu-
racy than GAT and pneumatonometry (PTG).

The dependence of central corneal thickness (CCT) could not
have been investigated in vitro. However, Kaufmann et
al.11,12 and Siganos et al.13 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 depen-
dence on CCT with that of PTG and GAT.

METHODS

The present prospective study included a random sample of con-
secutive patients with glaucoma and suspected glaucoma who con-
sented to the study protocol. All participants were seen at the
Department of Ophthalmology, University of California–San Fran-
cisco 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 509 eyes of 258 consecutive patients and 258 in-
dependent eyes were included in the study. To reduce variabil-
ity, only the right eyes were chosen. Ten right eyes had to be ex-
cluded owing to corneal edema, penetrating keratoplasty, pros-
thesis, 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 Hyperten-
sion Treatment Study who was masked to DCT readings. Gold-
mann applanation tonometry, PTG, and DCT were performed
in a randomized order. One measurement of at least 10 heart-
beats was taken for further analysis for DCT and PTG. To re-
duce 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 applana-
tion tonometry was calibrated weekly and performed in the man-
er originally described by Goldmann1 and Goldmann and
Schmidt4-7 using a BQ 900 slitlamp (Haag Streit, Bern, Swit-
zerland). If pulsating hemirings were noticeable, an average set-
ting was chosen with horizontally symmetric oscillation to both
sides. The model 30 classic pneumatonometer (Medtronic Inc,
Minneapolis, Minn) was used for all PTG readings through-
out 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 ob-
server 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 fluo-
rescein ring rather than 2 hemirings. The purpose of the fluo-
rescein ring is to visualize and confirm that the DCT is appro-
priately centered on the corneal surface. The ring should be
located in the midperiphery, evenly distributed in a concent-
tric manner around the pressure sensor (Figure 2), indicat-
ing the area of contour matching.
The CCT was assessed as an average of 5 consecutive mea-
surements using an ultrasound pachymeter (Humphrey In-
struments, San Leandro, Calif). The speed of sound was ad-
justed at 1640 m/s according to the internationally accepted
standard velocity for human corneas.

Statistical analysis was performed with a mixed-effects re-
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 exam-
ined using the Spearman nonparametric correlation (Spear-
man ρ). Nonparametric Kruskal-Wallis and Mann-Whitney tests
were also used to examine associations between categorical vari-

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 = 9.81 mN [milliNewton]).

Figure 1

View through the slitlamp microscope while the examination is
taking place. The miniaturized piezoresistive pressure sensor (1) (diameter,
1.7 mm) is built into the center of the concavity (radius, 10.5 mm) of the
contact surface and is surrounded by an evenly distributed and concentrically
located fluorescein ring (diameter, 3-7 mm) (2). The wire connection to the
infrared control unit (3) is also shown.

Figure 2

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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. 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 \( \text{CCT} = X_0 \). Mathematically, this model can be written as follows:

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

where \( X = \text{CCT} \), \( a \) is estimated \( \text{CCT} \) value when \( X = X_0 \), and \( I(X) = 0 \) if \( X < X_0 \) and \( I(X) = 1 \) if \( X \geq X_0 \).

This model was fit using multiple regression, and the F statistic for testing \( H_0 \) 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 having a form of open-angle glaucoma. This group included eyes with primary open-angle glaucoma (\( n = 125 \)), normal-tension glaucoma (\( n = 23 \)), congenital glaucoma (\( n = 1 \)), juvenile glaucoma (\( n = 1 \)), pseudoxfoliation glaucoma (\( n = 16 \)), and pigmentary glaucoma (\( n = 4 \)). Finally, 22 eyes were found to have angle-closure 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 \( \text{CCT} \) of the entire group was 543 ± 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 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 (\( r = 0.86 \) for DCT vs GAT; \( r = 0.87 \) for DCT vs PTG; and \( r = 0.87 \) 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 \( \text{CCT} \) (\( y = 0.025x + 2.70 \); \( R^2 = 0.06 \); \( P < .001 \)) with a 0.25-mm Hg change per 10-µm variation in \( \text{CCT} \) 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 \( \text{CCT} \) (\( y = 0.011x + 11.07 \); \( R^2 = 0.01 \)) (Figure 3B). Intraocular pressure measured with DCT showed no significant correlation to \( \text{CCT} \) (\( P = .80 \); \( y = 0.002x + 17.34 \); \( R^2 < 0.01 \)) (Figure 3C). Linear regression analysis of each of the diagnosis subgroups showed similar results with comparable significance levels for each tonometric device.

The possibility of different linear relationships between IOP and \( \text{CCT} \) for different ranges of \( \text{CCT} \) was investigated using a piecewise regression model.\(^{14}\) The value of the \( \text{CCT} \) 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, \( F = 3.39 \); significance level, 0.02) (Figure 4). Goldmann applanation tonometry showed a difference in the comparison of the linear regressions below 535 µm (slope, 0.047; \( P = .001 \)) and above 535 µm (slope, −0.040; \( P = .06 \)), which was significant (\( P < .001 \)). 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 \( \text{CCT} \) range with higher-order terms showed no significant nonlinear effects.

Figure 4. Testing of equal slopes (F Ratio) and value of central corneal thickness (CCT). The greatest difference between the slopes was found at 535 µm (\( P < .001 \)) for Goldmann applanation tonometry (GAT) (\( F = 6.24 \)). Dynamic contour tonometry (DCT) and pneumotonometry (PTG) also showed a similar cutoff at 535 µm (\( F = 3.15 \) and \( F = 3.39 \), respectively). However, unlike GAT, the differences did not reach statistical significance. (Significance level [F ratio testing equal slopes], 0.02).

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 Zaman\(^{20}\) found a chronological upward trend in the reported averages for \( \text{CCT} \) 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 \( \text{CCT} \) using optical pachymetry was 525 µm (median), and for ultrasonic pachymetry, 544 µm (median). Thus, Goldmann and Schmidt’s\(^{4-7}\) value for \( \text{CCT} \) 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 \( \text{CCT} \)s of 532 µm,\(^{18}\) 518 µm,\(^{19}\) 545 µm,\(^{20}\) 536 µm (a primary open-angle glaucoma sample), and 592 µm (an ocular hypertension sample).\(^{21}\) The Ocular Hypertension Treatment Study re-

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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 a mean±SD CCT of 573 µm, and the Rotterdam Study indicated a mean (95% CI) of 537 µm with a very wide range of 193 µm. Cen- tral corneal thinning by PRK Rosa et al, 1998

Table. Relationship Between CCT and GAT

<table>
<thead>
<tr>
<th>GAT, mm Hg per 10 µm</th>
<th>CCT, Mean ± SD, µm</th>
<th>Notes</th>
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<td>NTG</td>
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<td>OHT</td>
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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, pneumatonometry; TPN, Tono-Pen.

With respect to our study results, the general suggestion is that IOP as measured by GAT is dependent on CCT. Using a linear 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...
corneas (<535 µm) the slope between CCT and IOP is significantly steeper than with normal or thick corneas. This analysis confirms our clinical experience using DCT that GAT's underestimation with thin corneas is of a much greater issue than its overestimation with thick corneas. Taking only the slopes below and above the cutoff points at 20-µm steps, the correlation was always stronger and significant between thin CCTs (500, 520, and 540 µm) and IOP for GAT. Surprisingly, the slopes above the cutoff points turned out to be negative. However, this phenomenon was not significant owing to larger measurement errors on thick corneas. The reason for the higher measurement errors on thick corneas is not yet clarified. It is possible that thick corneas result in higher errors per se because corneal rigidity is increased, or that thick corneas may represent a nonhomogeneous group, some of which may be inherently thick while some may be thickened by subclinical edema. The latter would correspond to the negative correlation between relatively thick CCT and GAT, which was already observed by Simon et al.*

**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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