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 \(\mu\)m \(R^2=0.060\). Variation of CCT had no significant effect on intraocular pressure measurements by PTG \((P=.10; R^2=0.01)\) and DCT \((P=.80; R^2<0.01)\). A piecewise regression model showed that GAT readings are not linearly correlated with CCT. Comparison of the slopes below and above 535 \(\mu\)m 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, Goldmann\(^1\) 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 Schmidt\(^4\) 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 Schmidt\(^5\) performed all of their measurements on corneal thicknesses ranging from 500 to 520 \(\mu\)m, 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 al\(^6\) 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.\(^8\) Briefly summarized, the DCT tip has a radius that is slightly larger than that of an average human cornea. Kanngiesser et al\(^8\) 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 \(\text{mm}\)) is embedded in the shell-shaped tonometer tip (Figure 1). Forcing the central disc...
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 ac-
curacy than GAT and pneumatonometry (PTG).9,10 The de-
pendence 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 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 De-
partment 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 bulbii. 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 pneumotonometer (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
ometry 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 hemicircles. The purpose of the fluo-
rescein ring is to visualize and confirm that the DCT is ap-
propriately centered on the corneal surface. The ring should be
located in the midperiphery, evenly distributed in a concen-
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-
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:

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

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 $H_0$ ($b_1=b_2$) 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 $\mu$m in steps of 1 $\mu$m.

**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 ($n=123$), normal-tension glaucoma ($n=23$), congenital glaucoma ($n=1$), juvenile glaucoma ($n=1$), pseudoexfoliation 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 CCT of the entire group was 545±38 $\mu$m.

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, 9.7-27 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 interdevice 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 CCT ($y=0.025x+2.70$; $R^2=0.06$; $P<.001$) with a 0.25–$\mu$m 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 ($y=0.011x+11.07$; $R^2=0.01$) (Figure 3B). Intraocular pressure measured with DCT showed no significant correlation to CCT ($P=.80$; $y=0.002x+17.34$, $R^2<.01$) (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 CCT for different ranges of CCT was investigated using a piecewise regression model. The value of the CCT cutoff that maximized the $F$ statistic was found to be 535 $\mu$m for all 3 IOP measures (GAT, $F_{1,235}=6.24$; DCT, $F_{1,235}=3.15$; PTG, $F_{1,235}=3.39$; significance level, 5.02) (Figure 4). Goldmann applanation tonometry showed a difference in the comparison of the linear regressions below 535 $\mu$m (slope, $0.047$; $P=0.001$) and above 535 $\mu$m (slope, $-0.040$; $P=0.06$), which was significant ($P<.001$). However, the slope $-0.040$ is not significant owing to higher measurement errors above 535 $\mu$m. 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 Zaman22 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 $\mu$m (median), and for ultrasonic pachymetry, 544 $\mu$m (median). Thus, Goldmann and Schmidt’s value for CCT of 500 to 520 $\mu$m, which is based on optical means, might be, in fact, approximately 520 to 540 $\mu$m.

Therefore, recently published data are based on ultrasound pachymetry. These data showed mean CCTs of 532 $\mu$m,18 518 $\mu$m,20 504 $\mu$m,21 336 $\mu$m (a primary open-angle glaucoma sample), and 392 $\mu$m (an ocular hypertension sample).22 The Ocular Hypertension Treatment Study re-
reported 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 in his ocular hypertension group of 610±33 µm. Substantial corneal thinning by PRK is reported to be associated with CCT in the low 500-µm range.

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 factor to define real IOP in eyes with unusual corneal curvature. Stodtmeister published correction nomograms for applanation tonometry, whereas Wolfs et al. have plotted CCT to manometric values directly. 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 described a correlation between CCT and IOP, 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 observed 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).

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

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>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.23</td>
<td>552 ± 49</td>
<td>0.28 (PTG); 0.10 (TPN)</td>
<td>Bhan et al. 2002</td>
</tr>
<tr>
<td>0.27</td>
<td></td>
<td>n = 334; 0.48 (POBF)</td>
<td>Gunvant et al. 2004</td>
</tr>
<tr>
<td>0.19</td>
<td>518*</td>
<td>n = 395; CCT, mean (95% CI)</td>
<td>Wolfs et al. 1997</td>
</tr>
<tr>
<td>0.32</td>
<td></td>
<td>n = 60; 0.19; CCT, mean (95% CI)</td>
<td>Argus 1996</td>
</tr>
<tr>
<td>0.11</td>
<td></td>
<td>n = 1301; 554 ± 40</td>
<td>Brandt et al. 2001</td>
</tr>
<tr>
<td>0.7</td>
<td>521 ± 37</td>
<td>n = 273; 550 ± 31‡</td>
<td>Bron et al. 1999</td>
</tr>
<tr>
<td>0.7</td>
<td>514 ± 19</td>
<td>n = 508; CCT = mean (95% CI)</td>
<td>Shah et al. 1999</td>
</tr>
<tr>
<td>0.5</td>
<td>512 ± 35</td>
<td>n = 579; CCT = mean (95% CI)</td>
<td>Stodtmeister 1998</td>
</tr>
<tr>
<td>0.19</td>
<td>461/466</td>
<td>n = 133; CCT = mean (95% CI)</td>
<td>Copt et al. 1999</td>
</tr>
<tr>
<td>0.18-0.49</td>
<td>547.3§</td>
<td>n = 332 using TPN</td>
<td>Dohadwala et al. 1998</td>
</tr>
<tr>
<td>0.71¶</td>
<td>530 ± 5 µm</td>
<td>n = 209 in 3 studies</td>
<td>Ehlers et al. 1975; Ehlers et al. 1974</td>
</tr>
<tr>
<td>0.71</td>
<td></td>
<td>Manometric in vivo‡</td>
<td>Whitacre and Stein 1993</td>
</tr>
<tr>
<td>0.71</td>
<td>543 ± 35</td>
<td>(n = 15)</td>
<td>Rosa et al. 1998</td>
</tr>
<tr>
<td>0.71</td>
<td>542 ± 34</td>
<td>Review article</td>
<td>Shah et al. 1999</td>
</tr>
<tr>
<td>0.71</td>
<td>592 ± 39</td>
<td>Review article, 300 data sets</td>
<td>Doughty and Zaman 2000</td>
</tr>
<tr>
<td>0.71</td>
<td>583 ± 43</td>
<td>Manometric case report</td>
<td>Johnson et al. 1978</td>
</tr>
</tbody>
</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, pneumatonometry; TPN, Tono-Pen.

*Includes mostly rural Indians.
†Ocular Hypertension Treatment Study.
‡Indicates CCT of African American/CCT of white subjects.
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 thinned by subclinical edema. The latter would contribute to the negative correlation between relatively thick CCT and GAT, which was already observed by Simon et al. 36

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 applanation 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, in the case of stromal edema), 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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