# Effects of Corneal Thickness, Corneal Curvature, and Intraocular Pressure Level on Goldmann Applanation Tonometry and Dynamic Contour Tonometry

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***Purpose:*** To compare the measurements of intraocular pressure (IOP) with Goldmann applanation tonometry (GAT) and dynamic contour tonometry (DCT) and the effects of central corneal thickness (CCT), corneal curvature, and level of IOP on these methods.

***Design:*** Cross-sectional population-based study.

***Participants:*** From the Los Angeles Latino Eye Study, 2157 participants of primarily Mexican ancestry.

***Methods:*** Average GAT measurements were compared to DCT, and both were examined with respect to CCT (≤500, 501–550, 551–600, >600 microns), corneal curvature (<42, 42–46, >46 diopters), and level of IOP (0–10, 11–20, >20 mmHg).

***Main Outcome Measures:*** Mean GAT and DCT IOP levels were compared for the entire population, and then trends for the CCT, curvature, and IOP groupings were analyzed. The magnitude of the difference of GAT minus DCT was compared for these different strata, with special attention to a difference of ± 3 mmHg or greater, which was defined as clinically significant.

***Results:*** Mean IOP for the entire population by GAT was significantly lower (14.4±3.2 mmHg) compared with DCT (16.0±3.6; $P<0.0001$). Both GAT and DCT IOP levels were lowest for thin CCT and increased stepwise with increasing CCT, but this difference was more pronounced with GAT than DCT ($P<0.0001$ and $P = 0.0012$, respectively). The difference between GAT and DCT was largest for thin CCT and decreased for thicker CCT ($P<0.0001$). After adjusting for CCT, the corneal curvature affected IOP measured by DCT ($P = 0.02$) but not GAT ($P = 0.3$) such that mean DCT IOP increased with increasing corneal curvature. After adjusting for the CCT effect on IOP and stratifying by DCT IOP groups, the greatest difference between GAT and DCT was seen in the lowest IOP group (3.55±3.1), became negative in the intermediate group (−1.86±2.60), and was most negative in the highest IOP group (−3.88±3.3; $P<0.0001$).

***Conclusions:*** Intraocular pressure measured by GAT was consistently lower when compared with DCT, and this difference was greatest with thinner CCT. Dynamic contour tonometry was also less affected by variations in CCT. Corneal curvature affected IOP measurements with DCT but not GAT, but this effect was less than the CCT effect on GAT. Goldmann applanation tonometry tended to underestimate IOP at higher levels and overestimate it at lower IOP levels when compared to DCT. *Ophthalmology 2007;114:20–26 © 2007 by the American Academy of Ophthalmology.*

Intraocular pressure (IOP) is a key component to the diagnosis and treatment of glaucoma, and Goldmann applanation tonometry (GAT) remains the gold standard of obtaining this measurement. There are, however, known sources of error with this method including corneal thickness, curvature, and structure.[1] Goldmann and Schmidt assumed a central corneal thickness (CCT) of 500 microns using optical pachymetry, which tends to underestimate CCT compared to ultrasonic pachymetry because the former only measures between Descemet's membrane and Bowman's

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*For Study Group membership, see "Appendix."



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layer. They acknowledged that variations in this parameter could influence the IOP measurement using their applanation system. Although they thought such variations to be rare,[2] the development of ultrasonic pachymetry has shown a wide range of CCT with considerable variation among races.[3,4] In addition, a thin cornea has been recognized as a risk factor for both progression of ocular hypertension to primary open-angle glaucoma[5] as well as a significant predictor of glaucomatous damage at the initial examination.[6] Although CCT may be an independent risk factor separate from its effect on IOP, it is now an acknowledged confounder in the measurement of IOP by GAT. Specifically, thin corneas are associated with underestimation of GAT IOP, and thick corneas are associated with overestimation. Several studies have found that the mean CCT of eyes with ocular hypertension were significantly greater than those of glaucomatous or normal control eyes.[5,7] Whitacre et al[8] performed simultaneous manometry and Perkins applanation on eyes with different CCTs and found a clinically significant underestimation of IOP as low as 4.9 mmHg in thin corneas and overestimation as high as 6.8 mmHg in the thick corneas. Although nomograms for the correction of GAT IOP based on CCT have been published, none are generally agreed upon to be consistently accurate.[9] Thus, attention has turned toward methods of accurately measuring IOP despite variations in corneal thickness and structure.

Dynamic contour tonometry (DCT; SMT Swiss Microtechnology AG, Port, Switzerland) is a recently developed method of applanation that is theoretically unaffected by CCT or corneal curvature. Dynamic contour tonometry employs a contoured tip, which conforms the cornea to its inner curvature, theoretically placing it into a neutral shape such that no bending or tangential forces are acting on the area of cornea–tip contact. In this state, the forces acting on both the inside (IOP, rigidity) and outside (capillary, appositional) of the cornea are equal, and this pressure is measured by a small sensor inside the contour of the tonometer tip.[10] The IOP is indicated by a digital readout and the quality assessment on a scale between 1 and 5 is displayed.

This study examined the IOP readings obtained by the DCT and GAT and their relationship to CCT and corneal curvature in Latinos identified through a population screening of the Los Angeles Latino Eye Study. It also examined the differences between the 2 IOP measurement techniques with respect to level of CCT and IOP.

## Materials and Methods

Subjects were identified through the Los Angeles Latino Eye Study, a large population-based survey evaluating the prevalence of ocular disease, quality of life, and access to health care in noninstitutionalized, self-identified adult Latinos, aged ≥ 40 years, living in and around the city of La Puente, California. The Institutional Review Board at University of Southern California approved the study protocol, and all study procedures conformed to Health Insurance Portability and Accountability Act of 1996 regulations and the Declaration of Helsinki for research involving human subjects. Inclusion criteria were reliable GAT and DCT measurements completed from June 2004 to September 2005, and no prior history of intraocular surgery. One eye of each participant was selected at random. If only 1 eye underwent GAT and DCT measurements, that eye was selected. Measurements were initially performed on 2359 subjects; of these 53 were excluded for incomplete data and 149 for prior history of intraocular surgery. Due to study protocol, corneal curvature measurements were only performed if visual acuity was worse than 20/20. Thus, 911 participants of the original cohort (n = 2157) were included in the corneal curvature analysis.

After informed consent was obtained, participants underwent a complete ophthalmic examination including visual acuity, refraction, slit-lamp examination, and measurement of IOP, CCT, and axial length. The CCT was measured with an ultrasound pachymeter (DGH, Exton, PA). The measurement was performed 3 times, and the average of the results was recorded for each participant. Corneal curvature measurement was performed with the Automatic Refractor/Keratometer 599 (Zeiss Humphrey, Dublin, CA). The output is an average of several measurements that are given as the steepest and flattest axis in diopters. This was then averaged to obtain a single corneal curvature measurement.

The measurement of IOP with the DCT and GAT (Haag-Streit, Bern, Switzerland) were performed on each participant in a randomly assigned order. For the GAT reading, 3 measurements were taken, first in the right and then the left eye, and the average of the results was recorded. For the DCT reading, the contour tip was apposed to the cornea until a pressure tracing was visualized on the LCD screen. If the quality of data was ≤ 3 (optimal to acceptable), the tip was left in place for 5 to 10 seconds to allow for the ocular pulse pressure to be collected. This procedure was performed first in the right eye then in the left eye, and the IOP shown on the LCD screen was recorded. One eye of each participant was randomly selected if tonometry measurements were taken in both eyes. A small sample of 23 patients had IOP measured by DCT 3 times, and the coefficient of variation amongst the measurements was calculated to be low enough to allow only 1 measurement to suffice.

Because the data were not normally distributed, both parametric and nonparametric statistical methods were used. Statistical testing included analysis of variance for comparison of mean differences, and nonparametric test for median comparisons. The chi-square test was performed to test the association between the mean difference and CCT, corneal curvature, and IOP levels. The effect of CCT on IOP by GAT was adjusted using the general linear model procedure. The same adjustment was applied to corneal curvature with regard to CCT effect. All analyses were conducted at the 0.05 significance level and utilized SAS programs (Cary, NC).

## Results

The age, gender, IOP, and CCT measures of the study population are shown in Table 1. The average GAT measured IOP was

Table 1. Demographic Characteristics and Summary Statistics

| | n | Mean (SD) | Median (Range) |
|---|---|---|---|
| Age (yrs) | 2157 | 58.5 (9.8) | 57 (40–95) |
| Gender | 2157 | | |
| Male | | 825 (38.3%) | |
| Female | | 1332 (61.7%) | |
| GAT | 2157 | 14.4 (3.2) | 14 (4.7–33.7) |
| DCT | 2157 | 16.0 (3.6) | 16 (5.0–35.0) |
| Difference of GAT–DCT | 2157 | −1.65 (3.1) | −2.0 (−19–20) |
| CCT | 2150 | 0.55 (0.03) | 0.55 (0.4–0.7) |

CCT = central corneal thickness (microns); DCT = dynamic contour tonometry intraocular pressure (mmHg); GAT = Goldmann applanation tonometry intraocular pressure (mmHg); SD = standard deviation.

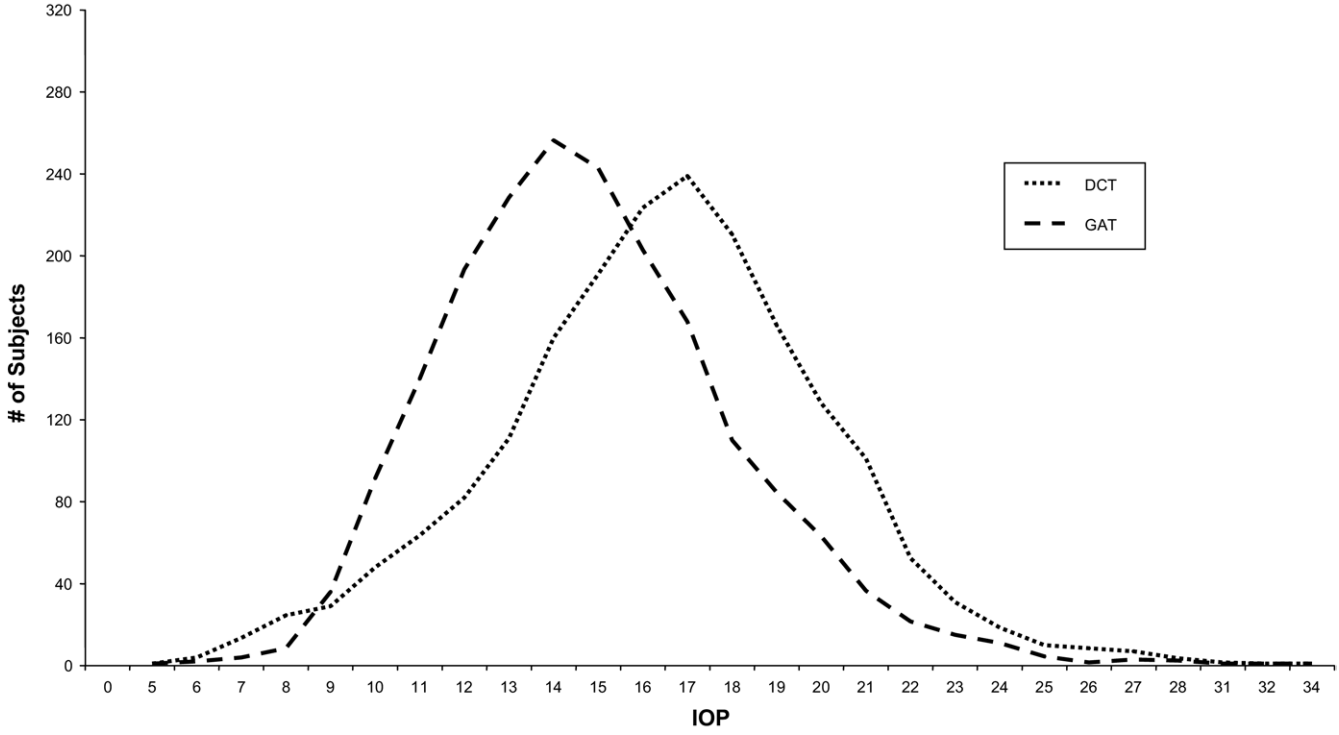


**Figure 1.** The frequency distribution of Goldmann applanation tonometry (GAT) and dynamic contour tonometry (DCT) intraocular pressure (IOP) measurements.

lower than the average DCT measurement by 1.7±3.1 mmHg ($P<0.0001$). Figure 1 illustrates the frequency distribution of the GAT and DCT IOP measurements.

The Bland–Altman plot, utilized for comparison of 2 methods (GAT and DCT) of measurement of the same variable (IOP) is shown in Figure 2. The average of the IOP measurement by the 2 methods is plotted on the x-axis and the difference (GAT−DCT) on the y-axis. The middle vertical line represents the mean difference across all measures, and the top and bottom lines represent differences of ≥+3 greater and ≥−3, respectively. These latter values were chosen to represent a meaningful difference in IOP measurement in a clinical setting. With 2 systems that show

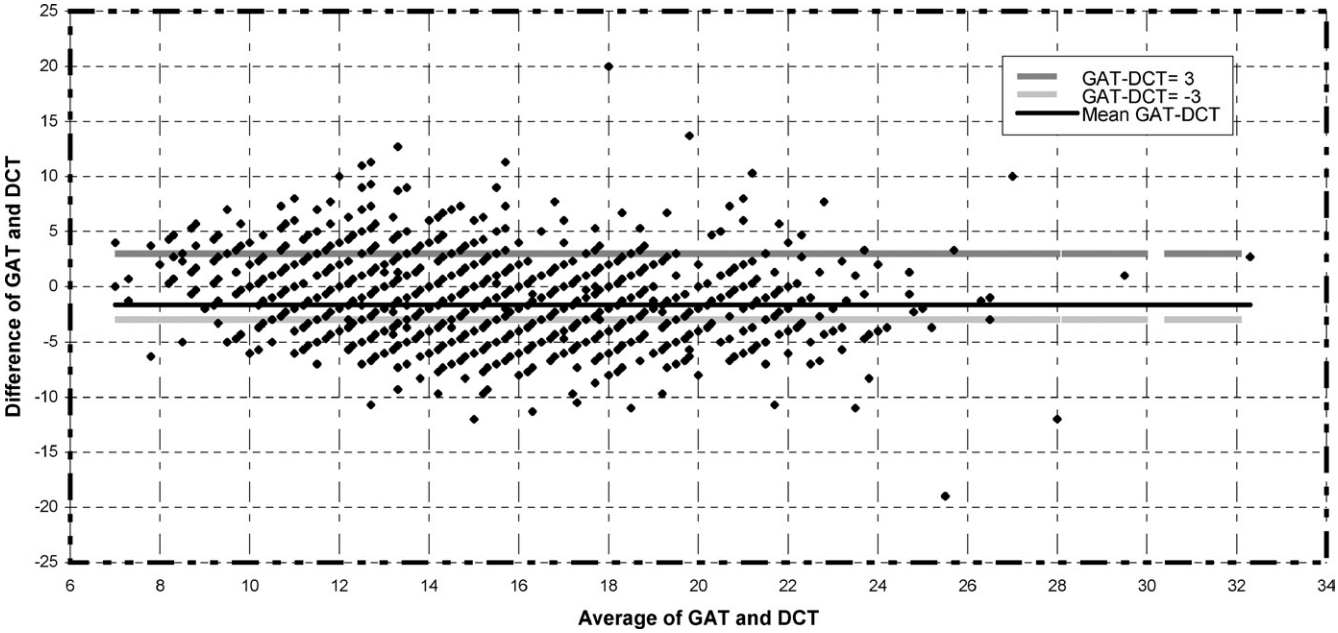


**Figure 2.** Bland–Altman plot comparing 2 methods (Goldmann applanation tonometry [GAT] and dynamic contour tonometry [DCT]) for measuring the same variable (intraocular pressure [IOP]).

Table 2. Comparison for Goldmann Applanation Tonometry (GAT), Dynamic Contour Tonometry (DCT), and GAT Minus DCT among Central Corneal Thickness Groups

| CCT Groups (microns) | ≤500 | 501–550 | 551–600 | >600 | *P* Value (Mean/Median Difference) | *P* Value (Trend Test) |
|---|---|---|---|---|---|---|
| GAT (mmHg) | | | | | | |
| Mean (SD) | 13.0 (2.9) | 14.1 (3.1) | 14.8 (3.2) | 16.1 (3.9) | <0.0001* | <0.0001 |
| Median (range) | 12.7 (7–26.7) | 13.7 (4.7–32) | 14.3 (6–33.7) | 15.3 (7.7–28) | <0.0001† | |
| DCT (mmHg) | | | | | | |
| Mean (SD) | 15.3 (3.5) | 16.0 (3.5) | 16.2 (3.7) | 16.9 (3.8) | 0.0012* | 0.0016 |
| Median (range) | 16 (6–26) | 16.0 (5–35) | 16.0 (6–31) | 17 (7–28) | <0.0001† | |
| GAT-DCT (mmHg) | | | | | | |
| Mean (SD) | −2.34 (2.9) | −1.87 (3.1) | −1.39 (3.1) | −0.82 (3.5) | <0.0001* | <0.0001 |
| Median (range) | −3.0 (−7.7–9.3) | −2.0 (−19–13.7) | −1.7 (−11–12.7) | −1.0 (−9.3–20.0) | <0.0001† | |

CCT = central corneal thickness (microns); SD = standard deviation.
*Analysis of variance was performed for comparison of mean difference.
†Nonparametric test (Wilcoxon rank sums) was performed for comparison of median difference.

excellent agreement, the mean difference will be near zero, and very few points will fall outside the upper and lower boundary limits. This plot shows that the mean difference (GAT−DCT) is negative, and that a significant number of points fall outside the +3 and −3 mmHg difference boundary limits.

Table 2 shows the mean GAT and DCT measured IOP stratified into 4 different CCT categories (CCT≤500 microns, 501–550 microns, 551–600 microns, or > 600 microns). The IOP measured with both GAT ($P<0.0001$) and DCT ($P = 0.0012$) significantly increases with increasing CCT. However, the magnitude of the effect is greater with GAT than DCT. Although mean and median GAT IOP was lower than the DCT IOP across all CCT groups, the difference between the means decreases with increasing CCT ($P<0.0001$). The convergence of these measures as CCT increases is represented in Figure 3.

The groups were further investigated with a clinically meaningful difference in IOP of > 3 mmHg between GAT and DCT (GAT−DCT); this was seen in 40.4% of participants. A difference of ≥ −3 mmHg was seen in 32.7%, and 7.7% showed a difference of ≥ +3 mmHg. Table 3 shows the results when stratified by the 4 CCT categories described. The highest percentage of subjects with GAT IOP 3 mmHg or more lower than DCT occurs in the thinnest CCT group, and incrementally decreases with thicker CCT. Conversely, the percentage of participants with GAT 3 mmHg or more higher than DCT is lowest in the thinnest CCT group, and rises steadily with increasing CCT ($P = 0.0002$).

The analysis of IOP by corneal curvature group, both unadjusted and adjusted for CCT, is presented in Table 4 and Figure 4. There is a significant effect on DCT IOP, with mean IOP lowest with flat corneas and increasing with increasing corneal curvature ($P = 0.02$). This effect is not seen with GAT IOP ($P = 0.3$). Corneal curvature was performed only on those subjects with visual acuity < 20/20. Because the corneal curvature analysis was performed on a subset (n = 911) of the original cohort (n = 2157), we compared the group that had corneal curvature measurements with those that did not (n = 1246) in terms of mean IOP and CCT. We found no significant difference in IOP, with a mean GAT IOP of 14.4±3.3 and 14.5±3.2 ($P = 0.63$) and mean DCT IOP of

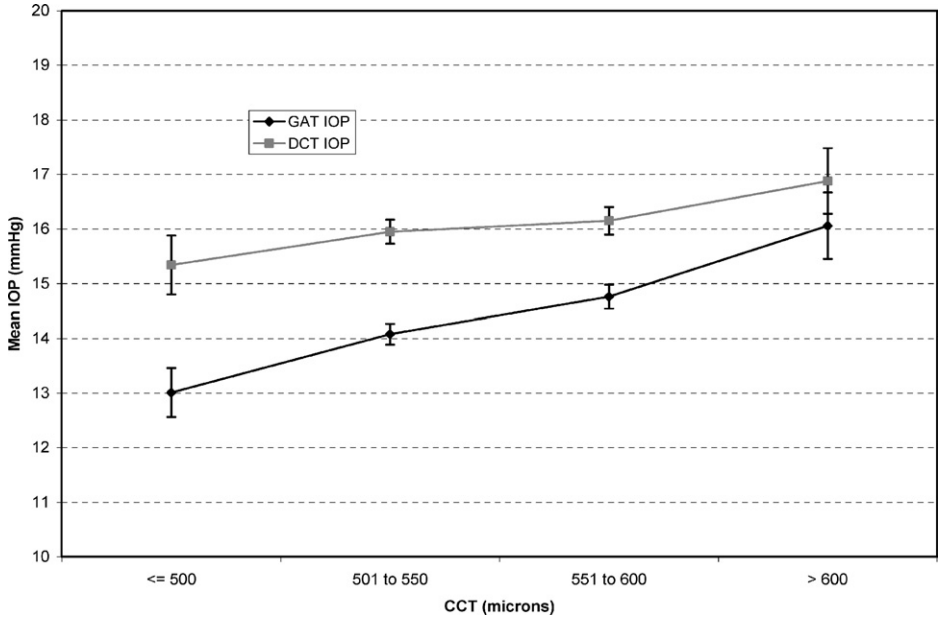


**Figure 3.** The mean intraocular pressure (IOP) for Goldmann applanation tonometry (GAT) and dynamic contour tonometry (DCT) across central corneal thickness (CCT) groups.

Table 3. Frequency Distribution of Goldmann Applanation Tonometry (GAT) Minus Dynamic Contour Tonometry (DCT) by Central Corneal Thickness (CCT) Levels

| GAT−DCT (mmHg) | CCT Groups (microns) ≤500 n (%) | 501–550 n (%) | 551–600 n (%) | >600 n (%) | P Value* |
|---|---|---|---|---|---|
| ≤ 3 | 89 (54.6) | 419 (41.8) | 323 (39.0) | 46 (29.5) | 0.0002 |
| −2 | 26 (16.0) | 169 (16.9) | 104 (12.6) | 24 (15.4) | |
| −1 | 13 (8.0) | 149 (14.9) | 130 (15.7) | 22 (14.1) | |
| 0 | 14 (8.6) | 88 (8.8) | 84 (10.1) | 20 (12.8) | |
| 1 | 9 (5.5) | 63 (6.3) | 53 (6.4) | 14 (9.0) | |
| 2 | 1 (0.6) | 39 (3.9) | 48 (5.8) | 12 (7.7) | |
| ≥ 3 | 11 (6.8) | 76 (7.6) | 86 (10.4) | 18 (11.5) | |

*Chi-square test was performed to test the association between GAT−DCT and CCT levels.

16.1±3.7 and 16.0±3.6 ($P = 0.48$) for those with and without corneal curvature measurements, respectively. Mean CCT did differ between groups; 545.5±34.3 microns and 550.6±33.5 ($P = 0.0005$), respectively, for the groups with and without corneal curvature measurements.

The differences in GAT and DCT IOP were also analyzed with respect to IOP levels (0–10, 11–20, >20 mmHg determined by DCT; Tables 5, 6). Dynamic contour tonometry was chosen as the standard to define IOP group categories because of the smaller effect of CCT as compared to GAT. Prior to analysis, the effect of CCT on GAT IOP was adjusted using the general linear model. At lower IOPs, GAT measures are higher than DCT, and this relationship is reversed at high IOPs (Table 4). Thus, as seen in Table 5, the low IOP group has the smallest percentage of participants with GAT−DCT measuring ≤ −3 mmHg, and the largest percentage with GAT−DCT ≥ 3 mmHg ($P = 0.0001$). Conversely, the highest IOP group has the largest percentage with GAT-DCT ≤ −3 mmHg and the smallest percentage of subjects with GAT measuring ≥ 3 mmHg higher than DCT.

## Discussion

This study observed overall that IOP as measured by GAT was lower than DCT by an average of 1.7±3.1 mmHg. Kniestedt et al[11] compared DCT- and GAT-obtained IOP to manometrically derived IOP in human cadaver eyes and found that GAT values were consistently lower than true IOP by an average of 4 mmHg, but DCT values were very close to true IOP. This is similar to clinical studies finding the pressure difference to be 2.3, 1.7, and 1.0 mmHg in their participants.[12–14] It also agrees with studies finding applanated pressures to be 1.2 to 2.0 mmHg lower than manometrically determined pressures in human eyes in vivo.[9,15]

The difference between the 2 measurements was greatest in participants with thin corneas, gradually lessening as CCT increased. This finding is also in agreement with Pache et al,[14] who recently observed this trend, and Ehlers et al,[16] who found GAT IOP values were correct for a CCT of 520 microns but that thicker and thinner corneas gave falsely higher and lower values, respectively. Similarly, Siganos et al[17] found that GAT tended to underestimate IOP in all patients after laser in situ keratomileusis, whereas DCT did not. They surmised such an underestimation to be due to the change not only in corneal thickness, but also in corneal rigidity.[17] They also found that DCT IOPs were not correlated with CCT. We found that DCT was correlated with CCT, but less so than GAT IOP. This is also in contrast to Pache et al,[14] who found neither DCT nor GAT IOP to correlate with CCT measurements. Based on the cumulative results of our study and others, the DCT measurements appear to be more accurate than GAT when compared with manometric findings, and they are not as affected by variations in CCT. However, DCT is not wholly independent of corneal thickness effects. Possible explanations for the difference in results from the current versus previous studies include differences in racial/ethnic populations and number of subjects evaluated.

This analysis presumed that a pressure difference of > 3 mmHg is clinically significant for diagnosis and treatment purposes. The thin CCT group had the largest percentage of participants with an underestimation of IOP by GAT of > 3 mmHg, whereas the thick CCT group had the largest percentage of an overestimation of > 3 mmHg. This may create a greater risk for the thin CCT group of being undertreated, because they have the largest chance of having a clinically significant underestimation of their IOP by standard examination methods.

The corneal curvature appeared to affect IOP as measured by DCT more than GAT. Dynamic contour tonometry IOP measurements were lowest with flat corneas and increased with increasing curvature, whereas GAT IOP measurements did not. This effect may be due to the need for conforming the corneal surface to fit the DCT probe contour for measurement. The hypothesis is that steeper corneas may require greater flattening and deformation to fit into the contoured probe and this may artifactually elevate the IOP reading. This observation may be affected by bias owing to corneal measurements taken in a subset of the total group. However, comparison of mean IOP between those that underwent corneal curvature measurements and those that did not indicated that the 2 groups were equivalent with both GAT and DCT. There was a statistically significant difference in CCT between the groups with and without

Table 4. Intraocular Pressure (IOP) by Dynamic Contour Tonometry (DCT) and Goldmann Applanation Tonometry (GAT) Among Corneal Curvature Groups

| Corneal Curvature (Diopters) | DCT IOP (mmHg) True Mean (SD) | DCT IOP (mmHg) Adjusted* Mean (SE) | GAT IOP (mmHg) True Mean (SD) | GAT IOP (mmHg) Adjusted* Mean (SE) |
|---|---|---|---|---|
| <42 | 15.0 (3.8) | 15.0 (0.6) | 14.4 (3.8) | 14.3 (0.5) |
| 42–46 | 16.1 (3.7) | 16.2 (0.2) | 14.4 (3.2) | 14.6 (0.2) |
| >46 | 17.2 (3.3) | 17.3 (0.5) | 15.0 (3.9) | 15.2 (0.5) |
| | $P = 0.02$ | $P = 0.007$ | $P = 0.5$ | $P = 0.3$ |
| Trend analysis | $P = 0.04$ | $P = 0.03$ | $P = 0.2$ | $P = 0.17$ |

SD = standard deviation; SE = standard error.
*For central corneal thickness.

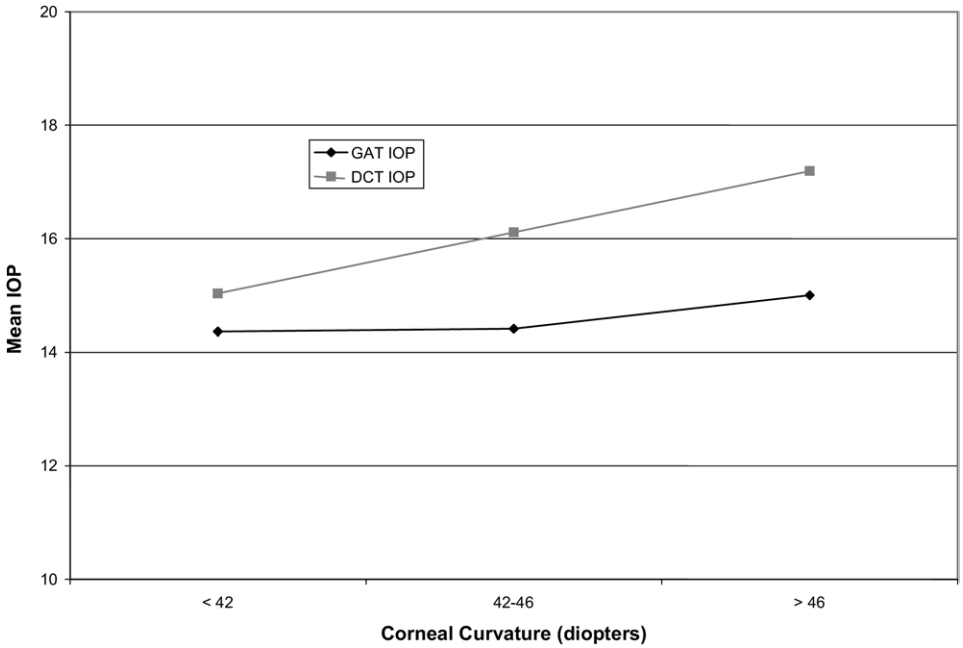


**Figure 4.** The mean intraocular pressure (IOP) for Goldmann applanation tonometry (GAT) and dynamic contour tonometry (DCT) across corneal curvature groups.

corneal curvature, but this was only 5 microns and is likely not clinically significant.

The differences in the GAT−DCT-acquired IOPs were also examined with respect to the IOP level as measured by DCT. In the low IOP group (0 to 10 mmHg), there was the greatest positive difference in GAT minus DCT measured IOPs with the largest percentage of subjects with a ≥ 3 mmHg difference. Conversely, in the high (> 20 mmHg) group, the difference of GAT minus DCT was at the highest negative value, with the highest percentage of subjects with GAT IOP being > 3 mmHg above the DCT IOP. This suggests that GAT tends to overestimate IOP compared to DCT in the lower range and underestimate in the higher range. One weakness in this analysis is that there is no true gold standard IOP to define IOP groups. The only way this could be obtained is with cannulation pressures. Thus, we chose DCT IOP to define the IOP strata because it was least affected by changes in corneal thickness. In studies of cadaver eyes, DCT was found to be more closely related to cannulation pressures than GAT, although this has not been shown in living eyes.[11]

Goldmann applanation tonometry is based on the modified Imbert–Fick principle of pressure inside a sphere, where pressure is equal to the external force necessary to flatten a portion of the sphere divided by the flattened surface area. The modified formula is $W + S = P \times A + B$, where $W$ is the external force, $S$ the surface tension, $P$ is intraocular pressure, $A$ is surface area of applanation, and $B$ is the force needed to bend the cornea. With a diameter of the external applanated corneal surface area of 3.06 mm, the values of corneal inflexibility and surface tension are balanced out, allowing measurement of IOP. However, it is now known that variations in corneal thickness and corneal flexibility can affect this balance and cause significant measurement errors.[10] Although corneal thickness is measurable, a reliable measure for corneal flexibility has not yet been established.

The Pascal tonometer utilizes the concept of DCT, in which

Table 5. Comparison for Goldmann Applanation Tonometry (GAT) and GAT Minus Dynamic Contour Tonometry (DCT) among DCT Groups

| DCT Levels (mmHg) | 0–10 | 11–20 | >20 | *P* Value (Mean/Median Difference) | *P* Value (Trend Test) |
|---|---|---|---|---|---|
| GAT (mmHg) | | | | | |
| Mean (SD) | 12.44 (2.9) | 14.10 (2.8) | 18.85 (3.6) | <0.0001* | <0.0001 |
| Median (range) | 12.3 (6.7–28) | 14 (4.7–26.7) | 18.5 (9.0–3.7) | <0.0001† | |
| GAT-DCT (mmHg) | | | | | |
| Mean (SD) | 3.55 (3.1) | −1.86 (2.6) | −3.88 (3.3) | <0.0001* | <0.0001 |
| Median (range) | 3.3 (−2–20) | −2 (−10.7–13.7) | −4 (−19–10) | <0.0001† | |

SD = standard deviation.
*ANOVA was performed for the comparison in mean difference.
†Nonparametric test (Wilcoxon rank sums) was performed for comparison of median difference.

Table 6. Frequency Distribution for Goldmann Applanation Tonometry (GAT) Minus Dynamic Contour Tonometry (DCT) by DCT Groups

| GAT-DCT (mmHg) | DCT Groups (mmHg) | | | P Value* |
|---|---|---|---|---|
| | *0–10 [n (%)]* | *11–20 [n (%)]* | *>20 [n (%)]* | |
| ≤ −3 | 0 (0) | 751 (41.5) | 129 (67.9) | 0.0001 |
| −2 | 3 (1.9) | 306 (16.9) | 16 (8.4) | |
| −1 | 4 (2.6) | 290 (16.0) | 20 (10.5) | |
| 0 | 14 (9.0) | 182 (10.1) | 11 (5.8) | |
| 1 | 15 (9.6) | 117 (6.5) | 7 (3.7) | |
| 2 | 26 (16.7) | 72 (4.0) | 2 (1.1) | |
| ≥ 3 | 94 (60.3) | 93 (5.1) | 5 (2.6) | |

*Chi-square test was performed to test the association between GAT−DCT and DCT levels.

the effects of corneal thickness, curvature, and flexibility are eliminated or minimized.[10] Because the method does not rely on applanation to measure IOP, it should not be affected by corneal thickness and flexibility. In short, the pressure exerted on the inside of the cornea by IOP is equal to that pressure measured on the external surface of the cornea when the cornea is in a neutral state without any bending or tangential forces acting upon it. The formula is $F_{IOP} + F_r + F_c + F_{ap} = 0$, where $F$ is force, IOP is actual aqueous pressure, r is rigidity (internal forces), c is capillary, and ap is appositional (external forces). The DCT tonometer tip is purported to create this relaxed state in the cornea and a piezoelectric pressure sensor flush with the external corneal surface is able to measure the IOP transmitted through the cornea. Theoretically, the DCT measures should be unaffected by corneal thickness and exhibit a flat mean IOP curve over CCT strata. By comparison, the GAT measures should be lower than DCT for thin corneas, but then cross over and become greater than DCT for thick corneas.

This data from the largest population to date examined with DCT partially support this claim. Measurements of DCT IOP are affected by corneal thickness, but to a much less degree than that seen with Goldmann applanation. It is possible that additional effects of corneal rigidity and hydration, which are not reliably measured, can explain some of this residual effect. It is also possible that, in some subjects, the cornea cannot be placed into the ideal relaxed state and that there may be some residual tangential forces acting upon it.

In addition, DCT appears to be more affected by extremes in corneal curvature than GAT. Thus, although DCT is likely to be the closest measure to "true IOP" available, it still can be affected by corneal parameters to some extent. As expected, GAT exhibits the most clinically significant errors in measurement as compared to DCT in eyes with thin corneas. Based on these findings, DCT can be useful in clinical practice, especially at extremes of CCT and IOP, but care must be taken at extremes of corneal curvature.

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## Appendix: Los Angeles Latino Eye Study Group


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