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JAMA Ophthalmology | **Original Investigation**

Correlation Between Dynamic Contour Tonometry, Uncorrected and Corrected Goldmann Applanation Tonometry, and Stage of Glaucoma

Josephine Wachtl; Marc Töteberg-Harms, MD, FEBO; Sonja Frimmel, MD, FEBO; Malgorzata Roos, PhD; Christoph Kniestedt, MD, FEBO

IMPORTANCE Accurate determination of intraocular pressure (IOP) is crucial for the diagnosis and management of glaucoma. Objective clinical evaluation of the correction equations for Goldmann applanation tonometry (GAT) is lacking.

OBJECTIVES To investigate the difference between corrected and conventional GAT and Pascal dynamic contour tonometry (DCT) measurements, as well as the correlation between discordant IOP values and stage of glaucoma.

DESIGN, SETTING, AND PARTICIPANTS This prospective cross-sectional case series was conducted at the Department of Ophthalmology, University Hospital Zurich, and Talacker Eye Center between July 1, 2011, and May 31, 2016, among 112 white patients with glaucoma.

INTERVENTIONS Intraocular pressure measurements were performed with GAT and DCT in a randomized order. Goldmann applanation tonometry measurements were modified with 5 correction equations.

MAIN OUTCOMES AND MEASURES The primary end point was degree of concordance between corrected or uncorrected GAT and DCT measurements. The secondary end point was association between discordant IOP measurements and the stage of glaucoma, as assessed by the Glaucoma Severity Score.

RESULTS Among the 112 patients (67 women and 45 men; mean [SD] age, 66.3 [13.1] years), 63 of the eyes in the study (56.3%) were left eyes and 85 patients (75.9%) were taking ocular antihypertensive medications. Mean (SD) IOP was 20.3 (4.5) mm Hg (95% CI, 19.4-21.1) as measured by DCT and 17.0 [4.1] mm Hg (95% CI, 16.3-17.8) as measured by GAT. The mean (SD) discordance between DCT and GAT measurements was −3.3 (2.0) mm Hg (95% CI, 2.9-3.6). The 5 corrected GAT values ranged from −2.7 to −5.4 mm Hg compared with DCT. The mean (SD) result of the Dresdner correction formula (17.6 [4.1] mm Hg) was closer to the DCT measurement than the original GAT measurement. The mean (SD) Glaucoma Severity Score was 4.7 (3.4) (95% CI, 4.1-5.4). The uncorrected discordance $IOP_{DCT} - IOP_{GAT}$ showed a positive correlation with the Glaucoma Severity Score ($r_s = 0.33$; $P < .001$) and a negative correlation with central corneal thickness ($r_s = -0.22$; $P = .02$).

CONCLUSIONS AND RELEVANCE In comparison with DCT measurements, these data suggest that GAT values are significantly discordant in eyes with thin corneas and advanced glaucoma. Application of GAT-based correction formulas involves a possible risk of creating an even greater number of unpredictable measurement errors. Hence, we advise with caution, especially pertaining to eyes with thin corneas, to not place reliance on GAT readings, and abandon any correction formula.

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Invited Commentary

Supplemental content

Author Affiliations: Department of Ophthalmology, University Hospital Zurich, Zurich, Switzerland (Wachtl, Töteberg-Harms, Frimmel, Kniestedt); Talacker Eye Center Zurich, Zurich, Switzerland (Wachtl, Kniestedt); Department of Biostatistics, University of Zurich, Zurich, Switzerland (Roos).

Corresponding Author: Christoph Kniestedt, MD, FEBO, Department of Ophthalmology, University Hospital Zurich, Frauenklinikstrasse 24, 8091 Zurich, Switzerland (kniestedt@tazz.ch).

Since 1954, Goldmann applanation tonometry (GAT) has become the criterion standard for measurement of intraocular pressure (IOP). However, the accuracy of GAT is limited owing to its dependency on corneal properties.[1-11] Although most correlations are largely unknown, the effect of central corneal thickness (CCT) on GAT measurements has been investigated.[4,12-18] Goldmann calibrated his tonometer on 500 µm, which he assumed to be normal.[11,12,19,20] In fact, CCT has a significantly large range, resulting in inaccurate GAT readings.[18,21-25] The overestimation of IOP on thick corneas and underestimation on thin corneas has been demonstrated.[11,12,18,26-28] Whereas slight overestimation is clinically acceptable, underestimation of true IOP must be avoided, as underestimation may delay the diagnosis of glaucoma and inhibit appropriate therapy.

In contrast to GAT, Pascal dynamic contour tonometry (DCT) measures IOP directly and continuously, eliminating most systematic errors caused by individual corneal properties.[18,29-32] The principle behind DCT is contour matching of the piezoresistive sensor tip with the cornea, allowing noninvasive and direct transcorneal IOP measurement. In vivo and vitro studies comparing DCT measurements with those of an intracameral manometric pressure have shown that DCT gives IOP readings highly corresponding to manometry and, thus, noninvasively best approaches the "true" IOP.[1,18,31,33,34]

Since the first prototype in 2001, we experienced that DCT readings lie at least 2.0 mm Hg above GAT measurements.[18,29,31,35,36] This systematical bias emphasizes the necessity to reevaluate GAT or seek out solutions to eliminate GAT measurement errors.[18] To improve the accuracy of GAT, several correction formulas have been proposed. Objective evaluation with a manometric or DCT reference pressure and validation in clinical settings is still lacking.

The aim of this clinical trial is to compare DCT with conventional (uncorrected) GAT and corrected GAT, and to determine their degree of concordance with DCT. The second aim is to investigate the hypothesis that patients with discordant IOP readings have a more advanced stage of glaucoma owing to inappropriate treatment based on inaccurate IOP measurements.

Key Points

Question How accurate are Goldmann applanation tonometry (GAT) correction equations, and is there an association between glaucoma stage and discordance of GAT and dynamic contour tonometry intraocular pressure readings?

Findings In this cross-sectional case series, GAT measurements were discordant from dynamic contour tonometry measurements in eyes with thin corneas and advanced glaucoma.

Meaning In the management of patients with glaucoma, measurement inaccuracy associated with GAT must be taken into account, but GAT correction equations still involve the risk of unpredictable measurement errors.

Methods

This prospective observational study included outpatient visits to the Department of Ophthalmology, University Hospital Zurich, or the Talacker Eye Center Zurich. All patients provided written informed consent before the first study intervention. The study was approved by the Cantonal Ethics Committee of Zurich (KEK-ZH-Nr. 2011-0311), is registered in the trials registry of the US National Institutes of Health (NCT01474070), and adhered to the Declaration of Helsinki.[37]

A total of 215 eyes of 112 patients were examined between July 1, 2011, and May 31, 2016. One eye per patient was randomly selected for statistical analysis. To be included in the study, patients had to be at least 18 years of age, with a diagnosis of open angle glaucoma or ocular hypertension. Exclusion criteria were histories of contact lens wear, acute or chronic corneal diseases, corneal astigmatism greater than 2.0 diopters, and a history of laser refractive surgery or other corneal interventions.

A thorough ophthalmologic examination of all patients included refraction, visual acuity, slit lamp biomicroscopy, optical biometry and pachymetry (Lenstar LS 900; Haag-Streit), echographic pachymetry (Tomey AL-1000; Tomey Europe GmbH), IOP measurement by GAT and DCT (Pascal; Ziemer Ophthalmic Systems), optical coherence tomography (OCT; Cirrus HD-OCT 5000; Carl Zeiss AG), and Octopus Perimetry (Octopus 900; Haag-Streit). Echographic pachymetry was performed after IOP measurements. The mean of 5 echographic CCT measurements was taken for subsequent analysis. Intraocular pressure was measured by applanation (IOP_{GAT}) and Pascal (IOP_{DCT}) twice each in a randomized order. The mean of 2 measurements was used for analysis. Goldmann applanation tonometry values were corrected by applying 5 correction formulas.[12,17,38-40] Only DCT values of best quality were used (quality score Q1, which indicates excellent measurements). Perimetry and optical coherence tomography were performed to graduate the stage of glaucoma. The 5 GAT correction formulas are in **Table 1**[13,17,38-40] and described in the eAppendix in the Supplement.

The primary end point of the study was the degree of concordance between IOP_{GAT}, its corrected values, and IOP_{DCT} as the reference pressure. A difference in IOP of 2 mm Hg or more was considered clinically relevant. The association between discordant IOP measurements and the stage of glaucoma was our secondary study end point.

Glaucoma Severity Score

To determine the stage of glaucoma, we developed a Glaucoma Severity Score (GSS) ranging from 0 to 10 points (where 0 indicates a low likelihood of a glaucoma diagnosis and 10 indicates a high likelihood of a glaucoma diagnosis), including the following criteria: (1) superior and inferior peripapillary retinal nerve fiber layer (RNFL) thickness, (2) perimetric mean defect, and (3) agreement of anatomical and perimetric defects, assessed by 2 glaucoma specialists (M.T.-H. and C.K.) (eTable 1 in the Supplement).[41]

Statistical Analysis

A pilot study with 35 patients found an SD of 3.9 mm Hg for the discordance of DCT and GAT. Given the clinically relevant

Table 1. Summary of Correction Equations for Goldmann Applanation Tonometry

Source	Correction Formula	Definition of Correction Factors and Variables[a]
Ehlers et al,[12] 1975	IOPT = IOPG+CF	Correction factor CF = 0.071 × [520 - CCT + 0.562 × (IOPG - 20)] × [0.012 × (IOPG - 20) +1]
Kohlhaas et al,[17] 2006	IOPT = IOPG+ΔIOP	Dresdner correction table ΔIOP = (−0.0423 × CCT) + 23.28
Elsheikh et al,[39] 2009	IOPT = IOPG/K	Correction factor K = ACCT × AR × AAge × AIOPG ACCT [mm] = 2.0 (CCT-0.520)2 + 1.4 (CCT-0.520) + 0.47 AR [mm] = 1 - 0.1 (R-7.8) AAge [y] = 0.00555 (Age-50) 2 - 0.0266 (Age-50) + 14.52 AIOPG [mm Hg] = (IOPG + 38.9) - 0.487
Elsheikh et al,[38] 2011	IOPT = IOPG/C	Correction factor C = ACCT × AR × AAge × AIOPG ACCT [mm] = 0.68 (CCT-0.520)2 + 1.12 (CCT-0.520) + 1.0 AR [mm] = 1 - 0.06 (R-7.8) AAge [y] = 0.3 × 10 - 6 Age3 - 88 × 10-6 Age2 + 0.0085 Age +0.815 AIOPG [mm Hg] = 1.427 (IOPG + 3.373) -0.119
Spoerl et al,[40] 2012	IOPT = IOPG+CF	Correction factor CF = 4.8 × 10 - 4 × age × (520-CCT)

Abbreviations: C, correction factor; CCT, central corneal thickness; CF, correction factor; IOP, intraocular pressure; IOPG, Goldmann intraocular pressure; IOPT, true intraocular pressure; K, correction factor; R, radius of corneal curvature.

[a] Because the correction formulas are from different sources, more than one abbreviation indicates "correction factor."

effect of 2 mm Hg, a significance level of P = .005 and power of 99%, a sample size of 105 patients (independent eyes) was calculated.

Data were coded in Excel 2016 (Microsoft Corp) and analyzed with SPSS, version 22 (IBM Inc). Descriptive statistics, such as mean, SD, median, and interquartile range, in addition to absolute and relative frequencies were computed. Moreover, 95% CIs for the mean were derived. An agreement between the 2 glaucoma specialists (M.T.-H. and C.K.) was investigated by using the κ statistic. According to Altman,[42] κ>0.8 indicates very good agreement. A 1-way analysis of variance (ANOVA) together with the Bonferroni post hoc test evaluated differences of discordance between DCT and GAT in addition to corrected GAT values in different GSS groups. Association between discordance of DCT and GAT, or corrected GAT values and the GSS score, as well as CCT, was investigated by using a nonparametric Spearman correlation and a simple and bivariate linear regression. In addition, the Bland-Altman method was applied to derive the 95% limits of agreement. Results of statistical analysis with P < .05 were considered statistically significant. All P values were adjusted for multiple testing. Adjustment was provided by the Bonferroni post hoc test for the 1-way ANOVA and by the multivariable regression analysis adjusting for confounders.

Results

Demographic Data and IOP

All 112 patients were examined between July 1, 2011, and May 31, 2016. Mean (SD) age was 66.3 (13.1) years (95% CI, 63.8-68.7), all patients were white, and there were 67 women and 45 men. Demographic data are summarized in **Table 2**.

Mean (SD) IOP was 17.0 (4.1) mm Hg (95% CI, 16.3-17.8) for GAT and 20.3 (4.5) mm Hg (95% CI, 19.4-21.1) for DCT. Mean (SD) CCT was 537 (36) µm (95% CI, 530-544). eTable 2 in the Supplement summarizes biometric data and IOP_{GAT} and IOP_{DCT} values. The mean (SD) IOP difference between the 2 tonometry principles (IOP_{DCT} - IOP_{GAT}) was 3.3 (2.0) mm Hg (**Table 3**).[13,17,38-40] A Bland-Altman plot of the agreement between IOP_{GAT} and IOP_{DCT} illustrates the discordance between the 2 methods against the mean of both, showing 95% limits of agreement between DCT and GAT of −0.5 to 7.1 mm Hg, with a mean discordance of 3.3 mm Hg (**Figure 1**A). The mean discordances of the 5 corrected GAT values ($IOP_{corrected}$) from the DCT reading are listed in Table 3.[13,17,38-40] All mean (SD) discordances were statistically highly significant (Ehlers et al,[12] 4.5 [2.9] mm Hg; Kohlhaas et al[17] [Dresdner correction formula], 2.7 [2.3] mm Hg; Elsheikh et al [2009],[39] 5.4 [2.8] mm Hg; Elsheikh et al [2011],[38] 4.8 [2.0] mm Hg; and Spoerl et al,[40] 3.8 [2.1] mm Hg; all P < .001) and positive throughout owing to the higher DCT readings. The mean (SD) results of the Dresdner correction formula (17.6 [4.1] mm Hg) were closer to the DCT measurement than the original GAT reading (Figure 1B and Table 3[13,17,38-40]).

Analysis of IOP Discordances and Glaucoma Severity Score

Our study population reached a mean (SD) GSS of 4.7 (3.4) points (eTable 3 in the Supplement). The Cohen κ coefficient (0.829) was determined and showed very good interrater agreement between M.T.-H. and C.K. for the parity of structural and functional defects. Thus, for statistical analysis, 1 specialist's (C.K.) rating was applied to avoid half-point scores.

The Spearman rank-order correlation test was applied for the analysis of the GSS. A negative correlation was found between both the OCT superior (r_s = −0.79; P < .001) and inferior (r_s = −0.78; P < .001) RNFL thickness (criterion 1A and 1B) and the GSS score. For criterion 2 of the GSS, a strong positive correlation was found between functional defect and increasing GSS score (r_s = 0.78; P < .001) (eFigure 1 in the Supplement). These findings are in accordance with the expected decrease of RNFL thickness with progressing glaucoma and increase in perimetric mean defect with higher GSS.

Discordant GAT values (IOP_{DCT} - IOP_{GAT}) and discordant modified GAT values (IOP_{DCT} - $IOP_{corrected}$) were analyzed separately for each of the 3 GSS criteria using 1-way ANOVA. Superior RNFL thickness (criterion 1A) showed a statistically significant correlation with the discordances of Spoerl et al[40] ($F_{2,109}$, 3.83; P = .03), Elsheikh et al[38] ($F_{2,109}$, 5.10; P = .008), and uncorrected GAT ($F_{2,109}$, 7.27; P = .001). Bonferroni post hoc testing revealed that the discordance between DCT and Spoerl et al[40] (IOP_{DCT} - IOP_{SPOERL}) was significantly higher for the superior OCT score of 2 compared with score 0 (1.1; P = .01). The same applies to the discordance of DCT and GAT (1.3; P = .001). This finding corresponds to a higher discordance for IOP_{DCT} - IOP_{SPOERL} and IOP_{DCT} - IOP_{GAT} with thinner superior

RNFL. Accordingly, there was a statistically significant difference between inferior OCT scores (criterion 1B) for the discordance of IOP_{DCT} - IOP_{GAT} as determined by 1-way ANOVA ($F_{2,109}$, 5.48; P = .005). Again, Bonferroni post hoc testing showed that the discordance was significantly higher for GSS inferior OCT score 2 compared with score 0 ($F_{2,109}$, 1.2; P = .006). No significant result was found regarding inferior OCT score for any of the discordant values from the correction formulas. Thus, the analysis demonstrates a significantly higher discordance of IOP_{DCT} - IOP_{GAT} in patients with structurally progressed glaucoma compared with patients with normal RNFL thickness, which was partly true for IOP values by Spoerl et al[40] concerning superior RNFL thickness. Testing the second criterion, there was no statistically significant association between the discordances of the correction formulas and functional defects. For criterion 3, the discordance of IOP_{DCT} - IOP_{GAT} showed a statistically significant difference between the different score values as determined by 1-way ANOVA ($F_{3,108}$, 4.1; P = .009). Results of the Bonferroni post hoc test were significant for scores 0 and 3 ($F_{2,109}$, 1.4; P = .02).

The Spearman correlation coefficient was r_s = 0.33 between the GSS and the discordance of DCT and GAT (P < .001). Thus, the Spearman correlation coefficient indicates increasing discordance of GAT and DCT glaucoma severity based on our score augments (**Figure 2**A). With the exception of the formula by Elsheikh et al[38] (2011) (r_s = 0.23; P = .01), none of the other correction equations indicated a significant correlation between the equations' discordances from DCT and the GSS.

Table 2. Demographic and Ocular Data

Characteristic	Value[a] (N = 112)
No. of eyes	
Right	49 (43.8)
Left	63 (56.3)
Sex	
Male	67 (40.2)
Female	45 (59.8)
Age, mean (SD), y	66.3 (13.1)
Glaucoma diagnosis	
POAG	68 (60.7)
Secondary glaucoma	24 (21.4)
OHT	20 (17.9)
Visual acuity, median (IQR) [range], decimal Snellen	1 (0.2) [0.01-1]
Lens status	
Cataract (early)	42 (37.5)
Pseudophakia	27 (24.1)
None of the above	43 (38.4)
History of trabeculectomy	16 (14.3)
Myopia (≤-3 diopters)	16 (14.3)
Antiglaucoma drugs, No.	
0	27 (24.1)
1	23 (20.5)
2	29 (25.9)
3	26 (23.2)
4	7 (5.4)

Abbreviations: IQR, interquartile range; OHT, ocular hypertension; POAG, primary open-angle glaucoma.

[a] Data are presented as number (percentage) of patients unless otherwise indicated.

Regression Analysis

Univariate regression analysis indicated a significant dependence of the degree of discordance of IOP_{DCT} - IOP_{GAT} on the GSS ($F_{1,110}$, 12.7; P = .001). The R^2 value was 0.1, which signifies that only 10% of variance in the dependent variable IOP_{DCT} - IOP_{GAT} can be explained by the independent variable GSS. Multiple regression analysis was performed to analyze the influence of age, CCT, axial length, corneal radius, and GSS on the degree of discordance between DCT and GAT, as well as the corrected values. However, only GSS and CCT had a statistically significant effect on the discordances of DCT and GAT (eTable 4 in the Supplement).

Analysis for CCT

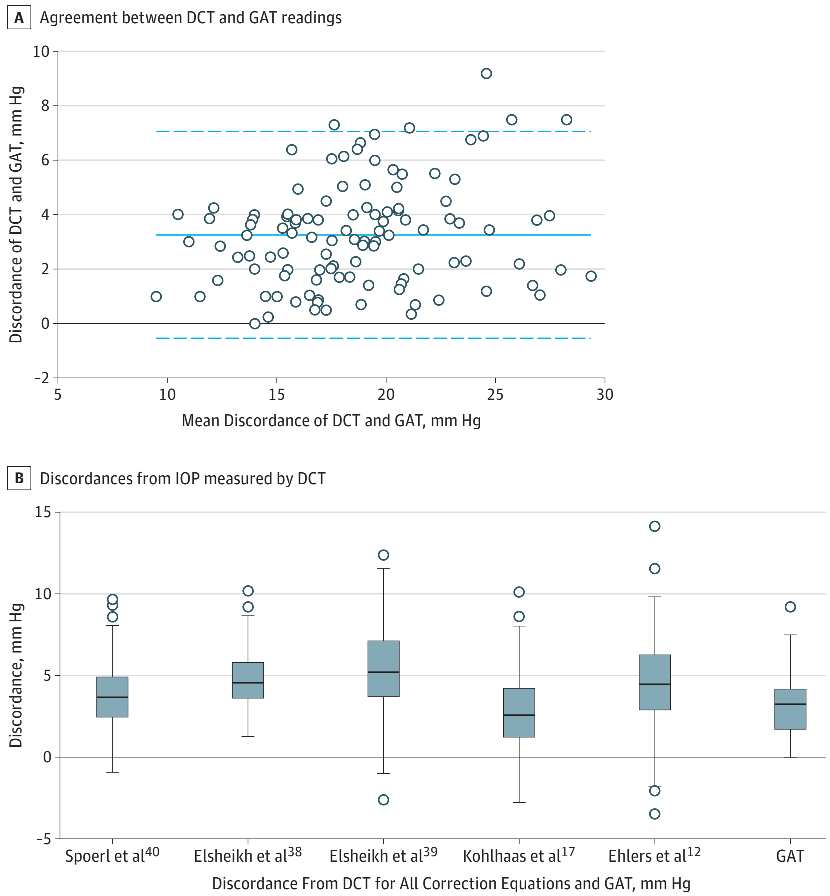
Positive correlations between the discordances of all correction equations and CCT were highly statistically significant, except for the Elsheikh et al[38] (2011) equation (eTable 4 in the Supplement). With increasing CCT, the discordances became larger and more scattered (eFigure 2A in the Supplement [the Dresdner correction table]). Thus, any formula provides even poorer corrections for thicker vs thinner corneas. The Elsheikh et al[38] 2011 formula showed the weakest positive correlation between its discordance from IOP_{DCT} and CCT (eFigure 2B in the Supplement). On the contrary, a negative correlation was found between the discordance of IOP_{DCT} - IOP_{GAT} and CCT (r_s = −0.22), indicating that with increasing CCT, the discordance between DCT and GAT becomes smaller (P = .02). Thus, GAT readings are closer to the "true" IOP in patients with thicker corneas.

Table 3. IOP_{GAT}, $IOP_{corrected}$, and Discordances From IOP_{DCT}

Characteristic	Value, Mean (SD), mm Hg		P Value
	IOP	Discordance	
	GAT: 17.0 (4.1)	IOP_{DCT}-IOP_{GAT}: 3.3 (2.0)	<.001
Correction formula			
Ehlers et al,[12] 1975	Corrected: 15.8 (4.5)	IOP_{DCT}-$IOP_{corrected}$: 4.5 (2.9)	<.001
Kohlhaas et al,[17] 2006 (Dresdner)	Corrected: 17.6 (4.1)	IOP_{DCT}-$IOP_{corrected}$: 2.7 (2.3)	<.001
Elsheikh et al,[39] 2009	Corrected: 14.9 (4.4)	IOP_{DCT}-$IOP_{corrected}$: 5.4 (2.8)	<.001
Elsheikh et al,[38] 2011	Corrected: 15.5 (4.0)	IOP_{DCT}-$IOP_{corrected}$: 4.8 (2.0)	<.001
Spoerl et al,[40] 2012	Corrected: 16.5 (4.0)	IOP_{DCT}-$IOP_{corrected}$: 3.8 (2.1)	<.001

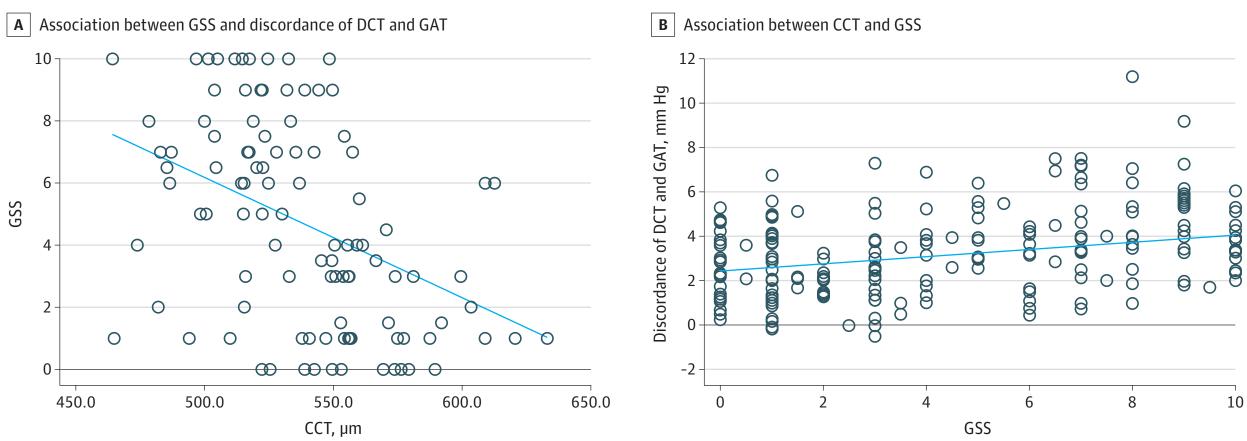
Abbreviations: DCT, dynamic contour tonometry; GAT, Goldmann applanation tonometry; IOP, intraocular pressure.

Figure 1. Agreement Between Dynamic Contour Tonometry (DCT) and Goldmann Applanation Tonometry (GAT) Readings and Discordances From Intraocular Pressure (IOP) Measured by DCT



A, Bland-Altman plot illustrating the agreement between DCT and GAT readings. The discordance of both readings is plotted against their mean. Circles indicate the cases. Solid line indicates mean discordance and broken lines indicate 95% limits of agreement. B, Discordances from IOP measured by DCT for all correction formulas and uncorrected GAT. Shaded bars extend from lower to upper quartile. Horizontal lines in shaded bars indicate the median. Vertical lines extend from minimum to maximum value, excluding outliers. Circles indicate the outliers. The dotted horizontal line at zero indicates concordance.

Figure 2. Association Between the Glaucoma Severity Score (GSS) and the Discordance of Dynamic Contour Tonometry (DCT) and Goldmann Applanation Tonometry (GAT) and the Central Corneal Thickness (CCT)



A, Association between the GSS and the discordance of DCT and GAT. Patients with discordant intraocular pressure readings tend to have a higher GSS. R_O linear = 0.162. Circles indicate cases. The diagonal line is the regression line.

B, Association between CCT and the GSS. Patients with thinner corneas tend to have more progressed glaucoma. Circles indicate cases. The diagonal line is the regression line. The dotted horizontal line at zero indicates concordance.

Spearman rank-order correlation showed a negative correlation between CCT and GSS (r_s = −0.38; P < .001). Therefore, our study population tended to have thinner corneas with advanced glaucoma as indicated by the GSS (Figure 2B). Analyzing CCT by glaucoma diagnosis resulted in a mean (SD) CCT of 531.3 (35.2) µm for eyes with primary open-angle glaucoma, 548.6 (32.7) µm for eyes with secondary glaucoma, and 541.2 (42.2) µm for patients with ocular hypertension. There was no significant difference in CCT among these diagnosis groups as determined by 1-way ANOVA (P = .11). A scatterplot showed equal distribution of all 3 diagnosis groups from thin to thick corneas.

Mixed-model analyses were performed for all 215 eyes (112 patients), adjusting for multiple observations (both eyes) within each patient. The results provided by the analyses at the patient level and the eye level were in strong agreement.

Discussion

Accurate determination of intraocular pressure is crucial for the diagnosis and management of glaucoma. Goldmann applanation tonometry retains the reference and standard for IOP measurements despite its well-known limitations. The Pascal DCT was designed to overcome these limitations, providing an IOP measuring technique largely independent of corneal properties.[3,27,30,33,36]

The poor agreement between GAT and DCT may influence therapeutic decisions. With a mean (SD) difference of 3.3 (1.9) mm Hg between GAT and DCT, our discordance is within the previously reported range.[3,15,35] In their systematic review, Cook et al[35] reported a mean difference of 1.8 mm Hg between GAT and DCT, with a 95% level of agreement between -2.9 and 6.5 mm Hg. When using the Pascal DCT, Kaufmann et al[36] suggested an addition of 2 mm Hg to the target pressure, which is usually based on GAT readings.

In our study, discordances of up to 9.2 mm Hg between GAT and DCT measurements were found. The correction equations resulted in a wider scatter and a larger deviation of DCT values compared with uncorrected GAT readings. The extensive scatter of the IOP values resulting from the correction equations is in accordance with Ang et al,[43] who reported no improvement of agreement with DCT after adjustments of their GAT readings.

Regarding the influence of IOP discordances on the stage of glaucoma, the discordance of DCT and uncorrected GAT (IOP_{DCT} - IOP_{GAT}), as well as the discordance of DCT and the GAT as determined by Elsheikh et al[38] (IOP_{DCT} - $IOP_{Elsheikh}$), increased with advanced GSS. Only the equation by Elsheikh et al[38] was independent of CCT, but nevertheless was influenced by severity of glaucoma. For all other formulas, the association was the reverse. Accordingly, the discordances of the remaining 4 correction formulas showed a positive correlation with CCT. Park et al[44] additionally described an increasing discordance between DCT and adjusted GAT readings with increasing CCT.

Concerning all equations, our analyses clarify that the correction of IOP in patients with thinner CCT gives a pressure value closer to the DCT reading as compared with patients with thicker CCTs, because they presumably were developed for thinner corneas. However, discordances from DCT are still clinically relevant even in the lower CCT ranges. The approximately linear Dresdner correction table shows the smallest discordance overall and corresponds to the DCT value at a CCT of 450 µm. However, owing to our small sample size at this CCT level and discordances of more than 10 mm Hg, this result should be interpreted with caution. Contrarily, the difference between DCT and GAT decreased with increasing CCT, which is in accordance with other studies and is well known.[15,18,45]

Boehm et al[33] compared DCT measurements with an intracameral IOP reference pressure in vivo and found excellent agreement, which had been described by Kniestedt et al[31] in 2005 for an in vitro setting. Of all corneal factors examined by Boehm et al[33] (CCT, corneal curvature, astigmatism, axial length, age), a statistically significant correlation between the discordance of both measurements was found only for CCT. Boehm et al,[33] however, acknowledged the effect of CCT as clinically irrelevant, owing to a very small and very weak correlation between DCT and CCT (R^2 = 0.00012; P = .03). With this study, we confirm their data with similar values of R^2 = 0.04 and P = .04.

The dependence of IOP_{DCT} - IOP_{GAT} on both CCT and the GSS was judged to be clinically relevant (eTable 4 in the Supplement). Therefore, the discordance between DCT and GAT increased with an augmenting GSS score and decreased with growing CCT. In our study group, patients with thinner corneas had more advanced glaucoma. We deduce a causative association between discordant IOP readings and the stage of glaucoma. Patients with thinner corneas may be underdiagnosed owing to measurement inaccuracy of GAT, leading to increased risk of disease progression.

Our study shows that all 5 correction formulas calculate IOP values, which differ to an even greater extent from the "true" IOP than the GAT value itself. It seems clear that simple linear correction equations, as proposed by Ehlers et al[12] or the Dresdner correction table, oversimplify the real association between CCT and IOP. The oversimplification may result in a corrected IOP, which may be much less accurate than the initial GAT measurement. In addition, other biomechanical properties of the eye are neglected. Contrarily, the more complex formulas, such as the equation by Elsheikh et al,[38] may better reflect the complexity of the association, as additional cofactors are considered. However, they are still not able to provide a sufficient IOP correction. Our results suggest that no correction equation is suitable for the approximation of "true" IOP, and therefore, the risk of creating a significant error is present. Conversely, DCT is known to provide precise measurements of good interobserver reproducibility.

Despite the commonly known limitations of GAT, it is currently the most accessible method for IOP measurement and will likely remain the preferred reference technique. Therefore, it is important to be aware of the limitations and its potential for inaccuracy.[35]

Limitations

This study has some limitations. We did not investigate the influence of previous cataract or glaucoma surgery and topical medication on the elasticity of the cornea and, thus, its possible influence on the discordance between corrected and uncorrected GAT and DCT. Furthermore, we did not investigate whether discordances remain unchanged in the same eye on follow-up visits and at different pressure levels. A follow-up study is warranted to address this issue and should be enhanced by corneal hysteresis as a measure for corneal elasticity.

Conclusions

We found a significant increase in discordance between GAT and DCT in patients with thin corneas and advanced glaucoma. Thus, we believe that patients with thin corneas may have a higher risk for glaucoma progression owing to measurement inaccuracy associated with GAT. It is advisable to investigate the discordance from the DCT value at the time of setting the treatment strategy. Furthermore, rather than correcting the GAT value with any correction equation, the discordance should be reevaluated when the glaucoma is uncontrolled and under progression.

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Study concept and design: Wachtl, Töteberg-Harms, Frimmel, Kniestedt.
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