Dynamic Contour Tonometry

A Comparative Study on Human Cadaver Eyes

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Objective: To compare intraocular pressure measurements obtained by recently introduced dynamic contour tonometry (DCT), Goldmann applanation tonometry (GAT), pneumatonometry (PTG), and intracameral manometry in human cadaver eyes.

Methods: Sixteen freshly enucleated human cadaver eyes were deepithelialized and dehydrated with dextran. A tube was placed in the anterior chamber and connected to a transducer and to a bottle system filled with balanced salt solution. The pressure in the eye was then altered between 5 mm Hg and 58 mm Hg. Intraocular pressure measurements were obtained with DCT, GAT, and PTG at each manometric pressure reading.

Results: On average, DCT values measured 0.58±0.70 mm Hg higher than real intracameral pressure. The GAT and PTG showed consistently lower values, −4.01±1.76 mm Hg and −5.09±2.61 mm Hg, respectively. At all bottle heights, DCT values were significantly closer to the reference pressure than GAT and PTG (P<.001).

Conclusions: Measurement with DCT provides IOP values significantly closer to true manometric levels than either GAT or PTG. Further studies are warranted to determine its reliability in patients and the effect of corneal thickness.


Oldmann applanation tonometry (GAT) has become the gold standard against which other tonometers have been compared.1-7 This is despite the fact that Goldmann himself recognized that the tonometer’s accuracy was questionable in corneas that were not of average thickness.1 Using optical pachymetry, Goldmann and Schmidt1 assumed that most corneas were about 520 µm thick. Recent evidence has confirmed the wide variation in corneal thickness and raised the possibility that corneas that are thicker or thinner than average might be associated with clinically significant overestimates or underestimates of intraocular pressure (IOP) when measured with the GAT.5-19 Some studies suggested that at least some cases of normal-tension glaucoma could be explained by the underestimation of IOP by GAT in these patients whose corneas are thinner than those with open-angle glaucoma.13,20-22

Other tonometers, such as the pneumatonometer (PTG),23,24 the McKay-Marg tonometer, and its derivative, the handheld tonometer (Tono-Pen; Mentor, Norwell, Mass), have been reported to be more accurate, especially in corneas outside the average in thickness.12,25 However, these observations have not always been confirmed by others.26-30 Recently, a new device, the dynamic contour tonometer (DCT), was introduced by Kaniigisser and Robert.31 Dynamic contour tonometry is a totally new method of measuring the IOP based on the principle of contour matching. The DCT tip is mounted in a tip holder of a GAT (Figure 1A), which provides for a constant appositional force of 1 g. The contoured tip features a concave surface with a radius of 10.5 mm, a contact surface of approximately 7 mm, and a miniaturized piezoresistive pressure sensor 1.7 mm in diameter built flush into the center of the contact surface (Figure 1B). Forcing the central area of the cornea into the contour of the DCT tip allows the examiner to measure the pressure of the eye directly and continuously on the external surface of the cornea. Pressure readings are sampled and digitized at 100 Hz. Data points are transferred to a microprocessor-based control unit, which computes and displays the measured pressure.

The purpose of this study was to compare the DCT, GAT, and PTG with manometric measurements in human cadaver eyes.
Twenty freshly enucleated human cadaver gloves that were unsuitable for transplantation were provided by the eye banks of San Diego, Calif, and Portland, Ore. Eyes were stored at 4°C in moist chambers until use. Consent for the use of the eyes was obtained by the eye banks either through premortem instructions or from postmortem next of kin. Institutional review board consent was not considered necessary for this in vitro study, but departmental approval was obtained. The eyes were used for this experiment on the day of arrival, an average ± SD of 27.0 ± 10.9 hours post mortem. The ages of the cadavers ranged from 64 to 84 years. The causes of death were either cardiovascular or neoplastic (other than ocular). Eyes with a history or evidence of previous intraocular surgery or corneal abnormalities were excluded. Four eyes served for a preliminary study evaluating closed vs open stopcock systems, and the remaining 16 eyes were included in the main study and final analysis.

Central corneal thickness (CCT) was measured with an ultrasonic pachymeter (Model 850; Humphrey Instruments, San Leandro, Calif), which was calibrated before each use. The speed of sound was adjusted at 1640 m/s according to the internationally accepted standard velocity for human corneas and did not require adjustment for corneal thickness differences. Five independent measurements in micrometers, their mean and standard deviation, and the 95% confidence interval (CI) were recorded. All 20 eyes were subject to corneal dehydration, since the untreated corneal thicknesses varied between 444 and 925 µm depending, in part, on the postmortem age of the eye. The globe was first brought to an IOP of 25 to 30 mm Hg by carefully injecting 20% dextran solution into the anterior chamber by means of a scleral entry with a 30-gauge needle. The 20% dextran was prepared by dissolving 20 g of 220 000–molecular weight dextran (Sigma-Aldrich Corp, St Louis, Mo) in 100 mL of balanced salt solution (Alcon, Ft Worth, Tex). The corneal epithelium was totally removed by manual abrasion with a cotton swab and a blunt scalpel blade. Corneal thickness was measured for the first time immediately after dextran injection. Next the globe was immersed in dextran solution. The ultrasonic CCT was measured after 15, 30, and 45 minutes of immersion. After 45 minutes, the ultrasonic CCT became relatively stable, at which time the anterior and posterior corneal curvature, astigmatism, and (optical) CCT were determined with a corneal topography system (Orbscan II; Bausch & Lomb Surgical, St Louis).

A 22-gauge needle with Y-adaptor (Saf-T-Intima, Vialon; Becton, Dickinson and Company, Franklin Lakes, NJ) was then inserted into the anterior chamber via a separate scleral approach. Extreme care was taken with all penetrations of the eye to avoid touching the endothelium, the iris, or the lens. The entire globe was mounted in an eye holder embedded in moistened gauze facing a slitlamp (30 SL-M; Carl Zeiss Meditec AG, Jena, Germany). The tube was connected to a manometric transducer, an isotonic sodium chloride solution infusion bottle, and an open-air reference tube. Multiple stopcocks were also attached to bleed all bubbles from the system and to allow either open or closed stopcock techniques. The transducer and the anterior chamber were kept at the same height. The isotonic sodium chloride solution infusion bottle was attached to an electrically driven intravenous pole for bottle height adjustment (Figure 2). The same instrument (Model 30 Classic; Medtronic Inc, Minneapolis, Minn) was used for all PTG readings.

In the preliminary series of 4 eyes, the pressure measurements were performed by means of the closed stopcock tubing system first to compare its applicability and accuracy with the open tubing system, which was used on the same eye immediately thereafter. The bottle height was altered between 5 cm and 50 cm and pressure readings were taken with DCT, PTG, and a handheld tonometer (Tono-Pen XL; Mentor) (TPN).

Sixteen human cadaver eyes were used for the main study. The bottle height was adjusted at 5 cm to begin each trial. At each bottle height, 5 independent measurements of DCT, GAT, and PTG were made in randomized order with manometric pressure measured and recorded between each set of measurements. The bottle heights were increased in 5-cm increments up to a maximum of 75 cm (58 mm Hg). After the experiment, the bottle height was lowered to the initial 5 cm. The series was accepted only if the initial and closing manometric pressures were within ±1 mm Hg.

To determine whether elevated IOPs alter the corneal curvature and the accuracy of DCT, 3 eyes were subjected to optical keratometry and corneal topography (Orbscan II) at a maximal IOP of approximately 58 mm Hg after the last trial series. The stopcock at the 22-gauge needle tube was closed at the maxi-
nal IOP and the globe was left in the cadaver eye holder but unhooked from the reservoir bottle distal to the stopcock. The cadaver eye holder was mounted to the topography instrument and fixed in a way similar to that done at the slitlamp for the IOP measurement trials. An average of 2 scans of corneal thickness (measured in micrometers) and anterior and posterior curvature (in millimeters and diopters) were taken of each cornea, ensuring that the cornea was well moisturized and the entry needle without torsion during the readings.

Statistical analysis was performed with a homoscedastic, 2-tailed t test. The t tests were run at all bottle heights separately and all 5 pressure readings were taken into calculation (n = 1120 for GAT and PTG, bottle heights of 10-75 cm; n = 1200 for DCT, bottle heights of 5-75 cm). A mixed-effects regression model was constructed by means of SAS software (SAS Institute Inc, Cary, NC). The model treated cadavers and eyes nested within cadavers as random effects and did not assume equal variability in the 3 devices. A separate analysis was run using only the data from trials with bottle heights from 10 to 30 cm (8-25 mm Hg) to derive the statistics for the “clinically significant” range. Data are given as mean±SD unless otherwise indicated.

RESULTS

Preliminary Study

Four eyes were used for the comparison of the open vs closed stopcock methods. These eyes were not included in the analysis of the main study. The open system showed an overestimation by DCT (+0.5±0.29 mm Hg) and an underestimation by PTG (−2.73±1.94 mm Hg) and TPN (−4.92±1.91 mm Hg). In a closed system, the cadaver globe is subject to uncontrollable fluid leakage.23,24,32 Any kind of tonometry that flattens or indents the cornea displaces a variable amount of fluid within the anterior chamber or to other compartments of the globe, which would result in a transient increase in IOP followed by a decrease due to a consequent further loss of fluid from the globe through the normal outflow pathways (tonographic effect) as well as through cut ends of the venous system. Therefore, it is difficult to determine at what point to measure the manometric IOP: either before probe application or during application (by PTG or TPN) or while contour matching (DCT) is taking place. The DCT values measured −0.1±0.72 mm Hg; PTG, −2.92±1.08 mm Hg; and TPN, −3.98±2.53 mm Hg compared with the starting pressure (before probe application). With the use of continuous manometric pressure measurement, the results were −0.59±0.31 for DCT, +3.01±1.13 for PTG, and +4.53±2.10 for TPN. Regardless of which point in time the tonometric pressure was compared with manometry using the closed stopcock method, DCT was significantly closer to manometric reference pressure than either PTG or TPN (P<.001). Furthermore, the data show little difference in results between open and closed stopcock methods.

Main Study

The 16 dehydrated and untreated human cadaver corneas presented initially with a CCT of 805±102 µm (95% CI, 755-855 µm). After 15, 30, and 45 minutes of exposure of both sides of the cornea to 20% dextran, CCT of 617±85 µm (95% CI, 575-659 µm), 512±59 µm (95% CI, 483-541 µm), and 462±49 µm (95% CI, 438-486 µm) was achieved. At the end of the experiment, CCT showed further thinning to 434±48 µm (95% CI, 411-457 µm). The median CCT was fairly stable until the IOP of 50 mm Hg was reached, falling back slightly in the markedly elevated pressure range.

Mean examination duration after dehydration was 85±19 minutes. Anterior corneal curvature was found to be 7.98±0.46 mm (42.47±1.79 diopters); posterior curvature was 6.40±0.40 mm. The CCT determined by the corneal topography system was 489±103 µm—surprisingly, 27 µm thicker than the CCT determined by ultrasonic pachymetry. The discrepancy may be due to the larger scatter from the topography device and the difficulty in centering the cadaver globe in the front of the laser scanning area.

Three eyes were subjected to CCT measurement by the orbital topography system when the IOP was greater than 55 mm Hg. In these eyes, anterior corneal radius before the experiment at an IOP of approximately 20 mm Hg was 7.71±0.21 mm (43.17±1.33 diopters) and posterior curvature measured 5.85±0.04 mm (37.4±0.3 diopters). At the end of the experiment, at an IOP of about 58 mm Hg, the anterior curvature was 7.69±0.18 mm (43.2±1.3 diopters) and the posterior curvature, 6.4±0.21 mm (52.8±1.7 diopters). For the anterior curvature, this change was not statistically significant (P=.31), but the posterior curvature flattened at the borderline of statistical significance (P=.03).

At each bottle height, all 3 tonometer devices were used to obtain 5 pressure readings. The bottle height was altered in 5-cm increments between 5 cm and 75 cm, except for GAT and PTG. Neither GAT nor PTG was able to produce consistent readings at the 5-cm bottle height. The IOP readings (with standard deviations) at defined bottle heights for manometry, DCT, GAT, and PTG are
Compared with the absolute manometric pressure, DCT measures were not significantly different (P = .18, n = 1200). The GAT and PTG measures were both significantly different from the manometric pressure (P < .001, n = 1120), as shown in Figure 3.

With manometric pressure used as the reference, DCT showed a slight absolute deviation between 0.3 mm Hg (95% CI, 0.2-0.4 mm Hg) at 20-cm bottle height (16.2 mm Hg) and 1.7 mm Hg (95% CI, 1.1-2.3 mm Hg) at 75-cm bottle height (58 mm Hg), whereas GAT underestimated the IOP with an absolute deviation between −3.2 mm Hg (95% CI, 2.6-3.8 mm Hg) at 20-cm bottle height (16.2 mm Hg) and −5.9 mm Hg (95% CI, 4.7-7.1 mm Hg) at 75-cm bottle height (58 mm Hg). The PTG was rather accurate in the low end of the pressure spectrum (absolute deviation, 1.1 mm Hg; 95% CI, 0.6-1.6 mm Hg) at 10-cm bottle height (8.5 mm Hg), but fell off with a significant underestimation by 9.6 mm Hg (95% CI, 8.8-10.4 mm Hg) at 75-cm bottle height (58 mm Hg). On average, DCT measured +0.58±0.70 mm Hg higher than the reference IOP.

### Mean IOP and Algebraic and Absolute Accuracy (N = 16)

| Bottle Height, cm | Reference IOP, Mean ± SD, mm Hg | IOP, mm Hg | \( \Delta \)IOP | \(| \Delta \)IOP| 95% CI | 95% CI |
|-------------------|---------------------------------|--------------|----------------|-----------------|----------|----------|
| 5                 | 5.1 ± 0.3                       | 5.8 ± 0.5    | 0.7            | 0.9             | 0.6-1.2  |
| 10                | 8.5 ± 0.8                       | 9.1 ± 0.8    | 0.6            | 0.6             | 0.4-0.8  |
| 15                | 12.5 ± 0.5                      | 12.9 ± 0.7   | 0.6            | 0.5             | 0.3-0.7  |
| 20                | 16.2 ± 0.6                      | 16.4 ± 0.7   | 0.2            | 0.3             | 0.2-0.4  |
| 25                | 20.0 ± 0.4                      | 20.2 ± 0.6   | 0.2            | 0.4             | 0.3-0.5  |
| 30                | 24.0 ± 0.5                      | 24.4 ± 0.7   | 0.4            | 0.4             | 0.2-0.6  |
| 35                | 27.4 ± 0.7                      | 28.0 ± 0.7   | 0.6            | 0.6             | 0.4-0.8  |
| 40                | 31.3 ± 0.6                      | 31.7 ± 0.9   | 0.4            | 0.6             | 0.3-0.9  |
| 45                | 35.1 ± 0.3                      | 35.8 ± 0.8   | 0.7            | 0.7             | 0.5-0.9  |
| 50                | 38.3 ± 0.8                      | 39.0 ± 0.9   | 0.5            | 0.6             | 0.4-0.8  |
| 55                | 42.2 ± 0.7                      | 42.9 ± 0.7   | 0.7            | 0.8             | 0.6-1.0  |
| 60                | 46.1 ± 0.9                      | 46.8 ± 1.0   | 0.7            | 0.8             | 0.6-1.0  |
| 65                | 50.3 ± 0.8                      | 51.2 ± 0.9   | 0.9            | 1.0             | 0.6-1.4  |
| 70                | 54.2 ± 0.5                      | 55.0 ± 0.7   | 0.8            | 1.0             | 0.8-1.2  |
| 75                | 58.0 ± 0.4                      | 58.6 ± 0.2   | 1.5            | 1.7             | 1.1-2.3  |

### Abbreviations
- CI: confidence interval
- IOP: intraocular pressure
- \( \Delta \)IOP: mean IOP deviation (pressure by device minus manometric pressure) (algebraic accuracy)
- \(| \Delta \)IOP: IOP deviation regardless of signal (absolute accuracy)
- NA: not applicable or not available.

Listed in the Table. Compared with the absolute manometric pressure, DCT measures were not significantly different (P = .18, n = 1200). The GAT and PTG measures were both significantly different from the manometric pressure (P < .001, n = 1120), as shown in Figure 3.

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than the manometric pressure. The GAT and PTG showed consistently lower average values: \(-4.01\pm1.76\) mm Hg and \(-5.09\pm2.61\) mm Hg, respectively (Table and Figure 4, algebraic accuracy).

A precise assessment of the IOP is usually most critical in clinical situations in which the pressure range is between 10 and 25 mm Hg. Within this range, DCT showed an average of \(+0.33\pm0.49\) mm Hg; GAT, \(-3.43\pm1.24\) mm Hg; and PTG, \(-2.97\pm1.82\) mm Hg compared with manometric readings (algebraic accuracy). Although all 3 tonometers performed reasonably well in this range, the DCT was considerably more accurate. In fact, DCT was significantly closer to manometric pressure throughout all bottle heights than GAT and PTG, with values always less than .001. The GAT and PTG readings had not only a larger IOP error than DCT but also greater variability.

Scattergrams and linear regression were plotted for DCT, GAT, and PTG for pressure values in the ranges 8 to 25, 8 to 38, and 8 to 58 mm Hg, respectively, in the hope of finding a linear correlation between corneal thickness and IOP values. No significant correlation could be found between the real IOP and the degree of error of any of the tonometers. The strongest correlation was obtained in the range of 8 to 28 mm Hg with slopes of 0.001 for DCT (\(r=0.089\)), 0.003 for GAT (\(r=0.111\)), and 0.0014 for PTG (\(r=0.036\)). Given the relatively narrow range of CCT measurements due to artificially distributed corneal thickness, significant correlation would be difficult to obtain.

**COMMENT**

The results of this study strongly suggest that DCT is superior in accuracy in eye bank eyes to GAT and PTG across the range of IOPs likely to be found in clinical practice. Furthermore, the accuracy seems to be independent of corneal thickness and corneal curvature (within the limits of this study). In the low- and moderate-pressure range, inaccuracy of the GAT and the PTG was not great and not likely to be of major clinical significance, but also was not linear. However, in the range of 18 to 23 mm Hg, an underestimation of 3 or 4 mm Hg could be clinically problematic, and the increasing underestimation of IOP by PTG in the high-pressure range (35-58 mm Hg) might also be clinically significant.

Goldmann and Schmidt\(^1\) themselves pointed out that applanation tonometry would be affected by corneal rigidity and thickness and set the applanation diameter at 3.06 mm so that the effect of corneal elasticity in an “average” cornea would offset the effect of the capsular attraction of tears. On the basis of relatively small numbers of patients and optical pachymetry, they concluded that “most” patients had a CCT between 500 and 520 \(\mu m\). Ultrasonic pachymeters tend to give greater corneal thickness measurements than optical pachymeters, perhaps because the latter “ignore” the epithelium and endothelium. Recent studies have shown that there is a variation of almost 200 \(\mu m\) in corneal thickness.\(^\text{8,13-16,22,24}\) It is likely that significant errors may be introduced by applanation tonometers in corneas significantly different from the “average” that Goldmann and Schmidt assumed.

Performing applanation tonometry with the GAT on cadaver eyes is challenging and fraught with potential for error. Corneal epithelial abnormalities are some of the most common sources of error in applanation tonometry.\(^\text{35}\) Because corneal epithelium was susceptible to damage during our initial preliminary study, we decided to remove corneal epithelium thoroughly in all eyes used for the study.\(^\text{16,17}\) The effect of absence of corneal epithelium on the accuracy of GAT has not been investigated and is still unknown.\(^\text{19}\) To our knowledge, Goldmann did not describe how to adjust the mires for GAT performed on the Bowman layer directly. On freshly enucleated cadaver eyes with corneal thicknesses of 475 to 500 \(\mu m\), on which GAT has been shown to be most accurate (keeping in mind that approximately 50 \(\mu m\) of corneal epithelium is removed), we found the best correlation to the manometric intracameral pressure by using the semicircle adjustment seen in Figure 5. In the absence
of corneal epithelium, the usual fluorescein hemirings cannot be detected. We used full semicircles that were brought into an overlapping position of approximately twice the width that Goldmann and Schmidt proposed for the ring.24,32

Controversy exists regarding the method to manometrically measure IOP in cadaver eyes. Proponents of the closed stopcock technique claim greater accuracy.24,32 However, in an enucleated eye, any displacement of fluid such as occurs with application tonometry or PTG will first cause an elevation of IOP and then a slow decline (similar to tonography) due to leakage of fluid from the normal aqueous outflow pathways as well as the cut ends of choroidal and episcleral vessels. Finding the right point in this changing environment at which to determine the “true” manometric pressure is difficult if not impossible. Most studies have used average pressures or some kind of algorithm to peg the manometric pressure.23,24,32,38

In this study, we tried to address the issue of an open vs a closed stopcock system by using both methods in a preliminary study performed on 4 human cadaver eyes defined by the same inclusion criteria as in the main study. In the closed system, the stopcock is closed immediately before the pressure reading by whatever device to simulate in vivo conditions and to reduce the effect of pressure-dependent fluid leakage out of the eye (approximately 5 mm Hg/min at an IOP of 45 mm Hg, and 2 mm Hg/min at 20 mm Hg). Pneumatonometry especially causes the initial rise in pressure by as much as 10 mm Hg. It is problematic which manometric pressure to pick and compare with the IOP obtained by PTG and TPN. On average, both PTG and TPN underestimated IOP compared with the actual manometric IOP peak (−2.29 mm Hg and −3.98 mm Hg, respectively). The DCT showed no significant difference in accuracy with the closed and open stopcock system, probably because the DCT displaces a negligible amount of fluid from the anterior chamber. The similar results obtained with both open and closed stopcock systems suggest that our observations are valid.

In this cadaver eye model, DCT is more likely to be consistent with the manometric pressure than both GAT and PTG. The use of cadaver eyes as the model did not appear to affect the accuracy of DCT. The use of DCT was quick and easy. Since a value is given automatically by the strain gauge and the automatic software in the base station, there is less chance for observer bias with this system than with GAT. Similarly, PTG gives a more objective value.

The use of a cadaver model introduces some potential error, but, noting the very small $P$ values ($<.001$), DCT seems to accurately reflect the internal pressure. The data also suggest that DCT is unaffected by the loss of the corneal epithelium in this model. The DCT does seem to measure slightly higher than manometric pressure at markedly elevated IOP (70 mm Hg). It is possible that this slight inaccuracy may be due to changes in the corneal curvature as the pressure becomes very high. However, in the 3 eyes in which orbital topographic measurements were obtained, no such changes occurred in the anterior curvature. This was a very small sample and might not be representative of the whole group, or other unknown histopathologic changes in the anterior part of the cornea may have occurred that were not detectable by the orbital topography system in these stressed eyes. The device did detect a significant flattening in the posterior curvature of the cornea when the IOP was extremely high.

In eyes with very elevated IOP, both GAT and PTG measured consistently too low compared with manometry. Applanation tonometry is certainly known to be influenced by corneal thickness. The eyes used in this study reached a CCT of 462 µm after dehydration; this is approximately 60 to 80 µm thinner than in living conditions. Furthermore, the corneas are subject to thinning even more during the experiments because of the dextran environment and evaporation, perhaps explaining the consistently low GAT and PTG values. In this sample of cadaver eyes, regression lines showed very small slopes and no significant linear correlation between CCT and IOP as measured by any device. This suggests that even in very thin corneas, DCT maintains a satisfactory representation of true IOP.

These results strongly suggest that DCT is a promising technology that may afford more accurate IOP measurement across the range of IOPs found in clinical practice. Further studies are indicated to further elucidate the properties, usefulness, and accuracy of DCT in clinical situations.

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**CONCLUSIONS**

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