Effect of Central Corneal Thickness, Corneal Curvature, and Axial Length on Applanation Tonometry

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Objective: To evaluate the effect of central corneal thickness (CCT), corneal curvature, and axial length on applanation tonometry in an in vivo study.

Methods: In a masked, prospective clinical trial, we examined 125 eyes of 125 patients scheduled for cataract surgery. Corneal curvature was measured by means of keratometry and axial length by A-scan ultrasonography. By cannulating the anterior chamber before surgery, intraocular pressure (IOP) was set to 20, 35, and 50 mm Hg in a closed system by means of a water column. After measuring thickness, the IOP was measured with an applanation tonometer. Pearson product moment correlations and multiple linear regression analyses were performed, and significance levels were evaluated by the paired, 2-tailed t test.

Results: The difference between measured and real IOP was significantly dependent (P < 0.001) on CCT. The associations between IOP and corneal curvature or IOP and axial length were not statistically significant (P = .31). The association between IOP reading and CCT is shown in the “Dresdner correction table,” which illustrates an approximately 1-mm Hg correction for every 25-µm deviation from a CCT of 550 µm. The correction values were positive as thickness decreased and negative as thickness increased.

Conclusions: Central corneal thickness significantly affects IOP readings obtained by applanation tonometry according to the Goldmann principle. A correction of IOP readings by considering CCT according to the Dresdner correction table might be helpful for determining an accurate IOP value.


Intraocular pressure (IOP) represents a fundamental factor of ocular health and disease. Intraocular pressure is important not only in the diagnosis and management of glaucoma but also in the assessment of the postoperative course of all intraocular surgical interventions. For almost 50 years, applanation tonometry according to the Goldmann method has been the gold standard for the evaluation of IOP.1,2 Intraocular pressure measurements obtained with the use of a Goldmann applanation tonometer are affected by central corneal thickness (CCT), corneal curvature, and axial length.3,4 Normally hydrated, thicker corneas lead to higher readings and thinner corneas, to lower readings. The clinical significance of these observations has been demonstrated in studies5-8 that showed a lower CTT in some cases of normal-tension glaucoma and a higher CTT in cases of ocular hypertension and some cases of refractory glaucoma.

Empirical studies6,7,9-11 suggest a correction factor for applanation IOP readings of 0.19 to 1 mm Hg per 10-µm deviation from the average CCT. Those studies were based on comparisons of individuals and groups of patients with different CCTs without knowledge of the actual IOP. To our knowledge, only 1 study, published by Ehlers et al,12 used a manometric, controlled closed system in which the actual IOP was known. However, that study included only a small series of eyes. Therefore, the aim of the present study was to examine the effect of CCT, corneal curvature, and axial length on Goldmann applanation tonometry in a manometric, controlled closed system in an in vivo model with a larger number of subjects.

METHODS

In a masked, prospective clinical trial, we examined 125 eyes of 125 consecutive patients scheduled for cataract surgery. Thirty-three of the patients were men and 92 were women, with a mean ± SD age of 72.9 ± 13.2 years (range, 18-91 years) (Figure 1). No eye had undergone previous intraocular surgery or had an abnormality other than cataract. All subjects received an ophthalmologic clinical examination,
including slitlamp evaluation of the anterior segment. Patients with any corneal abnormality, such as scars or Fuchs dystrophy, were excluded. All included patients provided informed consent before entering the study, which was approved by the institutional ethics committee of the medical department at University Carl Gustav Carus, Dresden, Germany.

Keratometry was performed preoperatively using a keratometer, and axial length was measured by A-scan ultrasonography (Sonomed 2500; Technomed, Baesweiler, Germany). After the administration of peribulbar anesthesia, an eyelid retractor was placed and a cannula was passed into the anterior chamber at the temporal limbus. The CCT was measured by the first investigator (M.K.) using an ultrasonic pachymeter. The 0.8-mm opening of the cannula permitted access to the aqueous humor. The cannula was connected to an adjustable saline (balanced salt solution) reservoir. The IOP was directly calibrated by means of a water column at 3 different IOP levels (20, 35, and 50 mm Hg). After each IOP level was reached, the cannula was closed after 1 minute to maintain a closed system during the actual IOP measurements. The precorneal film was stained with fluorescein solution, and the IOP was measured with a Perkins applanation tonometer (Haag-Streit USA, ) at each IOP level by the second investigator (A.G.B.). To maintain masking, the first investigator measured the CCT and the second measured the IOP without knowing the CCT. All variables (IOP, corneal curvature, axial length, and CCT) were measured 3 times and the means were calculated.

Pearson product moment correlations were calculated between the IOP readings and the CCT, corneal curvature, and axial length. In addition, multiple linear regression analysis was performed for the IOP readings, implementing CCT, corneal curvature, axial length, patient age and sex, arterial hypertension, and diabetes mellitus into the model. Significance levels were evaluated by the paired, 2-tailed t test. \( P<.05 \) was considered statistically significant. All statistical analyses were performed with SPSS software, version 11.0 (SPSS Inc, Chicago, Ill). All data are presented as mean±SD unless indicated otherwise.

**RESULTS**

Mean CCT was 569±44 µm (range, 462-705 µm) ([Figure 2](#)), corneal curvature was 7.72±0.27 mm (range, 7.07-8.32 mm) ([Figure 3](#)), and axial length was 23.62±2.05 mm (range, 18.84-32.93 mm) ([Figure 4](#)).

At 20 mm Hg, the IOP readings varied from 16 to 27 mm Hg (mean, 20.86±1.99 mm Hg); at 35 mm Hg, these
ranged from 31 to 42 mm Hg (mean, 35.74±1.97 mm Hg); and at 50 mm Hg, from 45 to 55 mm Hg (mean, 50.5±2.01 mm Hg). We found a strong correlation between IOP and CCT at all IOP levels: at 20 mm Hg ($r^2=0.83; P<.001$), 35 mm Hg ($r^2=0.78; P<.001$), and 50 mm Hg ($r^2=0.75; P<.001$).

We found no correlation between IOP and corneal curvature at 20 mm Hg ($r^2=0.12; P=.41$), 35 mm Hg ($r^2=0.18; P=.37$), and 50 mm Hg ($r^2=0.09; P=.87$), and no correlation between IOP and axial length at 20 mm Hg ($r^2=0.09; P=.86$), 35 mm Hg ($r^2=0.09; P=.87$), and 50 mm Hg ($r^2=0.08; P=.35$). We cannot rule out that there might be a difference in K values (from the keratometry readings) preoperatively and perioperatively. However, if such an effect exists, the difference would be small and most likely cause an offset but not affect the correlation significantly. Therefore, this effect would be negligible with regard to the multivariate analysis.

At all IOP levels, patient age and sex, arterial hypertension, and diabetes mellitus had no significant effect on IOP readings.

The correlations between IOP and CCT, corneal curvature, and axial length at 35 mm Hg are shown in Figure 5. The correlation between CCT and the difference between real IOP and IOP measured by application tonometry at 35 mm Hg is shown in Figure 6.

Multiple regression analysis showed similar equations describing the relationship between IOP and CCT for the 3 different IOP levels. Implementing the data of all 3 different IOP levels (20, 35, and 50 mm Hg), multiple regression analysis revealed the equation $\Delta IOP = (-0.0423 \times CCT) + 23.28$. (The equations for all 4 regression lines are given in the legend to Figure 7.) Using this equation, we calculated correction values for application IOP readings for different CCTs (Table), which we termed the “Dresdner correction table.” Using our equation, $\Delta IOP$ is approximately 0 at a CCT of 550 µm. A residual analysis using Q-plots showed that the linear approach is appropriate. Non-linear models were also calculated, which did not improve the fit ($R^2$) significantly. Therefore, the linear approach seems to be the most appropriate.

A deviation of ±10 µm from a CCT of 550 µm resulted in a measurement error of ±0.4 mm Hg. In other words, a deviation from 550 µm of ±25 µm in CCT was related to a difference of approximately ±1 mm Hg.

When we used the equation $\Delta IOP = (-0.0423 \times CCT) + 23.28$, the corrected IOPs showed a better goodness of fit to the actual IOP compared with the uncorrected IOP readings. The correspondence between actual IOP and uncorrected IOP readings is shown in Figure 8. As shown, 49.4% of the measured values were in the clinically relevant range of ±1.5 mm Hg of the actual IOP, and 50.6% of the values showed a larger deviation. After correcting the IOP readings according to our formula, 92% of the corrected IOP values were in the clinically relevant range of ±1.5 mm Hg of the actual IOP, and only 8% of the values showed a larger deviation (Figure 9).

Intraocular pressure measurements by application tonometry were linearly correlated with CCT at different IOP levels. We found no correlation between IOP readings and corneal curvature at 20 mm Hg ($r^2=0.12; P=.41$), 35 mm Hg ($r^2=0.18; P=.37$), and 50 mm Hg ($r^2=0.09; P=.87$), and no correlation between IOP and axial length at 20 mm Hg ($r^2=0.09; P=.86$), 35 mm Hg ($r^2=0.09; P=.87$), and 50 mm Hg ($r^2=0.08; P=.35$). We cannot rule out that there might be a difference in K values (from the keratometry readings) preoperatively and perioperatively. However, if such an effect exists, the difference would be small and most likely cause an offset but not affect the correlation significantly. Therefore, this effect would be negligible with regard to the multivariate analysis.

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**COMMENT**

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A deviation of ±10 µm from a CCT of 550 µm resulted in a measurement error of ±0.4 mm Hg. In other words, a deviation from 550 µm of ±25 µm in CCT was related to a difference of approximately ±1 mm Hg.

When we used the equation $\Delta IOP = (-0.0423 \times CCT) + 23.28$, the corrected IOPs showed a better goodness of fit to the actual IOP compared with the uncorrected IOP readings. The correspondence between actual IOP and uncorrected IOP readings is shown in Figure 8. As shown, 49.4% of the measured values were in the clinically relevant range of ±1.5 mm Hg of the actual IOP, and 50.6% of the values showed a larger deviation. After correcting the IOP readings according to our formula, 92% of the corrected IOP values were in the clinically relevant range of ±1.5 mm Hg of the actual IOP, and only 8% of the values showed a larger deviation (Figure 9).
neal curvature or axial length. To our knowledge, ours is the largest study to prove the correlation between IOP readings obtained by applanation tonometry and CCT using an in vivo model in which the real IOP was known and the actual deviation could be measured.

Various studies\(^4\),\(^6\),\(^7\),\(^9\)-\(^11\) examining the correlation between IOP readings by applanation tonometry and CCT have reported a measurement error ranging from 0.19 to 1 mm Hg per 10-µm deviation from the average CCT. In the present study, the measurement error was 0.4 mm Hg per 10-µm deviation from 550 µm. Those studies,\(^4\),\(^6\),\(^7\),\(^9\)-\(^11\) in contrast to ours, used eyes previously classified as normal or as having ocular hypertension on the basis of IOP readings. A portion of the ocular hypertensive eyes actually may have had a normal IOP but a false high IOP reading owing to a thick cornea. This might lead to an underestimation of the effect of CCT on IOP measurement and might be responsible for the discrepancy between our results and those of population studies.

In a study by Ehlers et al,\(^12\) a manometric, controlled closed system was used to examine the correlation between CCT and IOP measured by applanation tonometry in 29 patients. Ehlers et al reported an error of ±0.71 mm Hg between real IOP and IOP measured by applanation tonometry per 10-µm difference in CCT. We obtained a smaller correction factor of ±0.4 mm Hg per 10-µm increment. This difference might be caused by the sample sizes (29 patients vs 125) and by the fact that, in contrast to our study, corneal curvature affected IOP readings in the study by Ehlers et al. In addition, real and measured IOPs were the same at a thickness of 520 µm in the study by Ehlers et al; in our study, they were the same at a thickness of 550 µm. This is an offset of 30 µm between studies, which is most likely caused by the use of different techniques for measuring CCT. Ehlers et al used an optical pachymeter, which provides lower readings than does ultrasound pachymetry (our method).

Orssengo and Pye\(^13\) introduced a mathematical model that examined the influence of corneal properties on measurements of IOP obtained by applanation tonometry. Their calculations were based on a normal CCT of 520 µm. They reported good agreement with the data of Ehlers et al. However, at lower IOP levels, the calculated model showed lower correction values, suggesting that the correction factor obtained by Ehlers et al was too high. This is in good agreement with our results.

Feltgen and coworkers\(^14\) attempted in vivo measurements with direct intracameral IOP readings and observed no correlation between CCT and IOP. They concluded that no recalculation of IOP according to CCT was necessary.\(^14\) However, in contrast to Ehlers et al and the present study, Feltgen et al used an open system rather than a closed one. Because an open system allows the aqueous humor to leave the eye, IOP is lowered during the measurement. This might explain the difference in their results.

**Table. Dresdner Correction Table Showing the Dependence of the Applanation IOP Reading on CCT**

<table>
<thead>
<tr>
<th>CCT, µm</th>
<th>Correction Value, mm Hg</th>
</tr>
</thead>
<tbody>
<tr>
<td>475</td>
<td>+3.19</td>
</tr>
<tr>
<td>500</td>
<td>+2.13</td>
</tr>
<tr>
<td>525</td>
<td>+1.07</td>
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<tr>
<td>550</td>
<td>+0.02</td>
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<tr>
<td>575</td>
<td>−1.04</td>
</tr>
<tr>
<td>600</td>
<td>−2.10</td>
</tr>
<tr>
<td>625</td>
<td>−3.16</td>
</tr>
<tr>
<td>650</td>
<td>−4.21</td>
</tr>
<tr>
<td>675</td>
<td>−5.27</td>
</tr>
<tr>
<td>700</td>
<td>−6.33</td>
</tr>
</tbody>
</table>

Abbreviations: CCT, central corneal thickness; IOP, intraocular pressure.
In contrast to other studies, we could not detect an effect of corneal curvature and axial length on applanation IOP readings. In addition, we examined 125 consecutive patients scheduled for cataract surgery; therefore, the distributions of corneal curvature, CCT, and axial length were random and not influenced by the investigators. Compared with the empirical studies by Mark et al\textsuperscript{16} and Mark,\textsuperscript{17} our study population did not show a wide scattering of corneal curvature (mean corneal curvature, 7.72±0.27 mm; range, 7.07-8.32 mm) or axial length (mean axial length, 23.62±2.05 mm; range, 18.84-32.93 mm). This distribution may have caused the lack of correlation between IOP readings, corneal curvature, and axial length. Therefore, a study with a similar design but with a wider scattering of these measurements seems necessary to determine whether corneal curvature or axial length has any effect on IOP measurements obtained by applanation tonometry. However, even if such effects exist, according to our data they would be minimal in comparison with the effect of CCT.

The mean CCT in our study of 569±44 µm (range, 4620-705 µm) was higher compared with earlier-reported measurements in the general population. Mean CCT has been reported to be 530±29 µm for optical pachymetry and 544±34 µm for ultrasound pachymetry\textsuperscript{7} and may depend on the technique used. Ultrasound pachymetry, which gives higher readings than does optic pachymetry, was used to determine CCT in our study. In addition, our study population was older (mean age, 72.9±13.2 years), and CCT tends to be higher in older patients.\textsuperscript{4}

In conclusion, the present study demonstrates that thin corneas lead to an underestimation and thick corneas, to an overestimation of application IOP. Corneal curvature and axial length do not have a significant effect on IOP readings obtained by applanation tonometry. A deviation in CCT of 25 µm away from a measurement of 550 µm results in a difference of approximately 1 mm Hg between real IOP and IOP measured by application tonometry. Using the equation \( \Delta \text{IOP} = (-0.0423 \times \text{CCT}) + 23.28 \), we can provide evidence for goodness of fit. In the present study, 92% of the corrected IOP values were within the clinically relevant range of ±1.5 mm Hg, and only 8% showed larger deviations.

Because CCT affects IOP readings obtained by application tonometry, we suggest that IOP readings be corrected by CCT according to the Dresdner correction table to get a good approximation of the real IOP in each patient. However, further studies are needed to validate the scale and to demonstrate its value for the management of glaucoma.

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