Accurate Intraocular Pressure Measurement—The Myth of Modern Ophthalmology?

Intraocular pressure (IOP) measurement is an important parameter in the detection and monitoring of glaucoma. On statistical grounds, a cut-off value of 21 mmHg is widely used to differentiate between normal and abnormal IOP. Measurement of IOP is assumed to be accurate, with the Goldmann applanation tonometer becoming the international gold standard for IOP measurement. It is also generally assumed that Goldmann tonometry is equally accurate in all eyes and is not influenced by ocular parameters such as corneal thickness and radius of curvature. However, this assumption is increasingly being called into question.

Measurement of IOP by applanation tonometry is based on the Imbert-Fick law, which states that the force required to flatten or applanate a sphere (W) is equal to the product of the pressure inside the sphere (P) and the area applanated (A): $W = P \times A$. It is assumed that the object must be dry, perfectly flexible, infinitely thin, and perfectly spherical.[1] For the eye, two other major forces are at work when one looks at the force required to flatten the cornea. The surface tension of the tear film (S) pulls the tonometer head toward the cornea and facilitates applanation. The corneal rigidity (B) is the force required to bend the cornea and resists applanation. Thus $W + S = PA + B$.

Goldmann and Schmidt[2] determined that the surface tension and corneal rigidity would nullify one another and therefore could be ignored when using a tonometer head 3.06 mm in diameter and a normal central corneal thickness (CCT) of 500 μm. The calculations assumed that the necessary pressure that is expressed on the cornea to flatten it would be equal for all corneas. However, if a cornea is thicker than the average cornea, then it seems sensible that a larger force would be required to applanate it. The converse could be true for thin corneas, where a smaller force would be required to applanate it. There is, however, debate as to whether this effect is significant in clinical practice, and most clinicians do not take the effect of ocular rigidity into account when measuring IOP because most assume that the effect is minimal.

The Rotterdam study[3] revealed a population with a mean CCT of 537 μm, however, there was a very wide (193 μm) difference between the minimum and maximum recorded CCT (range, 427–620 μm). This study demonstrated that the IOP in normal eyes appeared to increase by 0.19 mmHg per 10-μm increase in CCT. Bron et al's[4] population demonstrated a 0.32-mmHg change in IOP for a 10-μm change in CCT, whereas Shah et al's[5] demonstrated a 0.11-mmHg change in IOP per 10 μm CCT for the normal eyes. However, all of these studies had previously classified eyes as normal or ocular hypertensive based on the IOP. A proportion of the ocular hypertensive eyes could actually have a normal IOP but have an artefactually raised IOP measurement because of an increased CCT.[6] Therefore, one could expect that the estimation of the effect of CCT on IOP measurement, in these studies, could be inaccurate because the data analyzed may be skewed. This may underestimate the effect of CCT on IOP measurement and could explain the discrepancy between population studies and manometric studies.

Ehlers et al[6–8] performed a number of studies in the 1970s assessing the effect of CCT on IOP. In a manometric study,[8] they demonstrated that the average error of tonometry was 0.71 mmHg for a 10-μm deviation from the normal CCT of 520 μm. Johnson et al[9] reported a patient with a CCT of 900 μm with a manometric IOP of 11 mmHg, but when measured by applanation, the IOP had ranged from 30 to 40 mmHg while the patient was receiving maximum medical therapy. Whitacre[10] demonstrated, in a manometric study with the Perkins tonometer, an underestimation of IOP by as much as 4.9 mmHg in thin corneas, with thick corneas producing an overestimation by as much as 6.8 mmHg. This corresponded to a calculated range of 0.18 to 0.49 mmHg of change in IOP for a 10-μm change in CCT from the mean CCT. The lower value was for the entire population, whereas the higher value was if only the eyes with corneas thinner than 520 μm were considered. Thus, it would appear that the relationship of CCT on IOP is not linear.

The advent of excimer laser refractive surgery, where the cornea is thinned to correct myopia, has given further information on the effect of CCT on IOP, because the IOP in the same eye could be determined with two different corneal thickness measurements. Chatterjee et al[11] previously demonstrated a mean drop in IOP of 0.46 mmHg per 10 μm thinning of the cornea as measured by noncontact tonometry (NCT) in a study of 1320 eyes. A group from Naples[12] found 0.62 to 1.00 mmHg per 10 μm thinning of the cornea on NCT and 0.71 mmHg per 10 μm thinning of the cornea on Goldmann applanation tonometry.[13] They also believed that the change in radius of

curvature of the cornea had had some effect, as had previously been demonstrated by Mark[14] (a 1-diopter change in keratometry was believed to affect IOP by 0.34 mmHg). Recent work by Orssengo and Pye[15] has confirmed that the correction factor for applanation tonometry to give a true IOP depends on the anterior corneal radius, the CCT, and the applanated area.

A number of studies[4,5,16,17] have looked at the distribution of CCT according to diagnosis in primary open angle glaucoma (POAG), normal tension glaucoma (NTG), and ocular hypertension (OHT). It was found that there was a significant difference in the mean CCT of these three groups. In a study by Shah et al,[5] normal eyes had a mean CCT of 554 μm. The POAG eyes had a mean CCT of 550 μm, the NTG eyes had a mean CCT of 514 μm, and the OHT eyes had a mean CCT of 580 μm. If the maximum recorded IOP in these eyes is corrected according to Ehlers et al's[8] manometric data, 44% of the NTG eyes would be reclassified as having POAG and 35% of the OHT eyes would be reclassified as normal. Argus[18] found that 30% of the OHT eyes could be reclassified as normal, and Herndon et al[16] found this figure to be as high as 65%. If this misclassification is actually so common, this may explain the differing prevalence of NTG between different populations by a variation in the CCT between these populations.

The studies on the effect of CCT on IOP can only provide a guide on how inaccurate the measured IOP is compared with the true IOP. Correlation between these variables is probably nonlinear (as demonstrated by negative IOP measurements if full corrections are applied to the measured figures). It is also important to recognize that the available data are valid only on normal corneas, and therefore measurements on, for example, scarred and swollen corneas and eyes that have undergone penetrating keratoplasty, may not be affected the same way by changes in CCT.

The Goldmann tonometer is most accurate at 520 μm,[10] however, the mean CCT for a normal cornea would appear to be between 537 and 554 μm,[3–5,17] but will vary among the population being tested. Therefore data are difficult to extrapolate outside individual populations. The CCT for an individual eye varies during the day (mean, 7.2%; range, 2.1%–14.3%),[19] but it does not appear to vary significantly during working hours, and the diurnal variation in CCT does not contribute significantly to the diurnal variation in IOP.[20] The CCT also does not vary significantly with age in adult life.[3] Therefore, a single measurement of CCT is likely to be adequate as a guide to its effect on IOP.

The importance of the findings of the above studies is clear. It would appear that large numbers of eyes could have been misclassified based on the IOP. A large number of patients may not be treated as well as they could be. Patients with OHT may be overinvestigated and overtreated, and this could be avoided by a simple test. Patients with NTG and also POAG could have appropriate target IOPs based on corrections from their calculated CCT. As a rough guide (with an overview of published studies), it can be taken that a 10-μm difference in CCT from the population mean (usually approximately 550 μm) means approximately a 0.5-mmHg difference between measured and true IOP with Goldmann tonometry. It is the author's opinion that changes in CCT affect NCT more than Goldmann tonometry, which in turn has been shown to be affected more than IOP measured using the Tono-Pen (BioRad Inc., Glendale, California) [Shah. Presented at the annual meeting of the American Academy of Ophthalmology, New Orleans, Louisiana, November 1998]. It has been suggested that the IOP measurement method using the ocular blood flow machine is not affected by changes in CCT. This has yet to be confirmed. Pachymetry has previously been suggested as helpful in cases where the clinical findings do not match the measured IOP. There would appear to be adequate information to suggest routine measurement of CCT to help in cases of suspected glaucoma to obtain the correct diagnosis and then to ensure that there is optimum management. Previous pressure-based studies of glaucoma outcomes may be flawed, because the measured IOP would not necessarily have been the true IOP. The financial implications of purchasing a pachymeter are easily offset by the global savings achieved by the optimum treatment of patients.

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If Intraocular Pressure Measurement Is Only an Estimate—Then What?

Most measurements we make of our patients are estimates. Refractions, whether automated or subjective, visual field thresholds, optic disc topography, axial lengths—all are subject to a variety of errors that mask the "true" value we would really like to know. Tonometry has always suffered from multiple sources of error. In the days of indentation tonometry, scleral rigidity was understood to be a common source of error, and repeating the test with a different weight on the Schiotz tonometer was a way of guessing how severe the error was. Applanation tonometry is far less prone to error, but we all realized that we should not depend on the result in patients with irregular corneas or epithelial edema. The Tono-Pen (BioRad Inc., Glendale, California) is generally understood to be less dependable with intraocular pressure (IOP) measurements out of the normal range.

An astute clinician recognizes the sources of error and makes adjustments in the interpretation of the test result. At times, it is prudent to repeat the test, if the source of error is likely to be nonrecurring. On other occasions, the test result may be ignored or discounted. On still others, it may be appropriate to adjust the test result to account for a known source of error.

In the companion editorial, Shah[1] presents evidence that central corneal thickness is a potentially large source of error in applanation tonometry. He attempts to make the case that we should measure central corneal thickness (CCT) in every patient to correct the IOP value. Before we rush to such a judgment, it may be wise to look at the evidence from a different perspective, for we may reach a different conclusion.

Shah points out that the literature suggests a range of error for Goldmann applanation tonometry between 0.11 and 0.71 mmHg for every 10 μm of deviation from a normal CCT measurement. Interestingly, recent cross-sectional studies have indicated a range of normal CCT between 537[2] and 550[3] μm, whereas Goldmann and Schmidt's[4] calculations for the Goldmann applanation tonometer assume a normal CCT of approximately 500 μm, and Ehlers et al's[5] conversion factor is based on a normal CCT of 520 μm. Thus if we are to adopt a conversion factor, we must first agree on what is the normal value from which deviations should be corrected.