Tonometry: Does historical precedent and familiarity constrain development?

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Introduction

Community optometrists rely heavily on guidelines and protocols to direct their clinical decision making. Busy practitioners, unlikely to critically appraise research, rely on governing bodies to discriminate evidence and disseminate concise implementations. The 16-page 'Quick Reference Guide'[1] synopsises the recommendations, but not the critiqued supporting evidence, of the full NICE guidance on the diagnosis and management of chronic open angle glaucoma.[2] This document, based largely on the evidence from major longitudinal studies, synopsised by the European Glaucoma Society,[3] states that patients should be offered Goldmann Applanation Tonometry (GAT) (Figure 1) for measurement of intraocular pressure (IOP) and pachymetry as part of the diagnostic process. NICE[2] further emphasise that GAT remains the 'gold standard' for tonometry, albeit with a correction for central corneal thickness (CCT), since this is well established as a strong predictive factor for conversion to frank glaucoma.[3-5]

International Standard ISO 8612 for tonometers states that new tonometers must be tested against the reference standard, GAT.[6] Since no instrument can be assured to be perfectly accurate, such a comparison can suggest higher variability for the instrument being assessed.[7] The Guideline Development Group of NICE considered evidence for other tonometers, but the status of GAT as 'reference standard' was not disputed. The exercise was to consider whether other tonometers demonstrate acceptable agreement to GAT rather than accuracy in measuring true intracameral IOP. The group also cite 'expert opinion', lowest on the evidence hierarchy, to support the continued use of GAT as the reference standard. Yet Whitacre and Stein[8] state categorically that acceptance of the accuracy of GAT is unwarranted and Brandt[9] considers our ability to accurately measure IOP is far weaker than imagined and we rely on a flawed measure on which to base clinical decisions. Is historical precedent and familiarity therefore helping to falsely maintain GAT as 'gold standard'?

Historical milestones: expert opinion, reference standards and the introduction of GAT

Digital palpation tonometry became an essential skill for all ophthalmologists after Bowman first reported its importance in 1826.[10] Mechanical tonometers appeared from the early 1860s and included the Maklakoff Applanation Tonometer and the Schiotz, introduced in the early 20th Century.[11] These innovative approaches to IOP measurement were met with scepticism[11] and as late as 1908 Isador Schnabel, discussing mechanical tonometry, told the Vienna Ophthalmology Society 'to expect little from this test since digital tonometry by an expert is a much more accurate test'.[9] Over a century later it is easy to consider this statement risible, but it was ingenuous and reflected contemporary expert opinion. Chakrabarti and co-authors[10] suggest that ophthalmologists of the time felt so confident with their palpation skills that mechanical devices were considered inferior. A consideration of the refinements made by Goldmann half a century later may support their scepticism.

Goldmann's first paper describing his refined version of an applanation tonometer appeared in 1955 (not cited). GAT was certainly the result of a methodical and analytical assessment of the variables involved in IOP measurement in the 1950s. Schmidt[12,13] convincingly argues the Goldmann tonometer to be superior to all previous applanation tonometers, as well as the Schiotz. However, the author was only considering the application of the technique. Variables that could be controlled or eliminated included machine variables, which were reduced from 20 with the Schiotz to with the Goldmann.[12,13] Operator variability could only be minimised by correct and accurate application of technique. Likewise physiological variability of individual corneae, an area of immense current interest, was normalised but could not be eliminated. For all the refinements incorporated in the Goldmann, Schmidt still acknowledged that the ideal tonometer would be a compensated membrane manometer.

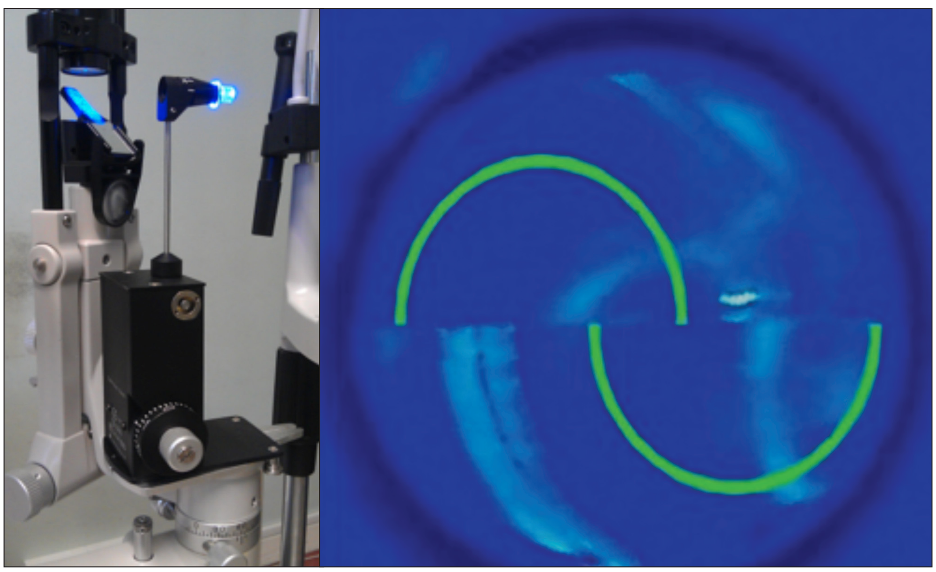

Figure 1
The well-known Goldmann Applanation Tonometer (GAT)

A flawed standard?

GAT and its many non-contact mimics rely on the 'Imbert Fick' principle, not a law but an explanation for applanation tonometry where none of the assumptions are true.[8] The Imbert-Fick principle states that 'the pressure inside a sphere is roughly equal to the external force needed to flatten a portion of the sphere divided by the area of the sphere which is flattened'.[14] The term 'roughly' immediately suggests errors in the fundamental principle on which GAT is based.

The very act of applanating a sphere increases the pressure inside; the larger the applanation zone the larger the artificial change in internal pressure.[12] Practical application of the principle is further compromised by the fact it only applies to surfaces that are perfectly spherical, dry, flexible, elastic and infinitely thin.[14] While a formulaic compensation for the force tending to push the applanating surface away from the eye was incorporated, other variables such as CCT and corneal curvature had to be normalised but cannot be considered constants. Goldmann and Schmidt assumed a uniform CCT of 500µm.[8] Operator variability, a very significant problem[8] was not considered, a totally objective method not being available in the 1950s. The arguments presented by Schmidt[12,13] are compelling and convincingly support GAT as a worthy gold standard for its time. However, our far more precise and ever growing understanding of corneal biomechanics demands a more radical reappraisal of techniques.

A reappraisal: the conundrum of corneal biomechanics

Brandt[9] suggests that a failure to question techniques has led to the proposal of a variety of hypotheses to explain variations. He argues that the incorporation of CCT into our IOP estimations represents the beginning, not the culmination, of tonometry refinement. Certainly Hager et al[15] and Boehm et al[16] emphasise the number of nomograms proposed to adjust GAT readings for CCT and indicate that none are satisfactory. Brandt[9] further questions the simplistic CCT correction, stating no correction algorithm has been validated, and without validation clinicians cannot use the data. Brandt et al[17] report correction factors by various authors ranging from 2.0mmHg per 100µm change in CCT, to 7mmHg per 100µm. These authors further indicate that a linear correction for CCT is an oversimplification; using linear nomograms, they suggest, could lead to a negative value of IOP in specific cases. Brandt et al[17] consider the question on correcting for CCT as open, while Doughty and Zaman[18] argued that CCT has been adopted as a standard much by repeated usage.

It would seem the introduction of a CCT correction factor is a bid to maintain a flawed instrument and that the correction factor itself is flawed. The paper by Gordon and co-workers[4] was pivotal to the acceptance of CCT in the management of glaucoma.[9] However, these authors reported that CCT was not an initial consideration but was included later when it was observed that thick corneae caused over-estimation of true IOP. A cautionary note that CCT may be inter-related with other factors was included. However, the correlation between CCT and IOP measurements was established. Factors such as corneal biomechanics and corneal curvature were not considered and CCT appears to have become, by default, an accepted global index of corneal biomechanics. Never-the-less, corneal shape and biomechanics are recognised to affect the accuracy of GAT and its non-contact mimics.[8,15,19-21] Presumably thicker corneae would also demonstrate different biomechanical properties, explaining why a simple correction for CCT is problematic.

While an historical review does implicate CCT as a confounder of IOP measurement,[22] the advent of refractive surgery exponentially increased the observed inaccuracies with GAT.[19,23] Certainly refractive procedures significantly modify CCT, but the magnitude of the reduction in measured IOP post-refractive surgery is not easily reconcilable to reduced CCT in isolation.

GAT depends on factors other than CCT, including biomechanics of the cornea and corneal curvature,[19] not considered as possible effect modifiers by Gordon and colleagues. Since the end point of the applanation process is a plane surface,[8,14] the clinically observed reduction in IOP post-corneal refractive surgery must be due to exaggerated corneal flattening as well as corneal thinning or changes in biomechanical properties.

While CCT has gained credence as a confounder to accurate IOP measurement since the 1970s, shape was recognised as a potential source of error from the earliest introduction of GAT,[8] and is incorporated into recommended procedures when measuring IOP on astigmatic corneae. Of much greater potential significance is the role corneal biomechanics plays on IOP measurement. Liu and Roberts[24] estimated that, for normal corneae, the range of IOP variation attributable to the variables of corneal radius, CCT and corneal biomechanics were 1.76mmHg, 2.87mmHg and 17.26mmHg, respectively. This was based on a mathematically modelled system, Young's Modulus being used as the measure of corneal biomechanics. Regardless of possible errors in the model, recognised by the authors, these results highlight the need to pursue other avenues of research. It could in fact be argued CCT is simply a contributing factor to overall corneal biomechanics, as would be collagen rigidity or stromal hydration, and should not be considered a separate variable at all.

Future innovations

The potential significance of corneal biomechanics as a confounder to accurate IOP measurement must be a priority for

Figure 2
The Pascal dynamic contour tonometer mounted on a conventional slit lamp

Figure 3
The measurement probe of the Pascal dynamic contour tonometer. Note that the probe tip is concave

research. The model proposed by Liu and Roberts[24] considered normal corneae, but Grabner and colleagues[25] describe a plethora of corneal interventions that profoundly affect corneal properties. Ablation and incisional techniques, wedge resections and thermal effects on collagen lamellae as well as riboflavin cross linking (as used in keratoconus treatment) all affect corneal biomechanics, making a single correction factor for GAT unrealistic.

It would seem that accurate tonometers of the future must either bypass the cornea completely or incorporate measures that comprehensively model the biomechanical properties of individual corneae. Kakaday et al[26] describe a number of techniques to bypass the cornea; all involve surgery and would only be considered for patients already diagnosed with glaucoma or at risk of conversion. For screening and diagnostic purposes the ability to model individual corneae would seem essential.

Holographic Interferometry,[27] Dynamic Corneal Imaging[25] and Corneal Strain Imaging[28] all assess corneal responses to deformation. The corneal response, it is postulated, reflects its individual biomechanical properties. Available now are two highly innovative tonometers; the Dynamic Contour Tonometer (DCT) and the Ocular Response analyser (ORA), both of which strive to tackle the problem of CCT and biomechanics. DCT (Figure 2) does not consider the Imbert-Fick principle but rather the actual physical Law of Hydrostatic Pressure by Pascal.[29] This law states that 'pressure exerted anywhere in a confined incompressible fluid is transmitted equally in all directions throughout the fluid such that the pressure ratio remains the same'.[30] The cornea is gently moulded to the shape of the concave tonometer probe (Figure 3), at which point the pressure on either side of the cornea is equal; the force needed to achieve this is believed to exactly counterbalance the force of IOP.[16]

Kanngiesser et al[29] stress that the corneal shape on which the probe contour is modelled is idealised but indicate this sufficiently matches the physiological range of human corneae. Surgically modified corneae were considered and the authors acknowledged that, theoretically, each cornea requires a bespoke contour-matched tip. Just as Goldmann had to normalise for CCT, the DCT seems to necessitate normalisation for corneal shape. Kanngiesser et al[29] and Boehm et al[16] only sampled physiologically normal eyes; anatomically altered corneae, whether pathological or surgical, are always the most problematic and are unlikely to conform to these rules.

The ORA (Figure 4), while still a non-contact air-puff tonometer and consequently a GAT mimic, has exponentially advanced the applanation process. This machine records two applanation readings. The first traditional measure is taken as the air pressure increases and the convex cornea is flattened to a plane surface. After this first measure, the cornea continues into a concave shape before returning to its natural configuration via a second plane surface, allowing a further recording to be made. Significantly, the inward acquisition reading does not correspond to the outward acquisition. Luce[31] and Luce and Taylor[32] suggest the difference between these two readings is caused by the delay created by the viscous damping of the cornea. The term corneal hysteresis (CH) has been coined for this new measure, which the authors advocate characterises corneal biomechanical integrity; it allows for a corneal compensated IOP (IOPcc) reading uninfluenced by CCT to be obtained.

Luce and Taylor[32] only consider CCT and corneal biomechanics; corneal shape was not a consideration. These investigators presented data suggesting IOPcc is only minimally lower in patients having undergone LASIK corneal refractive surgery, apparently confirming a new measure independent of CCT. Liu and Roberts[24] found corneal shape to be the least significant of the three variables considered, although only physiologically normal corneae were considered. Ablation of the cornea, as occurs in refractive surgery, must influence the reading of any machine using the applanating technique. Corneal shape, particularly surgically manipulated shape, needs to be convincingly discredited as a possible confounder or incorporated into future developments. If corneal shape could be mathematically modelled, after varying degrees of refractive surgery, a nomogram compensating for shape alone could be the final refinement to maximise the accuracy of machines like the ORA.

Figure 4
The Ocular Response Analyser (ORA) and computer

Conclusion

While there is enough evidence to suggest that GAT is a flawed standard upon which to base clinical decisions, it is reasonably priced and space efficient. Furthermore Drexler and Fujimoto[33] commented that clinicians do not accept new instrumentation that increases the time and cost of examination. As such, is it likely that a replacement to GAT will be received with open arms? Familiarity and trust over a 50-year period, in the face of mounting evidence to the contrary, is helping to maintain the unquestioning acceptance of GAT as the most accurate method of clinically measuring IOP. At the research level it would appear that the verdict on the value of GAT is answered. Its replacement is slightly more elusive, whilst breaking tradition will be harder still.

About the author

Peter Frampton studied optometry in Brisbane, Australia, and moved to the UK in 1986. He attained a Masters Degree in ocular therapeutics from Bradford University and has additional supply, supplementary prescribing, and independent prescribing qualifications. He is also a Fellow of the College of Optometrists and is currently doing his Ophthalmic Doctorate at Aston University.

References

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