The technology used to estimate intraocular pressure has evolved tremendously since Sir William Bowman emphasized the importance of ocular tension measurements. In an address delivered at the 1826 meeting of the British Medical Association, Sir William underscored the critical role that digital estimation of ocular tension played in his practice. (In this case the term “digital” refers to palpation of the eyes using the fingers – the digits.)

Soon afterwards, digital palpation tonometry became an essential clinical skill to be mastered by all ophthalmologists. When mechanical tonometry was first introduced in the late 1800s, many ophthalmologists felt so confident with their ability to estimate IOP by palpation that they viewed the new technology as inferior. Schnabel, in a 1908 address to the Vienna Ophthalmological Society, stated that although he did not object in principle to mechanical tonometry, he expected “…very little from this test since digital tonometry by an expert is a much more accurate test.”

Impression tonometry

Although Albrecht von Graefe is credited with the first attempts to create instruments that mechanically measured IOP in the early 1860s, his proposed instruments were neither designed nor built. Rather, it was Donders who designed the first instrument capable of estimating IOP – albeit not accurately – in the mid 1860s. The principle behind Donders instrument was to displace intraocular fluid by contact with the sclera. Ophthalmologists first measured the curvature of the sclera at the site of contact and then used the measurement as a reference plane to measure the depth of indentation produced by the tonometer. Smith and Lazerat refined this technology in the 1880s, and the discovery of cocaine by Carl Koller in 1884 led the way to corneal impression tonometry. Using corneal anesthesia, corneal tonometry became the definitive choice for IOP measurement because it offered a well-defined and uniform site of impression.

The major shortcoming of impression tonometry was that it displaced so much fluid upon contact with the eye that the measured readings were highly variable and mostly inaccurate. What was needed was a way to displace a minimal amount of fluid to record IOP.

Indentation (Schiotz) tonometry

This type of tonometry uses a plunger to indent the cornea. IOP is determined by measuring how much the cornea is indented by a given weight. The test is less accurate than applanation tonometry and is not commonly used today by ophthalmologists and optometrists. However, some family medicine or urgent care doctors still use the Schiotz tonometer. The first commonly used mechanical tonometer was designed and introduced by Hjalmar Schiotz in the early 1900s. The instrument was simple, easy to use, and relatively precise. It was quickly accepted and became the new gold standard beginning the 1910s. (Fig 1)

Innovations in calibration led to its increased use, and a tremendous amount of knowledge about the normal and glaucomatous eye was quickly acquired.
Applanation Tonometry

This breakthrough came in 1867 when Adolf Weber designed the first applanation tonometer that gave a highly defined applanation point without indentation. After two decades of skepticism, the value of applanation tonometry was re-discovered when Alexei Maklakoff and others introduced new versions of applanation tonometers. (Fig 2)

In the early 20th century, there were about 15 tonometer models in use. (Fig 3) However, digital palpation tonometry remained the “gold standard” among most ophthalmologists during the early 1900s.

Goldmann introduced an adjustment for ocular rigidity in the 1950s, which led to the development of the Goldmann applanation tonometer. (Fig 4) The Goldmann tonometer displaces so little fluid that variations in ocular rigidity were then thought to be mostly negligible.

Goldmann applanation tonometry

The Goldmann applanation tonometer (GAT) is a variable force tonometer, which makes a static measurement of the force required to flatten a fixed area of the cornea. For the past fifty years, it has been considered to be the clinical gold standard in IOP measurement. When Hans Goldmann designed the tonometer, he recognized that certain corneal effects (e.g., resistance to deformation) would influence pressure measurements. (Fig 5) Therefore he based his calculations on the resistance to deformation of an average corneal thickness (520 microns) and estimated that the resistance to deformation would be cancelled by the surface tension generated by the pre-corneal tear film when the area applanated had a diameter of 3.06 mm.

Facts on Applanation Tonometers

- Assumptions (Imbert-Fick Law)
  - CCT = 520um and consistent
  - Surface tension
  - Corneal / Scleral rigidity
- Measurement variability: +/- 3mmHg
- Based on Imbert-Fick principle
  - Pressure = force/area
- 0.1g force to applanation head 3.06mm = 1 mmHg
- Surface tension and ocular rigidity
  - Negate each other
- BUT, assumption of CCT 520um....
- Other factors: corneal curvature, elasticity

Non-contact Tonometry (NCT)

Non-contact (also called air-puff) tonometers do not touch the eye because they use a puff of air to flatten (applanate) the cornea. Once initiated, the puff force increases until the cornea is applanated by a predetermined amount. The tonometer then translates this force into a measure of IOP.

Because the air puff tonometer relies on corneal applanation, (Fig 6) it is subject to the same potential measurement errors induced by variations in corneal properties, as is the Goldmann tonometer.

Principle of NCT

The NCT was the brainchild of Grolman and was introduced in 1972. A puff of air creates a constant force, which momentarily deforms the cornea. It is difficult to determine the exact nature of corneal deformation, although it is postulated that the central cornea is flattened at the moment the pressure measurement is made.

Types of NCT

1. Table mounted – Xpert NCT
2. Hand held - Pulsair tonometer from Keeler

Pneumatic System

Generates a puff of room air which is directed against the cornea.

At the moment the central cornea is flattened, the greatest numbers of reflected rays are received, which is recorded as the peak intensity of light detected. The time from an internal reference point to the moment of maximum light detection is converted to IOP based
on prior comparison with readings by Goldmann tonometry. In the newer version the force of air required to achieve peak light detection is the measured variable when air puff is automatically triggered on meeting the alignment criteria.

**Fallacies with NCT**

The time interval for an average measurement is 1 to 3 ms (1/500th of the cardiac cycle) and is random with respect to the phase of the cardiac cycle, so that the ocular pulse becomes a significant variable and it cannot be averaged as with other tonometers. Glaucomatous eyes have significantly greater range of momentary fluctuations in IOP. It is recommended that more than 3 readings within 3 mm Hg range be taken and averaged as IOP.

This phenomenon can be directly observed by viewing pulsation of mires during Goldmann tonometry. (Fig. 7) (To some degree, Goldmann takes this pressure variation into account because measurements are made when the inner aspects of the pulsating mires just touch.) In some individuals, IOP can vary as much as 5 or 6 mm Hg within one second while the choroid fills and empties. The NCT has no ability to determine at what point in an individual’s intraocular pressure cycle the IOP was measured.

**Accuracy**

Comparisons against Goldman applanation tonometers indicate that NCT is reliable within normal IOP range. The reliability is reduced in the higher pressure ranges and is limited by abnormal corneas and poor fixation. One study indicated that central corneal thickness has a greater influence on NCT than on Goldmann tonometry.

**Advantages**

- comfort
- no contamination
- no chance of corneal abrasion
- no reactions to topical anesthetics
- of value in mass screening and in studies of newer antiglaucoma drugs

**Caution**

There have been reports of sub epithelial air bubbles after repeated use of NCT.

NCT is a safe and reliable method of measuring IOP. Caution to be used when measuring glaucomatous eyes as lower pressure may be recorded at IOPs above the normal range as in abnormal corneas.

**Problems with the application standard**

Until the late 1990’s, the Goldmann applanation tonometer enjoyed an unchallenged 45-year reign as the “gold standard.” However, two thought provoking events caused many to begin questioning whether GAT was measuring true IOP in a variety of situations: the acceptance and use of refractive surgery, and publication of the Ocular Hypertensive Treatment Study (OHTS) results.

- Thin cornea = risk for progression
  - Ocular Hypertensives (OHTS)
  - POAG
  - Normal Pressure Glaucoma (NPG)
- GAT underestimates IOP in these eyes (and overestimate in thick cornea)
  - Mounting evidence regarding GAT inaccuracies

**Refractive Surgery and Applanation Error**

As soon as radial keratotomy (RK) became commonplace, Ophthalmologists observed differences in pre- and post-operative Goldmann IOPs. Commonly, IOP was found to decrease by 3 to 5 mm Hg after surgery. Similar observations were made with newer refractive technologies such as Photorefractive Keratectomy (PRK) and Laser Assisted In-Situ Keratomeilusis (LASIK).

Some observers accounted for this apparent pressure decrease exclusively in terms of the decrease in central corneal thickness caused by the PRK and LASIK surgery. However, with the case of radial keratotomy (RK), a decrease in CCT could not explain the IOP changes because RK causes no decrease in CCT. Indeed, one could argue that post-RK corneas often show increased CCT resulting from varying degrees of corneal edema.
**OHTS, CCT, AND GAT**

Although the central theme of the well-known Ocular Hypertensive Treatment Study was an analysis of the tendency for ocular hypertensives to convert to primary open angle glaucoma (POAG) over time (with or without treatment), it was also an opportunity to observe the effect of variables other than IOP in this tendency. CCT was one variable measured in OHTS subjects.

Among the results of this portion of the study, the investigators reported that they had observed an increased propensity to convert from ocular hypertension to POAG in those individuals who had comparatively low CCT (under 545 microns). They suggested that an error in GAT imposed by variability in CCT might cause an under- or over-estimation of IOP when measured with Goldmann.

**Applanation Tonometry and Central Corneal Thickness**

Given the compelling results of the OHTS, it seems quite natural that investigators would start to look closely at the true impact of CCT on the Goldmann measurement.

Ironically, in the early 1950’s, Hans Goldmann revealed in his renowned (but seldom read) publications that IOP measurements with his tonometer could be seriously flawed if the subject’s corneal biomechanics did not fulfill certain stringent criteria. CCT was one of the significant criteria that Goldmann discussed.

A commonly used CCT correction formula was published by Ehlers. The fundamental supporting concept for this correction formula is that as corneas get thinner, GAT reads too low. If CCT is “average,” GAT is essentially correct. And, if the cornea is thicker than average, GAT overvalues true manometric IOP.

Other IOP correction formulae beyond Ehlers’ formula have also been developed. Below, is a simplified version of the Orssengo-Pye Formula that has been advocated by James Tsai and Stephen Trokel at Columbia University.

\[
\text{Corrected IOP} = \text{Measured IOP} - \left( \frac{\text{CCT} - 545}{50} \right) \times 2.5 \text{ mm Hg}
\]

Corrected IOP = Measured IOP – (CCT-545)/50 x 2.5 mm Hg

This simplified formula instructs the clinician to correct IOP by 1.0 mm Hg for every 20 microns of CCT variation from the 545 standard. For example, a patient with a 645-micron cornea has a 5 mm Hg Goldmann overestimation and a patient with a 445-micron cornea has a 5 mm Hg underestimation.

However, as is usually the case with most biological functions or processes, things are not so simple as these formulae and correction tables suggest. Newer investigations have shown that the formulae represented an incorrect and sometimes dangerous oversimplification of the complex relationship between corneal biomechanics and IOP.

**A Problem with CCT-based Corrections – Corneal Elasticity**

An easy way to think of corneal elasticity is in terms of relative corneal rigidity or softness. Reliable GAT measurements rely on average corneal rigidity. When the cornea is more rigid than average, GAT reads too high, and, when the cornea is softer than average, GAT reads too low.

Some corneal scars, high CCT (without edema or refractive surgery), and microcornea can cause a cornea to be unusually rigid. The circumstances that can cause a cornea to be unusually soft seem to be more common.
Low CCT
Edematous corneas – regardless of CCT
Children under age 7 – regardless of CCT
High corneal diameter
History of any corneal refractive surgery – regardless of CCT
Endothelial dystrophies
Epithelial dystrophies

Can we do better than the 50 year old “Gold Standard?”
In view of recent investigations, interest in tonometry has increased and research engineers were charged with the mission of developing a better understanding of various corneal properties and their respective influences on GAT measurements, as well as developing new techniques to more accurately determine true IOP.
With these goals in mind, the technology has taken two different directions: the Reichert Ocular Response Analyzer and The PASCAL Dynamic Contour Tonometer (Ziemer Ophthalmic Systems, AG, Switzerland) have been developed.

The Reichert Ocular Response Analyzer (ORA)
The Reichert Ocular Response Analyzer utilizes a “dynamic bi-directional applanation process” to measure both the biomechanical properties of the cornea and the IOP. The basic output is a Goldmann-correlated applanation pressure measurement (IOPG) and a measure of corneal tissue properties called corneal hysteresis (CH), which is related to viscous damping in the corneal tissue. The CH measurement also provides a basis for two additional parameters measured by the ORA: the corneal-compensated intraocular pressure (IOPCC) and the corneal resistance factor (CRF).
IOPCC is an IOP measurement designed to be less affected by corneal properties than is IOP measured by Goldmann or NCT. IOPCC has essentially a zero correlation with CCT in normal eyes and stays relatively constant pre-versus post-LASIK.

CRF appears to be an indicator of the overall “resistance” of the cornea to applanation and is significantly correlated with CCT and GAT, but not with IOPCC.

Understanding hysteresis: elastic, viscous, and visco-elastic materials
In order to understand the Ocular Response Analyzer, a brief discussion of properties of visco-elastic materials will be presented. Elastic materials are those for which strain (deformation) is directly proportional to stress (applied force) independent of the length of time or the rate at which the force is applied. Therefore, if the elastic modulus of a structure (e.g., a steel beam) is known, one can easily predict the amount of force required to bend it a specific amount.
Viscous materials are those for which the relationship between strain and stress depends on time or rate of force application.
The human cornea is a complex visco-elastic structure.
The corneal hysteresis measurement is an indication of viscous damping in the cornea. In other words, it is related to the ability of the cornea to absorb and dissipate energy. Subjects whose corneas exhibit low CH can be thought of in simple terms as having a “soft” cornea.

Operation of the Ocular Response Analyzer
The ORA utilizes an air pulse to apply force to the cornea and an advanced electro-optical system to monitor the resultant corneal deformation. Alignment to the patient’s eye is fully automated.
A precisely metered, collimated air pulse causes the cornea to move inwards, past applanation, and into a slightly concave shape. Milliseconds after applanation, the air pump shuts off and the pressure declines in a smooth fashion. As the pressure decreases, the cornea begins to return to its normal configuration and once again passes through the applanated state. An applanation detection system monitors the cornea throughout the entire process and pressure values are recorded for the inward and outward applanation events.
Fig 1. Schiotz Tonometer.

Fig. 2. Maklakoff’s original tonometer, circa 1885.

Fig 3. Maurice applanation apparatus, circa 1951.

Fig 4. Dr. Hans Goldmann and the Goldmann applanation tonometer.

Fig 5. An older prototype model of the Goldmann Applanation tonometer

Fig 5 An applanated cornea showing a reading of 20

Fig 6. The original AO (Reichert) non-contact tonometer.

Fig. 7. Intraocular pressure pulsation.

Fig 8. Reichert Ocular Response Analyzer

Fig 9. The difference between “inward” applanation pressure and “outward” applanation pressures defines corneal hysteresis.
One might initially expect these two pressure values to be the same. However, viscous damping in the cornea causes delays in the inward and outward applanation events, resulting in two different pressure values. The average of these two pressure values provides a repeatable, Goldmann-correlated IOP value (IOPG). The difference between these two pressure values is corneal hysteresis (CH). The ability to measure this effect is the key to understanding the biomechanical properties of the cornea and their influence on the IOP measurement process.

**CH, CRF, and IOPCC: New Ocular Parameters**

Ongoing clinical studies over the past three years have shown that CH is a function of corneal properties and not an artifact of any other variable. Corneal hysteresis is a phenomenon that results from the dynamic nature of the air pulse and the viscous damping inherent in the cornea.

The corneal resistance factor is also derived from this response. CRF is a measurement of the cumulative effects of both the viscous and elastic resistance encountered by the air pulse while deforming the cornea. CRF exhibits the expected property of increasing at significantly elevated pressures.

Although CH and CRF are related, in some instances they are significantly different, and each provides distinct information about the cornea. Corneal-compensated IOP is a pressure measurement that utilizes information provided by the corneal hysteresis measurement to provide an IOP value that is less affected by corneal properties.

Although the manufacturer of the ORA cannot yet claim to be measuring “true intraocular pressure,” early investigations have demonstrated that IOPCC is a better indicator of the real IOP than traditional NCT or GAT can provide. 17

**The Pascal – Dynamic Contour Tonometer (DCT)**

Dynamic contour tonometry (DCT) is a novel measuring technique using the principle of contour matching instead of applanation to eliminate the systematic errors
inherent in previous tonometers. These factors include the influence of corneal thickness, rigidity, curvature, and elastic properties.

The PASCAL is a relatively new device that uses DCT to measure IOP. Although this device is similar in appearance to a Goldmann, the PASCAL® it is unlike Goldmann applanation in that it is not a variable force tonometer. PASCAL uses a miniature pressure sensor embedded within a tonometer tip contour-matched to the shape of the cornea. The tonometer tip rests on the cornea with a constant appositional force of one gram. This is an important difference from all forms of applanation tonometry in which the probe force is variable.

When the sensor is subjected to a change in pressure, the electrical resistance is altered and the PASCAL’s computer calculates a change in pressure in concordance with the change in resistance.

The contour matched tip has a concave surface of radius 10.5 mm, which approximates the cornea’s shape when the pressures on both sides of it are equal. This is the key to the PASCAL’s ability to neutralize the effect of intra-individual variation in corneal properties. 18-21

Once a portion of the central cornea has taken up the shape of the tip, the integrated pressure sensor begins to acquire data, measuring IOP 100 times per second. A complete measurement cycle requires about 8 seconds of contact time. During the measurement cycle, audio feedback is generated, which helps the clinician ensure proper contact with the cornea.

**Conclusion**

Today, digital palpation tonometry has largely been replaced by more sophisticated technologies used to estimate IOP. Today’s instruments are far more accurate and easier to use. Yet, sometimes, there is no good substitute for palpation tonometry. For example, some optometrists and ophthalmologists may still have to rely on digital palpation to estimate IOP in patients who are uncooperative.

**References**

2. Schnabel I., Klin Montasbl Augenh 1908; 48:318
14. Carolyn Y. Shih, MD; Joshua S. Graff Zivin, PhD; Stephen L. Trokel, MD; James C. Tsai, MD - Clinical Significance of Central Corneal Thickness in the Management of Glaucoma Arch Ophthalmol. 2004;122:1270-1275
15. Liu and Roberts, JCRS, JCRS 31, Issue 1, p 146-155 (January 2005)


22. Pacific Optometry Continuing Education Programme: Intraocular Pressure And Glaucoma, Kirstein 28.08.2006 08:32 Uhr