



Review Article

Intraocular pressure measurement techniques: Current concepts and a review

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ABSTRACT

According to the World Health Organization, glaucoma is the leading cause of irreversible blindness worldwide. Although intraocular pressure (IOP) is not considered any more to be a defining feature of the disease, its lowering remains the only treatment option for glaucoma. Therefore accurate and precise measurement of IOP is the cornerstone of glaucoma.

Intraocular pressure is a highly dynamic physiological parameter with individual circadian rhythms. The main limitation of current tonometry methods remains the static and mostly office-based nature of their measurements.

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1. Introduction

Intraocular pressure (IOP) is one of the most critical risk factors and the only modifiable one in glaucoma. Several major clinical trials have shown that even small increases in IOP may lead to visual field damage and the development and progression of glaucoma.¹ Therefore accuracy and precision in measuring IOP are important requirements to predict and monitor disease progression.²

Through non invasive tonometry, IOP is estimated as a transcorneal pressure gradient rather than directly measured, as there is currently no safe and practical way to measure it invasively.

Normal IOP is due to a balance between aqueous inflow and its outflow by trabecular and uveo-scleral pathways.

Non pigmented ciliary epithelium secretes aqueous humor at a rate of 2–3 μL per minute. In humans, anterior chamber volume is estimated to be ~250–300 μL . Turnover rate of aqueous humor is ~1% of anterior chamber volume (~2.5 μL per minute).

Actually there is no fixed IOP value above or below which it can be said that damages can occur or not. But still

IOP continues to be the one factor which can altered to treat this condition of glaucoma in patients.

In normal individuals, IOP varies by 2–6 mm Hg over the course of a 24-hour period as aqueous humor production changes. Higher IOP is associated with greater fluctuation and a diurnal fluctuation > 8 mmHg is suggestive of glaucoma. Many people reach their peak IOP in the morning hours, but others do so in the afternoon, in the evening, or during sleep, still some follow no reproducible pattern

Recent innovations in the methods of tonometry have led to many devices, each with different advantages and clinical applications. These advances have focused on estimating the biomechanical properties of the cornea, such as central corneal thickness (CCT) and corneal curvature, as they may confound the accuracy of tonometry. Thus, the aims of newly developed tonometers have been to (1) Obtain a measurement that accurately and precisely resembles the “true” IOP, as established via invasive methods, (2) Characterize corneal biomechanical factors to determine not only the “true” IOP but also their importance in determining disease progression, and (3) Provide ease of use and practicality both in the clinical office and in patient’s homes.

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The major benefit of each device is described, along with the setting in which each is the most accurate and beneficial. Currently, Goldmann applanation tonometry (GAT) is widely considered to be the reference standard, to which all other tonometers are compared.

2. Types of Applanation Tonometers

2.1. Variable area (fixed force applanation tonometer)

2.2. Variable force (fixed area applanation tonometer)

Applanation tonometry is based on a modification of the Maklakoff-Fick law, also referred to as the Imbert-Fick law.³ This law states that an external force (W) against a sphere equals the pressure in the sphere (P_t) multiplied by the area flattened (applanated) by the external force (A) $W = P_t \times A$.

The validity of the law requires that the sphere should be (a) perfectly spherical (b) dry (c) perfectly flexible and (d) infinitely thin. The cornea fails to satisfy any of these requirements, in that it is aspherical and wet, and neither perfectly flexible nor infinitely thin. The moisture creates a surface tension (S), and the lack of flexibility requires a force to bend the cornea (B), which is independent of the internal pressure. In addition, because the cornea has a central thickness of approximately $550 \mu\text{m}$, the outer area of flattening (A) is not the same as the inner area (A_1). It was, therefore, necessary to modify the Imbert-Fick law in the following manner to account for these characteristics of the cornea: $W + S = P_t A_1 + B$.

When A_1 equals 7.35 mm^2 , S balances B and W equals P_t . This internal area of applanation is obtained when the diameter of the external area of corneal applanation is 3.06 mm , which is used in the standard instrument. The volume of displacement produced by applanating an area with a diameter of 3.06 mm is approximately 0.50 mm^3 , so that P_t is very close to P_0 , and ocular rigidity does not significantly influence the measurement.

3. Sources of Error with Goldmann Tonometry

GAT has potential sources of error. The appropriate amount of fluorescein is important because the width of the semicircle meniscus influences the reading. Wider menisci cause falsely higher pressure estimates. Improper vertical alignment (one semicircle larger than the other) will also lead to a falsely high IOP estimate.

The mathematical calculation for Goldmann applanation tonometry is based on a presumed average CCT of $520 \mu\text{m}$.⁴ Deviations from the average CCT are a source of error with corneal edema underestimating the true IOP, whereas variations of CCT in normal corneas can lead to falsely higher pressure readings with thicker corneas and falsely lower ones with thinner corneas. After refractive surgery, the IOP is lower due to a thinner cornea as a result of laser-



Fig. 1: Procedure of goldmann applanation tonometry

assisted in situ keratomileusis (LASIK)

Goldmann applanation tonometry measurements have also been noted to be rather inaccurate with various types of corneal irregularities. With marked astigmatism, the applanated area is elliptical, instead of circular. To minimize the resulting measurement error, the tonometer can be used at 43 degrees to the meridian of the axis of the minus cylinder.

In summary, GAT remains the most widely used instrument of tonometry, but corneal structural factors are a major limitation to its accuracy. Attempts have been made to establish

specific formulas to calculate the influence of CCT on IOP measurement, but no consensus has been reached regarding the use of these formulas in clinical practice.⁵ Because GAT is still the reference standard despite its limitations, it remains the method to which the other types of tonometry described further in this review will be compared.

4. Perkins Handheld Tonometer

The Perkins tonometer was developed as a portable version of GAT that does not require a slit-lamp mount. It is essentially a Goldmann tonometer with a magnifying glass instead of a microscope enabling the reading of the mires. Thus, it is useful for IOP measurement in some patients unable to be positioned at the slit lamp, for example, children, patients who must be supine, and anesthetized patients.⁶ The Perkins handheld tonometer has similar advantages and disadvantages as the GAT, as they use the same principle of tonometry. The accuracy of the Perkins tonometer is similar to that of GAT, with a mean difference between the two of 1.0 mm Hg . Theoretically; the Perkins tonometer may be even more reliable in obese patients and those performing Valsalva manoeuvre at the slit lamp, because GAT is affected by transitory changes in IOP

related to inspiratory and expiratory changes in intrathoracic pressure.

The Perkins tonometer also has good reliability, in a study comparing various tonometers to GAT, it was found that the Perkins tonometer had the second lowest variability, with 59% of its measurements within 2 mm Hg.⁷ Therefore, the Perkins tonometer is a reasonable option for portable tonometry, because of its similarity in measurements compared with GAT.

5. Noncontact Tonometer

The noncontact tonometer (NCT), also known as the pneumatic applanation tonometer, is a tonometer in which the applanating force is provided by air. A rapid impulse of pressurized air causes transient applanation of the cornea, whereas a weak laser beam is reflected by the surface. The amount of light reflected during the applanation period is compared with the time during which the air puff causes applanation, which determines the electronic measurement of IOP.

The NCT has many advantages, including possible patient preference, more automation, and the benefit of no direct contact and thus no risk of transmission of infectious agents.

In a recent study comparing multiple tonometers, Cook et al. determined that modern versions of the NCT had the least variability in IOP; more than 60% of its IOP measurements were within 2 mm Hg of the measurement provided by GAT.⁷

The NCT may be even more influenced by CCT than GAT. The correlation with GAT readings is better with thinner corneas, as thicker corneas typically yield higher IOP measurements with the NCT than with GAT. Another limitation is that patients may squeeze their eyelids, as a reflex in anticipation of the air puff, which may hinder the measurement.

6. Ocular Response Analyzer

The ocular response analyzer (ORA) is the most modern version of noncontact tonometry. It provides characterization of parameters related to corneal biomechanical factors. It provides measurements of IOP that have been adjusted for some of these factors. Similar to noncontact tonometry, the ORA uses an impulse of air as the applanating force and an almost-instantaneous electro-optical system to take measurements. It records 2 IOP values at the point the cornea is flattened: the first while the cornea is moving inward by the force of the air column (inward applanation), and then second while the cornea is returning to its baseline (outward applanation). Because of its biomechanical properties, the cornea provides resistance during these movements, and thus the 2 pressure values are different. This difference is termed corneal hysteresis

(CH), which is assumed to account for the effects of corneal viscoelasticity.⁸ It is almost constant throughout the day and it is unassociated with refractive error or axial length. However, because the ORA does not measure corneal displacement but rather represents the difference between the 2 peak applanation pressures, the biomechanical implication of “corneal hysteresis” reported by the ORA remains ambiguous.

Besides CH, the ORA provides 3 other values as part of its readout: the Goldmann-correlated IOP, corneal-compensated IOP (IOPcc), and the corneal resistance factor (CRF). The IOPcc provides an IOP reading that is less affected by corneal structural factors (particularly CCT), compared with GAT measurements. In fact, Ehrlich et al suggest that IOPcc may be superior to GAT IOP in the clinical evaluation and management of primary open-angle glaucoma. In a study involving 153 eyes of 78 subjects without glaucoma and without topical hypotensive medications, CCT was determined to be significantly correlated with GAT IOP, but not with IOPcc.⁸

As discussed above, a hypothetical advantage of the ORA is its design intended to minimize the influence of corneal properties on IOP measurement. There is no need for contact and thus no need for topical anesthesia or tip sterilization. It also minimizes user bias via automatic electronic input and digital readout. With respect to glaucomatous eyes, Sullivan-Mee et al found clinically acceptable measurement repeatability and reproducibility among GAT, the ORA, and the DCT.²

Mollan et al determined that the ORA is one of the most accurate tonometers to use with keratoconus.⁹ Corneal hysteresis may even aid in the diagnosis of keratoconus.

With post refractive procedures, the literature states that GAT on average underestimates IOP. The ORA was determined to be more accurate than GAT in this setting. In addition, as has been found with keratoconus, the ORA provides supplementary, clinically applicable information by specifying CH; eyes status post laser-assisted in situ keratomileusis (LASIK) and other refractive surgeries show significantly decreased CH, which may be related to weakening of the corneal tissue surface.

Despite the important clinical data provided by the ORA and the substantial accuracy of the tonometer in several ophthalmologic settings, there are still several limitations to its use, namely, related to practicality. The instrument must be placed on a table and thus is not portable, and because of its complicated electro-optical system, it requires frequent maintenance.

Although the ORA provides a measure of CH and CRF, direct measurement of the corneal dynamics, such as the displacement of the cornea (strain) in response to an external pressure (load), has not been attainable in vivo. Overall, however, the ORA is a reliable and clinically useful tonometer, with moderate to good reproducibility in

different settings.

7. Corvis ST

The Corvis ST (Corvis ST; Oculus, Arlington, Wash) is a novel NCT that allows investigation of the dynamic reaction of the cornea to an air impulse. It consists of an ultrahigh-speed Scheimpflug camera equipped to record the movements of the cornea. The CST gathers 4330 frames per second within a 100- millisecond period, therefore recording dynamic deformation of the cornea to calculate the IOP value. Its measurement range is from 1 to 60 mm Hg. The complete theory behind the CST has not been published yet, but it is designed to measure IOP as well as corneal thickness and biomechanical properties. With frame by frame analysis of the corneal images, parameters, including corneal deformation amplitude, corneal applanation length, and corneal velocity, can be quantified and analyzed, providing insights into the biomechanical properties of the cornea and its impact on IOP measurement. There are limitations in the way the CST measures the response to corneal deformation. Similar to the ORA, it cannot determine the load-unload (pressure) displacement. The current CST software measures only corneal displacement, but not the corresponding load during the deformation, and therefore, it cannot measure corneal elasticity and CH directly.

A recent study has shown good agreement with GAT. Leung et al.¹⁰ have recently investigated the test-retest variability of the CST. They showed that the main CST parameter, corneal deformation amplitude, had a low test-retest variability, associated with age, IOP, and CCT, and was more influential than CCT in GAT measurement.

8. MacKay-Marg Tonometer

The MacKay-Marg tonometer has a design that involves a 5-mm diameter disc with a 1-mm central plunger; this design allows for improved stabilization of the tip and thus more accurate measurements. It may be more accurate than GAT in eyes with irregular corneas. It correlates well with other applanation tonometers and is perhaps less influenced by corneal properties than GAT, because the method in obtaining measurements with the former is mechanical (instead of optical, as with the latter). The MacKay-Marg tonometer is a very accurate and precise tonometer to date, but for various reasons, GAT has superseded its popularity, and this tonometer is no longer manufactured.¹¹

9. Tono-Pen XL

A descendant of the MacKay-Marg tonometer, the Tono-Pen XL (a newer model of the original Tono-Pen) has advantages of its portability, independent battery source of power, and ease of calibration and operation. It includes a digital readout, which minimizes user bias, and requires

a minimum of four measurements to increase precision. As part of its readout, the Tono-Pen XL also includes a coefficient of variation: ideally, the value must be less than 5% for the measurement to be considered accurate. The instrument allows measurements in both the supine and sitting position, as probe orientation has no significant effect on IOP measurements.

Ease of use also applies to tip sterilization; disposable latex covers are used, which decreases the chance of transmission of infectious agents. The Tono-Pen XL is able to record IOP through bandage contact lenses, which is useful for eyes that are covered in the setting of chemical burns, neurotrophic keratopathy, and other situations in which the contact lens should not be removed. In addition, the tip of the Tono-Pen XL has a smaller contact area than does GAT (2.36 versus 7.35 mm² for the latter). It is controversial whether this smaller tip decreases or increases its accuracy in eyes with irregular corneas, compared with GAT.¹² It has not been found to be as accurate or as precise as the MacKay- Marg tonometer. Horowitz et al¹³ determined that for IOP measurements less than 20 mm Hg, the Tono-Pen XL agrees well with GAT, but for IOP measurements greater than 20 mm Hg, the Tono-Pen XL shows significant underestimation.

Salvetat et al¹² demonstrate the opposite: for higher IOP Measurements, they recorded overestimates. Also they found that increased CCT correlated with underestimation of IOP with the Tono-Pen XL. Similarly, other corneal structural abnormalities, such as keratoconus, demonstrate significant difference in measurement, when comparing the Tono-Pen XL to GAT (mean overestimation by 3.6 to 10.1 mm Hg). With eyes status post keratoplasty, however, the Tono-Pen shows an acceptable level of agreement with GAT (mean difference of 0.14 mm Hg). Therefore, accuracy of the Tono-Pen XL has yet to be determined conclusively.

10. Pneumotonometer

A pneumatic sensor that floats on a piston of air indents the cornea slightly via a membrane resistor, and IOP is recorded when the pressure applied by the tip equals the pressure in the anterior chamber, and the measurement is provided in a digital readout or can be traced on graph paper for real-time data. In other words, PT measures the air resistance in the input line. Real-time IOP measurements can be followed, over the course of 5 to 10 seconds, while the probe is on the eye. The newer models of PT do not use air canisters but use an air pump so that replacement of canisters is no longer a problem.

A distinct advantage of the PT involves accuracy and ease of use with abnormal corneas. It can reliably measure IOP in contact lenses wearers as well as in patients with corneal scarring/edema or patients with barely visible corneas (eg, post tarsorrhaphy). Similarly, the PT can be used safely with neurotrophic corneas, as actual contact with

the cornea is extremely minimal (due to the air column upon which the tip floats). The PT has been determined to be more accurate than GAT in eyes status post LASIK. It may also be more accurate than GAT in young eyes, which makes it particularly useful in cases of pediatric glaucoma. Pneumotonometer is portable and does not need a slit-lamp mount, and its probe orientation does not affect accuracy of IOP measurement.

Despite reports of improved accuracy compared with GAT, some studies¹⁴ have found that the PT underestimates IOP at lower ranges and overestimates IOP at higher ranges in respect to GAT. Also, multiple studies have found that the PT is significantly correlated with CCT. Overall, the PT provides an easy-to-use and relatively accurate tonometry device, especially in eyes with abnormal corneal pathology. It is the only tonometer able to measure IOP with nystagmus and tremor. It is a preferred device for use in 24-hour IOP sleep laboratories because of its accuracy, ability to measure IOP in the supine body position, and recordable measurements.

11. Types of Indentation Tonometers

The principle behind indentation tonometry, also known as impression tonometry, is that a force will indent into a soft object further than into a hard object. Thus, for the eye, the higher the IOP, the harder it is (i.e. the more weight that is required) to push against and indent the cornea.

12. Schiøtz Tonometer

The Schiøtz tonometer is portable, sturdy, relatively inexpensive, and easy to operate. The instrument is accurate over a wide range of IOPs, although pressures may vary from those obtained with GAT, particularly when relatively untrained examiners are administering the test.¹⁵ An important concern is that placing the heavy tonometer (total weight at least 16.5 g) on the eye raises IOP. The rise in pressure reflects the dispensability of the ocular coats, a property termed ocular rigidity. All of the tables that relate the change in volume to the IOP assume a normal ocular rigidity, and this introduces a substantial error for some measurements. Eyes with high ocular rigidity (e.g. high hyperopia or long standing glaucoma) give falsely high Schiøtz IOP readings, whereas eyes with low ocular rigidity (e.g., myopia, strong miotic therapy, retinal detachment surgery) give falsely low Schiøtz IOP readings. It is possible to estimate ocular rigidity by comparing applanation and Schiøtz measurements or by repeating the Schiøtz measurements with two or more weights using the Friedenwald nomogram. Recent data based on cadaver eye experiments suggest that the Friedenwald nomogram may have some errors and that there is a larger increment of volume change per unit pressure than was found by Friedenwald.¹⁶

The Schiøtz tonometer may also affect the IOP estimation by altering the outflow facility, rate of aqueous humor formation, episcleral venous pressure and blood volume of the eye.

The Schiøtz pressure reading is also influenced by the size of the foot plate hole and the thickness and curvature of the cornea.



Fig. 2: Procedure of schiøtz tonometry

13. Electronic Schiøtz Tonometer

The electronic Schiøtz tonometer has a continuous recording of IOP that is used for tonography. The scale is also magnified, which makes it easier to detect small changes in IOP.

14. Rebound Tonometer

The iCare rebound tonometer (RT), is a handheld, battery-operated instrument that uses a lightweight magnetized probe to make brief, light contact with the eye. The magnet induces a voltage in a solenoid, which uses the speed of the deceleration on impact with the eye to estimate IOP. The deceleration is more (versus less) rapid with higher (versus lower) IOP. The contact with the eye is so momentary that topical anesthesia is not required.

The second reason for which no anesthesia is required is that the RT requires much less force to applanate the cornea compared with the force required by GAT. The RT is portable and can be easily used by non specialized personnel and uses disposable tips. It requires 6 measurements and, after discarding the highest and lowest readings, automatically determines mean pressure and SD. Also, RT IOP measurements near the corneal periphery correlate well with readings done at the centre. Also, it may allow for easier measurements of postsurgical or pathologic corneas, even when GAT is not able to acquire readings.

Newer model of the I Care is usable in supine position; However, there are conflicting reports regarding accuracy.

Several studies show that the RT, compared with GAT, slightly overestimates IOP,¹⁷ with some groups reporting a difference as low as 0.6 mm Hg and others finding a difference up to 7.7 mm Hg in eyes with higher IOPs. Central corneal thickness has been found to affect IOP measurements, by affecting the impact of the magnetized probe; the instrument overestimates readings in thick corneas, of both non glaucomatous and glaucomatous eyes. The RT has also been found to be dependent on other corneal parameters, such as CH and CRF, but not others, notably corneal curvature. There may be less repeatability with the RT, compared with GAT, because the former has such brief contact with the ocular surface. The reading acquired may be of any point during the IOP pulse cycle.

Practical difficulties of using the RT include its limited use in only upright patients (as the pin falls out if the instrument is pointing down) and its cost associated with the disposable pins. However, it does not account for the effects of corneal biomechanical properties on IOP.

15. Transpalpebral Tonometry

Since the identification of intraocular pressure as a risk factor for glaucomatous damage, attempts have been made to measure IOP through the eyelid, obviating the need for topical anesthetic and the risk of eye-to-eye transfer of pathogenic organisms.

In addition to all the problems facing indentation tonometry, such as scleral rigidity, transpalpebral tonometry adds variables such as the thickness of the eyelids, orbicularis muscle tone and potential intrapalpebral scarring. Recently, two attempts have been made to develop more quantitative transpalpebral IOP measuring devices. The TGDc-01 (Envision Ophthalmic Instruments, Livonia, Michigan, USA) was developed in Russia and bases its measurement on a weight falling within the instrument onto the closed eyelid and the amount of indentation it causes. Initial studies suggested good correlation with Goldmann tonometry, but more rigorous, controlled studies suggest that, at least in a significant minority of patients not identifiable prospectively, the accuracy is limited.¹⁸

Furthermore, interobserver and intraobserver variability was large, making the readings unreliable for most clinical purposes.

Fresco¹⁹ had an ingenious idea – that pressure on the eyelid in most eyes produces retinal phosphenes. The pressure on the eyelid required to induce these phosphenes is proportional to the intraocular pressure. He then developed this into a usable Transpalpebral tonometer – the Proview (Bausch & Lomb, Rochester, NY, USA) and found good correlation with GAT.¹⁹

Other studies raised the promise that patients could measure their own IOP at home, or wherever they were, and obtain information about their diurnal IOP variation that would be useful in managing their glaucoma.

16. Dynamic Contour Tonometer

The DCT, also known as the Pascal tonometer, was developed in 2005 as a digital, slit lamp mounted instrument that is assumed to be less independent of corneal effects than other tonometers. It uses the principle of contour matching, instead of applanation; the tip has a tight-fitting cover in the same shape as the cornea, with a pressure sensor in the center that measures IOP 100 times per second. Therefore, the tip avoids deforming the cornea during the measurement process, which theoretically circumvents the influence of CCT and other important corneal properties. However, abnormalities in corneal curvature may affect the measurement, given that the tip has the shape of the normal cornea. From the multiple real-time readings, the instrument determines the average IOP and the ocular pulse amplitude, which is the difference between the average systolic and diastolic IOPs. The ocular pulse amplitude reflects choroidal vessel filling and thus could be interpreted as a measure of ocular blood flow. The DCT also provides an automated quality check, with a score ranging from 1 (optimal) to 5 (unacceptable).

The tip was designed for the advantage of minimizing error from corneal structural properties, especially CCT, when compared with GAT. On average, GAT has been found to underestimate the true IOP by 4 mm Hg, whereas DCT readings have been higher and of better estimation of this true value. In a study²⁰ with 2157 participants to determine the effects of corneal properties on GAT and the DCT, Francis et al determined that the DCT was less affected by CCT but still influenced by corneal curvature; however, the effect of corneal curvature on DCT remained less than the effect of CCT on GAT. In keratoconus, postkeratoplasty and post-LASIK eyes, the DCT is particularly accurate when compared with GAT likely because the former is less influenced by corneal structural changes after these procedures. In glaucomatous eyes, the DCT was found to have good measurement repeatability and reproducibility when compared with the ORA and GAT.

Goldmann applanation tonometry had the greatest intra observer repeatability, followed by the DCT and then the ORA. Sullivan-Mee et al² tested GAT, the DCT, and the ORA simultaneously on subjects with primary open-angle glaucoma, normal-tension glaucoma, ocular hypertension, and glaucoma suspect. They found significant differences in mean IOP readings among the 3 tonometers and thus concluded that the IOP values measured by the different instruments are not interchangeable. Via multi regression analyses, they found that the most consistent confounders of this difference among tonometers are CH and CRF, which are measured by the ORA. This finding is expected, as the ORA reads IOP values over a longer duration compared with the other tonometers and thus would be more affected by corneal structural factors such as viscoelasticity. Of note, while corroborating a relative lack of influence by corneal

factors on DCT measurements, Milla et al²¹ found that the DCT did not correlate well with GAT at the extremes of corneal thickness; optimal agreement was found at CCT between 540 and 545.

The DCT is not without its practical limitations. The tonometer is slit lamp mounted so it lacks portability, and then disposable tips add an extra expense. To obtain the repeated measurements and averages, the tip must be in contact with the cornea for at least 5 seconds. Also, clinicians need special training to learn proper technique in its use. However, the literature thus far demonstrates its potential as an accurate and useful tool, especially in situations in which IOP may be more difficult to obtain using GAT or other more established tonometers.

17. Continuous IOP Monitoring

Intraocular pressure is a dynamic parameter with a circadian rhythm and spontaneous changes. Diurnal sitting IOP fluctuations of 4 to 5 mm Hg in healthy individuals and substantially higher in some glaucoma patients are common. There is evidence that single IOP measurements in the sitting position during normal office hours reflect neither the true range of an individual's IOP nor the peak IOP or variation throughout the day. Studies that measure IOP several times over the entire day find that approximately two-thirds of glaucoma patients had their highest IOPs outside regular clinic hours, most frequently during the nocturnal/sleep period.²² It has been suggested that a suboptimal approach to IOP assessment may account for nearly one-third of treated glaucoma patients showing progressive vision loss.

The development of ambulatory, frequent, round-the-clock IOP measurement methods has been pursued for several decades.

These attempts have been pursuing two different strategies: (1) permanent IOP monitoring and (2) temporary IOP monitoring.

Downs et al²³ adapted an existing implantable telemetric pressure transducer system to monitor IOP in nonhuman primates. They showed that the system was able to provide accurate and continuous IOP monitoring for several months. However, the implantation of the transducer system requires extensive surgical intervention involving the orbital bone and insertion of a tube inside the anterior chamber. At present, human data are lacking for this approach. Todani et al²⁴ were able to measure IOP continuously using a ring-shaped intraocular sensor placed in the lens capsule of rabbit eyes for up to 25 months. Their results are promising, and data from human trials are eagerly awaited. The main impetus behind the development of this device was the inability to measure IOP in patients after keratoprosthesis surgery who often would suffer from uncontrolled (unmeasurable) IOPs. The current approach for IOP estimation in these patients remains digital IOP

assessment, an extremely imprecise method, which predates indentation tonometry. Currently, the main limitation of all approaches to permanent continuous IOP monitoring is the safety associated with surgical implantation.

Combining IOP sensors with intraocular lens used in routine cataract surgery may facilitate patient acceptance. However, certain risks have to be addressed before these technologies can obtain regulatory approval for clinical use in humans. These include the potential for device failure after implantation, leakage of potentially toxic materials when hermeticity of the intraocular device is breached, and inaccuracy of measurements due to signal drift over time with the necessity of subsequent intervention for recalibration.

Another drawback is that the group of patients who could benefit from this approach would be restricted to those requiring intraocular surgery.

Temporary IOP monitoring is an alternative to the permanent approach with three potential advantages: (1) no surgical implantation, (2) easy reversibility, and (3) widespread availability to patients. Leonardi et al.²⁵ introduced a soft contact lens sensor (CLS) with embedded strain gauges that measure ocular dimensional changes (Triggerfish). The device is based on the assumption that small changes in ocular circumference measured at the corneoscleral junction correspond to changes in IOP and intraocular volume. Manometry studies in enucleated eyes have shown that the device's signal correlates well with true IOP, but similar experiments *in vivo* have not been completed. The device is approved for clinical use in Europe. It received FDA approval in march 2016.

The main challenges with this device is to understand how its measurements correlate to IOP change. The SENSIMED Triggerfish CLS is a soft silicone contact lens with intelligent elements such as strain gauges and an application-specific circuit embedded in it.

The software uses blinking patterns for automated detection of sleep times (gray zones). Analysis software is also available for detection of acrophase and mesophase to determining how to interpret the sheer volume of data the device produces in a 24-hour period. Approximately 300 data points are acquired during a 30-second period, every 5 minutes, providing a total of 288 measurements over a 24-hour period. The major value of the device is that it can record IOP in an outpatient setting for up to 24 hours including during undisturbed sleep.

Two prospective clinical studies investigated the safety and tolerability of the first-generation CLS in healthy subjects and glaucoma patients. In both series, the device was judged to be safe, with the main adverse effects being superficial corneal staining and conjunctival hyperemia, occurring in about half of studied individuals.^{26,27}

The device's main limitation is the fact that its output signal is provided in relative units corresponding to

millivolts. At present, it is not known how these would translate into the widely used scale of millimeters of mercury (mm Hg), making clinical decisions challenging. Furthermore, the effect of corneoscleral biomechanical properties on its readings has not been sufficiently investigated. At present the average cost is \$650 for 1 Triggerfish CLS monitoring one eye for 24 hours.

18. Conclusion

In this review, we have described various tonometers in clinical practice today and their advantages and limitations.

Determining which tonometer to use depends on several factors, most importantly if the tonometer is to be used as an in-office tool (for diagnosis and management) or as a population screening device (to identify the patients who may benefit from further evaluation). It is also important to choose one tonometer and use it consistently for the same patient, as IOP readings should not be compared between instruments.

Goldmann applanation tonometry remains the standard for in-office tonometry, as it has been used most thoroughly in the literature to evaluate the IOP-lowering effects of antihypertensive drugs and glaucoma procedures. However, the newer methods do offer additional clinical information that early studies have shown do add diagnostic knowledge, for example, ocular pulse amplitude of the DCT and corneal biomechanical properties of the ORA. The DCT and ORA also provide good reproducibility and repeatability, and they are largely free of the influence of corneal biomechanical properties. They are useful in the setting of corneal abnormalities, as in keratoconus and post refractive procedures.

The Perkins tonometer is easy to use and has fairly good agreement with GAT, within normal IOP and CCT range.

The Tono-Pen XL offers a reduced applanation area and thus is helpful in eyes with corneal irregularities. The RT makes almost no contact with the cornea, which aids in evaluating eyes covered by bandage contact lenses. Lastly, the PT provides multiple real time measurements that capture the inherent variation of IOP through the systolic-diastolic blood pressure cycle.

Previous and current generations of ophthalmologists had to rely on single static IOP measurements for glaucoma management. In recent years, continuous 24-hour IOP monitoring has overcome major obstacles and may soon become a routine part of management for glaucoma patients.

19. Source of Funding

None.

20. Conflict of Interest

None.

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