



Tonometers— which one should I use?

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Abstract

Although several factors are known to play a role in the development and progression of glaucoma, intraocular pressure (IOP) remains the only modifiable risk factor. Medical and surgical treatments for glaucoma both aim to reduce IOP to minimize disease progression. Tonometry is therefore an essential element of the ophthalmological exam. There are several types of tonometers available currently. These range from well-established instruments that have been in clinical use for decades to new devices, which are the result of recent technological advances. The various instruments have advantages and disadvantages that affect their suitability for a given setting, purpose, and patient population. In this review, we aim to describe the most commonly available tonometers today along with their advantages, disadvantages, and applicability.

Introduction

Aqueous humor is produced in the eye by the non-pigmented ciliary epithelium and provides nourishment to the cornea, lens, and the trabecular meshwork [1]. The balance between its production and drainage pressurizes the eye and this is measured as the intraocular pressure (IOP). IOP is a key factor in the development and worsening of glaucoma, a leading cause of irreversible blindness worldwide [2, 3]. IOP reduction has been shown to delay or prevent the onset of glaucoma in individuals with high IOP and is associated with slowing of disease progression in individuals with established glaucoma [4, 5]. Accurate measurement and management of IOP are crucial parameters of glaucoma monitoring and therapy.

Tonometry is an essential component of routine ophthalmological examination. This review aims to discuss the most common types of tonometers available today with their applicability, advantages, and disadvantages.

Applanation tonometry

Applanation tonometry is based on the Imbert–Fick law, according to which, the pressure inside a sphere surrounded

by an infinitely thin and flexible membrane can be measured by the force required to flatten a certain area of the membrane [6, 7]. There are several instruments that use an applanating force to flatten an area of the cornea.

Goldmann applanation tonometer

The Goldmann applanation tonometer (GAT) [Haag-Streit, Koeniz, Switzerland and other manufacturers] consists of a biprism mounted on a slit lamp. Fluorescein dye is instilled in the eye to highlight the tear film of the patient. The double prism splits the formed image of the tear film meniscus into a superior and inferior arc. The moment of applanation is ascertained when the arcs are aligned such that their inner margins just touch. GAT uses an applanating force to flatten a constant area of 7.35 mm² (diameter of 3.06 mm). At this selected area, the forces of tear surface tension pulling the tonometer tip toward the eye and the corneal elasticity pushing the tip away are almost equal and opposite. Moreover, at this area, the flattening force(g) multiplied by 10 is equivalent to the IOP (mmHg) [6, 7].

GAT is considered the reference standard for IOP measurement in current clinical practice due to its historical use in most clinical research studies to date and the extensive publications on its validity, reliability, and reproducibility [8, 9]. GAT has relatively low intra and inter-observer variability [10]. In a population-based study including two parts: an inter-observer variation study ($n = 40$) and an intra-observer variation study ($n = 22$), subjects had their IOP measured by GAT thrice in a consecutive manner.

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After a wait of 10 min, the three measurements were obtained again by the same observer in the intra-observer variation study and a different observer in the inter-observer variation study. Median values for the three measurements were calculated for both series of measurements. In the intra-observer variation study, the mean difference was 1.64 (SD 2.07) mmHg between the first measurements and 1.50 (SD 1.96) mmHg between the medians of the three measurements. In the inter-observer variation study, the mean difference was 1.79 (SD 2.41) mmHg between the first measurements and 1.60 (SD 2.15) mmHg between the medians of the three measurements [10]. In another study comprising 420 eyes, Phelps and Phelps reported an inter-observer variability of 3 mmHg or more in 30% of the eyes [11]. Another study including various tonometers found GAT to have the best repeatability followed by non-contact tonometry, ocular blood flow tonography, and Tono-Pen, respectively [12].

There are several limitations associated with GAT. Corneal factors such as corneal thickness and elasticity can be a source of error and affect the accuracy of measurements obtained. Thin corneas can lead to underestimation, whereas thick corneas can lead to overestimation of the IOP [13–15]. That said, a population-based study in Singapore found that IOP increased by 0.15 mmHg in right eyes and 0.19 mmHg in left eyes for every 10 μ m increase in central corneal thickness (CCT). As the standard deviation of CCT was found to be around 30 μ m across all 10-year age groups in the study, it was deduced that a CCT range of 120 μ m would include 95% of the study population in each age group. Thus, a variation in GAT-measured IOP of only between 1.8 mmHg and 2.3 mmHg, based on data from right and left eyes respectively, was determined to be attributable to variations in CCT among individuals of equal age [16]. Using similar reasoning, authors of another population-based study in East Asia determined a variation in GAT-measured IOP of between 2.3 mmHg and 3.1 mmHg to be attributable to variations in CCT [17]. Another study used a corneal biomechanical model to evaluate errors in applanation tonometry measurements due to corneal factors. The results showed that variation in corneal biomechanical properties may cause a larger error in IOP measurements as compared with CCT and corneal curvature [18]. Moreover, factors such as corneal irregularities and scarring, inappropriate amounts of fluorescein dye, pressure applied on the eyelids, Valsalva maneuver, breath holding, and high astigmatism can all affect the accuracy of measurements taken with the GAT [7]. The GAT also requires the use of fluorescein dye, topical anesthetics, and a slit-lamp arrangement. It is not portable and requires patients to be seated upright. Therefore, it might not be suitable for certain populations, such as the pediatric, elderly, or those with disabilities [19, 20]. Moreover, it requires a trained

person to operate it and its calibration needs to be checked monthly [8, 21].

Perkins tonometer

The Perkins tonometer (Clement Clarke, Haag-Streit, UK) uses the same underlying principles as GAT, but is portable and can be used in any position. IOP is similar to GAT [22]. These qualities make it useful in situations where the patient is unable to sit upright or GAT is not possible such as in the operating room or at the patient bedside [8].

Non-contact tonometer

The non-contact tonometer (NCT) [various manufacturers] also called the air-puff tonometer is an applanation tonometer, which uses a column of air to flatten the cornea. The force of the air increases in a steady and linear fashion. The instrument contains a light emitter and a photodetector. The light emitter generates a beam of light that is aimed at the cornea and the reflected light is captured by the detector. The wave form of the reflected light is used to determine when the cornea is applanated. The NCT uses an internal algorithm to convert the force required to flatten the cornea to IOP in mmHg [8, 9].

The advantages of the NCT include its non-contact nature, which eliminates the risk of infection and corneal abrasions. It does not require topical anesthesia or instillation of fluorescein dye and can be used by paramedical staff, making it a potential screening tool [23, 24]. Several studies have reported NCT to compare well with GAT [25–27]. However, the NCT has shown to overestimate IOP at higher levels and underestimate at lower levels of GAT-measured IOP [12]. In another study, the NCT was found to overestimate IOP as compared with GAT with the difference being greater at higher IOP values [9]. Corneal properties can also affect the measurements. There is a trend toward the readings being more comparable to GAT in thinner corneas whereas higher measurements are obtained in thicker corneas [28]. The NCT has been shown to be more influenced by CCT than GAT, with a reported change in IOP for a 10 μ m increase in CCT of 0.46 mmHg as compared with 0.28 mmHg for GAT [29]. A suggested reason behind this observation is greater stiffness of the cornea when deformation occurs at a rapid pace, which is around 8 ms for the NCT [29].

Ocular Response Analyzer

The Ocular Response Analyzer (ORA) [Reichert Technologies, Depew, NY, USA] is a relatively new device that also uses a jet of air as the applanating force for the cornea. It has a sophisticated alignment system, which can apply air

pressure to a precise location relative to the apex of the cornea. The force from the air pulse flattens the cornea beyond applanation into a slight indentation. The air pulse stops and the cornea returns back to its original position, passing through a second flat stage. The ORA measures the force at both applanation points, the initial flattening caused by the air pulse and the second point of flattening as the cornea returns to its original shape. It relies on an algorithm to produce two IOP summary measures, a Goldmann-correlated IOP and a corneal compensated IOP (IOPcc) [30–32]. The ORA also measures corneal hysteresis and corneal resistance factor [30–33]. Low corneal hysteresis is associated with progression of glaucoma in some studies [34, 35]. The ORA appears to provide higher IOP measurements as compared with GAT [36, 37] with one study reporting a mean difference of 3.65 ± 3.85 mmHg between IOPcc and GAT [38]. In another study, the ORA was shown to be less repeatable but more reproducible than GAT, whereas the dynamic contour tonometer was reported to be more precise than both ORA and GAT [39]. The ORA is also relatively expensive, limiting its use to more affluent settings.

Pneumatonometer

The pneumatonometer (Model 30, Reichert Technologies, Depew, NY, USA) contains a silicone tip, measuring 5 mm in diameter, at the end of a floating piston. The tip is used to gently indent the cornea with pressure from a controlled flow of air. The pressure forcing the tip ahead, when the tip and cornea are both flat and an equilibrium is achieved, is used to provide an IOP measurement [7, 40].

The pneumatonometer is portable, easy to use, and has minimal contact with the cornea. This makes it a useful tool for screening purposes. However, the tip can be difficult to disinfect [7] and anesthetic is required. Calibration is essential to acquire reliable readings [8]. As compared with GAT, a study found it to underestimate IOP at lower values and overestimate it at higher values [12]. The measurements were also affected by variation in CCT with a reported change in IOP of 0.38 mmHg for a 10 μ m increase in CCT as compared with 0.28 mmHg for GAT, 0.31 mmHg for Tono-Pen, and 0.46 mmHg for NCT [29]. This study used a pneumatonometer, which had disposable tips and a probe that was mounted on a slit-lamp.

Tono-Pen

The Tono-Pen (Reichert Technologies, Depew, NY, USA) is a portable, hand-held tonometer that combines applanation and indentation to determine IOP. The Tono-Pen consists of a small plunger connected to a strain gauge that projects from the applanating surface. The plunger

faces increasing resistance from the eye as the tonometer touches the cornea. At the point of applanation, this force is shared by the plunger and the footplate. This causes a momentary decrease in the rising force. The force at this point is used to determine the IOP in mmHg based on empirical studies as the area of applanation is known [7].

The Tono-Pen is an electronic hand-held device, which is lightweight, portable, and easy to use. It can be used in any position and does not require special training. It takes multiple readings and displays the average and provides an estimate of the accuracy of the reading based on the standard deviation of the measures. As it only requires a small contact area, it can be used to measure IOP in patients with irregular corneas [32]. Similarly, it has been shown to provide reliable measurements in eyes with therapeutic contact lenses with no significant difference in the measured IOP with and without a lens. Therapeutic contact lenses may be indicated for an array of reasons and their repeated removal may disrupt epithelial healing of the cornea. Therefore, the Tono-Pen may be useful for situations where measurement of IOP without removal of the lens is preferred [41]. Despite its various advantages, the Tono-Pen has several limitations. As compared with GAT, it can over or underestimate the IOP [42, 43]. Geyer et al. reported the Tono-Pen to overestimate IOP as compared with GAT [44]. In a study by Salvetat et al., a nonsignificant trend was observed towards Tono-Pen underestimating IOP at lower GAT values (<24 mmHg) and overestimating it at higher GAT values (>24 mmHg) [42]. On the other hand, some studies have reported the Tono-Pen to overestimate GAT-measured IOP at lower values and underestimate it at higher values [45, 46]. CCT can also influence Tono-Pen readings [42, 47], with one study reporting a mean change of 0.74 mmHg in the obtained IOP for a 10 μ m increase in CCT [42].

Indentation tonometry

Indentation tonometry is based on the principle that a force or weight will cause more indentation in a soft object as compared with a hard object [7].

Schiotz tonometer

The Schiotz tonometer (various manufacturers) is based on the principle of indentation. It became the most widely used tonometer worldwide for the bulk of the 20th century until GAT took over during its last quarter. It consists of a plunger that floats in a barrel. The barrel has a curved footplate attached to its bottom. The weight of the plunger can be altered from 5 to 15 g in order to indent the cornea.

The amount of indentation is indirectly proportional to the IOP [7].

The Schiøtz tonometer is cumbersome as the patient needs to assume a supine position, but it is affordable and robust. It has no complicated electronics. Therefore, it is suitable for screening especially in low resource and remote settings [48]. On the other hand, a study comprising 1280 eyes found Schiøtz obtained measurements to be lower than GAT-measured values in 84% of the eyes. Moreover, 19% of the eyes demonstrated an IOP difference of 5 mmHg or greater between the two instruments [49]. It also has a risk of corneal abrasion if the patient is unable to stay still and can displace aqueous humor resulting in lower IOP with serial attempts at measurement [7]. Scleral rigidity can also influence the IOP measurements [50].

Rebound tonometry

Rebound tonometers use a magnetized probe that is propelled toward the cornea. The device measures the deceleration of the probe when it contacts the cornea to provide an IOP measurement [7].

Icare tonometer

The Icare tonometer (Icare Finland Oy, Vantaa, Finland) is a contact rebound tonometer. It consists of an assembly of two coaxial coils, which propel the probe toward the cornea. As the magnetized probe bounces back, variation in the motion parameters are detected by a sensor to calculate the IOP [51]. The Icare has shown good agreement with the GAT with a small, nonsignificant mean difference (0.64 mmHg) between the two [52]. It has also been reported to estimate IOP within ± 3 mmHg of GAT in 74.1% of the eyes in a study [53]. However, in some studies it underestimated GAT measurements at high IOP values [54, 55]. Other studies have found it to overestimate GAT-measured IOP [19, 56, 57]. The Icare is influenced by CCT where it obtains higher IOP than GAT in thicker corneas [58].

The older version of the Icare cannot be used in an inclined position. A newer version, the Icare PRO allows inclination, which enables it to be used on patients lying supine. The Icare PRO has shown good agreement with GAT with a study reporting a small mean difference of -0.38 mmHg [59]. Another study showed that the difference in IOP measurements between the Icare PRO and the GAT was not affected by CCT, age, axial length, or spherical equivalent [20]. Another reported that the Icare PRO overestimated IOP at lower GAT values and underestimated it at higher GAT values [60].

The Icare is a hand-held, lightweight, and portable device. The measurement does not cause patient discomfort with no need for anesthesia or fluorescein dye. These attributes make it suitable for screening purposes. The Icare measurements have shown to not be affected if the probe does not precisely touch the central corneal apex [61]. Disposable probes are required and cost about one US dollar each.

The Icare HOME is a newer version of the device that can be used by patients to perform self-tonometry. About 75% of patients were able to obtain measurements on their own eyes with the device in one study [62]. However, it seems to overestimate measurements as compared with GAT [63] and IOP can differ from GAT by a substantial amount in some patients [62].

Dynamic contour tonometry

The Pascal dynamic contour tonometer (DCT) [SMT Swiss Microtechnology AG, Port, Switzerland] uses the Pascal principle to calculate IOP. According to the Pascal principle, the change in pressure is transmitted undiminished in all parts of a fluid contained in an enclosed space [64]. The DCT consists of a tiny piezoelectric sensor installed in its tip. The tip also contains a contour, which, when applied to the cornea, causes the shape of the cornea to conform to the preferred contour. The IOP is then measured by the sensor transcorneally [65]. The instrument also generates a score ranging from 1 (optimum) to 5 (not acceptable) to represent the quality of the IOP measurements obtained. A score of 1 or 2 is thought to be reliable for clinical practice [32].

The DCT has shown to be more repeatable and reproducible than GAT or ORA [66]. IOP measured by the DCT is reported to be higher than that obtained by the GAT with their difference being greatest at low CCT [67]. Similarly, poor agreement with the GAT has been reported for both very thin and very thick corneas [68], which may indicate that DCT measurements are less influenced by corneal factors as compared with the GAT [69, 70]. It therefore may be useful after keratoplasty and refractive surgery as it is less affected by variations in corneal properties following such procedures [70, 71]. A study has shown DCT to agree well with intracameral IOP (Lin's concordance coefficient = 0.9763), however, it significantly underestimated the reference IOP at higher values. There was no statistically significant effect of corneal curvature, astigmatism, axial length, and age on the difference between DCT and intracameral IOP. Although CCT was found to have a statistically significant effect on their difference, it was not deemed to be clinically pertinent [72].

The disadvantages of DCT include its nature as a contact tonometer, lack of wide use at present, and the need for trained staff and patient cooperation for accurate measurements [73].

Corvis ST

The Corvis ST (Oculus, Wetzlar, Germany) is a novel device, which comprises an air-jet indentation system and ultra-high-speed Scheimpflug technology, to monitor the corneal deformation response. It provides in vivo characterization of corneal biomechanical properties in two dimensions. The Scheimpflug camera has a blue light LED with a horizontal coverage of 8.5 mm. It monitors the corneal response to the air puff by taking >4300 frames per second [74]. A study including healthy eyes reported the device to have good repeatability and reproducibility for measurement of IOP and dynamic corneal response [75]. Another study including both glaucoma patients and healthy controls reported the obtained IOP to be 1.3 mmHg lower, on average, as compared with GAT [76]. Advantages of this device include its non-contact nature and in vivo monitoring of corneal properties. The disadvantages include its cost, lack of wide use at present, need for trained staff, and the table mount setup.

Conclusion

Accurate and precise measurement of IOP is an important component of glaucoma management. There are numerous types of tonometers available today. The GAT has the advantage of its long history of use, reliability, and reproducibility. Furthermore, almost all clinical trials in glaucoma have relied on GAT as the gold standard. Non-contact devices such as the NCT, ORA, and Corvis ST have the advantage of reduced risk for infections and corneal abrasions. Tonometers that are portable and do not require anesthetic or specialized training for use such as the Icare can be useful for screening purposes, as well as in the clinic. Devices that allow use in the supine position such as the Tono-Pen and Perkins are helpful in cases where patients cannot sit upright. Devices that produce rapid deformation of the cornea such as the NCT may be more influenced by corneal properties. Newer devices, such as the ORA and DCT, are proposed to be less influenced by corneal properties, however, they are not widely used at present. In summary, different types of tonometers vary in terms of their portability, positioning, agreement with the GAT, influence of corneal properties, and the need for trained operators and patient cooperation. These factors should be taken into consideration when selecting the appropriate instrument to be used for a specific purpose, setting and patient population.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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