

## TONOMETRY- A JOURNEY OF TWO CENTURIES

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### ABSTRACT:

*Centuries of research on Glaucoma have not been able to add any factor to 'Intraocular Pressure (IOP)' the modification of which can halt the progression of this blinding disease. Therefore, the need for accurate IOP measurement has always been the interest of researchers and industry. An array of instruments has, thus, been developed, each surpassing the errors of the previous modalities. Although all of them have certain advantages, they have their limitations too. The present article puts light on the various developments in the field of tonometry over two centuries starting digital tonometry to the latest developments. It has also briefly touched the factors affecting intraocular pressure and its measurement.*

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Time and again, it has been understood that the only modifiable factor in glaucoma management is intraocular pressure (IOP). Therefore, the need for accurate and reproducible measurement of IOP is being felt more than ever before. The research on this subject is regularly identifying patient and instrument related factors which affect IOP and also the sources of error in its measurement. This is an effort to have IOP measurements as close to manometric (manometry is measurement of actual intraocular pressure by cannulation of the globe) values as possible under all circumstances and in all variety of patients.

Way back into 1826, Sir William emphasized the critical role that digital estimation of ocular tension played in his practice.<sup>1</sup> Soon afterwards, digital tonometry became an essential clinical skill necessary 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 intraocular pressure (IOP) by palpation that they viewed the new technology as inferior.

Von Graefe is credited with the initial attempts to create instruments that mechanically measured IOP in the early 1860s, which is still a part of the collection at Utrecht eye clinic. It was Donders who designed another mechanical 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. The ophthalmologist first measured the curvature of the sclera at the site of contact, and then used this measurement as a reference plane to measure the depth of indentation. The discovery of local anesthetic, cocaine, by Carl Koller in 1884 led the way to corneal impression tonometry soon thereafter.

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. Professor Hjalmar Schiøtz devised his impression tonometer, originally for use against the sclera of the eye, in 1905. He then developed this into a corneal plunger. The higher the pressure of the eye, the lower amount of indentation would result.

For the next half century, the Schiøtz was generally accepted as a reliable means of measuring IOP and became the first tonometer to achieve mass sales. It required a calibration scale, as designed by Friedenwald, taking into account that placing a tonometer onto the eye automatically raises the IOP.

At the time of its introduction, it had the advantage that the pressure of the fingers in steadying the instrument was virtually, nil. It was slightly modified in 1924 when an un-weighted version, the X-tonometer, was introduced. However, large volume of fluid displacement, in indentation techniques, resulted in a huge impact of sclera rigidity on the measured IOP (figure 1a). However, due to its simplicity combined with reasonable accuracy and versatility, it is not uncommon to see Schiøtz tonometer being used in actual clinical practice of today (figure 1b).

An adjustment for ocular rigidity was introduced by Goldmann in the 1950s, which led to the development of Goldmann applanation tonometers. The Goldmann Tonometer, introduced by another Bern professor in 1954, pressed a plexiglass plate onto the cornea, controlled by a coiled spring and lever system. Because of the very small area touched, ocular rigidity did not affect the quality of the readings (figure 2). In Goldmann applanation tonometry (figure 3, 4), the force is changed until a defined area of flattening is achieved.

Maklakov (or Maklakoff) applanation tonometry uses a constant force and then determines the amount of area flattened. In theory, this style of

applanation should be less accurate than Goldmann style because corneal flattening is not linear, but this has not been well studied because the instrument has mostly been abandoned after having been popular in Russia and east Europe.

Late twentieth century tonometer design featured various mechanical and non-mechanical innovations. The Mackay Marg model of 1959 was the first electronic tonometer and can be said to have combined the principles of applanation and indentation.

The electronic and non-contact tonometers used today rely heavily on the principles and instrumentation first introduced by Malakoff, Schiotz and Goldmann.

With the advancement of modern physics, ophthalmology has also been revolutionized. Presently, intraocular pressure estimation can be done via wide range of instruments, each with their own advantage and limitation. The newer devices are:

1. Non-contact Tonometry and Ocular Response Analyzer
2. Corvis ST
3. Tonopen
4. Pneumatic tonometer
5. Dynamic Contour Tonometer – Pascal
6. Rebound Tonometer
7. Transpalpebral Tonometers
8. Continuous IOP Monitoring Systems

### Goldmann Applanation Tonometer (GAT)

Prior to discussing any recent developments, Goldmann Applanation tonometer deserves little more details as it is still the gold standard instrument for the purpose in the management of glaucoma. Goldmann tonometer is based on modification of Malakoff-Fick law, called Imbert-Fick's law. It states that an external force against a sphere equals the pressure in the sphere multiplied by the area flattened by the external force. It, however, presumes that the sphere is perfectly spherical in shape, dry, infinitely thin and perfectly elastic. In case of its application to eye, surface tension created by moisture and lack of flexibility require a force to bend cornea independent of the internal pressure. In addition, cornea is not infinitely thin, thus, this law is further modified. When inner area of flattening equals  $7.35 \text{ mm}^2$ , surface tension balances out force required to bend cornea. Volume displacement of  $0.5 \text{ mm}^3$  in GAT is too small to be significant and thus ocular rigidity plays no role. Therefore, this law becomes applicable at this stage. Internal area of flattening of  $7.35 \text{ mm}^2$  is achieved when diameter of external applanation is 3.06 mm. Thus, this is the size of the applanator tip in GAT. While performing tonometry with this instrument, a fluorescent dye is instilled in anesthetized conjunctival sac. A cobalt blue light activates this dye that turns the tear layer to a bright

color. At the point of applanation, the tear layer is pushed out from between the applanating surface of the tonometer tip and the cornea, forming a meniscus at the perimeter of the flattened corneal surface. A doubling prism inside the tip divides this circular meniscus into a superior and inferior arc, which, when they are aligned so that their inner margins just touch, allows the determination of the exact moment of applanation (figure 4).

Being a contact instrument, GAT does carry a risk of contamination and cross infections. Therefore, GAT prism should be cleaned between two cases and disinfected after the day's use. For the same reason, it should be avoided in infected or injured eyes. Disinfection could be done by home bleach, sodium hypochlorite, 3% hydrogen peroxide or proprietary disinfectants as advised by the manufacturers. Disinfectant must be washed out thoroughly from the prism tip prior to use. Although manufacturers recommend monthly calibration of the instrument, Glaucoma Society of India has informally accepted a calibration check every 3-6 months, depending on age of instrument, to be sufficient. Goldmann had presumed a universal corneal thickness of  $520 \mu\text{m}$ , measured optically. It was later observed that GAT gives lower readings in thin corneas and higher in thicker corneas. This can lead to errors when it comes to glaucoma management, as one is likely to miss glaucoma cases in eyes with thinner corneas. No nomogram for conversion of IOP in relation to CCT has found universal acceptance. The general consensus is to consider  $520\text{-}540 \mu\text{m}$  as normal and consider rest of corneas as thin or thick and control IOP accordingly. However, as a general guideline, it is accepted that  $14 \mu\text{m}$  changes in CCT causes an error of 1 mm Hg. Another factor in measurement of IOP with GAT includes amount of astigmatism. For.....red mark, placed  $43^\circ$  from the white mark. This red mark should be aligned to the highest minus axis of the cornea of patient.

Thus, Goldmann applanation tonometer is a fixed area type of applanation tonometer. Its structure has five main parts viz. measuring prism, feeler arm and control weight insert, housing and revolving knob with measuring drum (figure 3). The probe tip consists of a doubling prism which is used to applanate cornea & it optically splits the circular area of corneal contact in two horizontal semi circles by inducing horizontal shift. The semi-circles should interlock with equal sized semi-circles with thickness of mires equal to  $1/10^{\text{th}}$  the diameter of applanation (figure 4). Details of this can be seen on youtube link '<http://www.youtube.com/watch?v=Zx0xslEv9q0>'.

### Non- Contact Tonometry (NCT)

Reported first by Grolman in 1972, it uses jet of air to applanate anterior corneal surface.<sup>2</sup> With source of air in centre, there is optical system

consisting of light emitter & detector on the two sides. As air-puff flattens the cornea, reflected light increases. The moment of appplanation is the moment of maximal light detection by optical sensor which shuts air pulse. The computer inside calculates IOP & displays it digitally. In the older machines, time from internal reference to the peak was converted to IOP whereas in newer machines, the IOP is measured from the actual air jet pressure required to appplanate cornea (figure 5). The instrument is user friendly, does not require anaesthesia and is reasonably accurate except in very low or high IOPs. These qualities make it a popular machine especially among optometrists (figure 6).

### **Ocular Response Analyser (ORA -Reichert Corporation; USA)**

It is a new version of non-contact tonometer. Similar in principle, it measures the corneal response to appplanation by a bi-directional rapid air pulse (figure 7). Precisely metered collimated air pulse appplanates cornea and even further into slight concavity. After the cessation of air pulse, cornea again returns to its normal shape and while doing so, it passes through a second appplanation state (figure 8). Independent pressure values are derived from inward and outward appplanation effects. Due to dynamic nature of air pulse and the viscoelastic properties of cornea, the events result in two different pressure values. The difference between “inward” and “outward” appplanation pressure depends on the viscoelastic properties of the corneo-scleral shell. In other words, because of energy absorption, the inward and outward appplanation events are delayed, resulting in two different pressures. The average of these two pressures provides a reproducible Goldmann-correlated IOP (IOPg) and the difference between the two pressures is called corneal hysteresis (CH). Thus, corneal hysteresis is an indication of viscous damping in the cornea, due to the viscoelastic resistance of the cornea to a deformation pulse by an air jet, reflecting the capacity of corneal tissue to absorb and dissipate energy. Cornea compensated IOP (IOPcc) utilizes information of individual corneal elasticity and viscosity. Thus, it measures not only IOP but also deformability of cornea. Ocular Response Analyzer can also calculate corneal resistance factor (CRF) which reflects elastic properties. Corneal resistance factor (CRF) indicates overall resistance of cornea. The thicker the cornea, the greater is the CRF.

### **Corvis ST**

The Corvis ST (CST) is a novel noncontact tonometer that allows investigation of the dynamic reaction of the cornea to an air impulse (figure 9a). The CST gathers 4330 frames per second within a 100 ms period, therefore recording dynamic

deformation of the cornea to calculate the IOP value.<sup>3</sup> Its measurement range is from 1 to 60 mm Hg. It measures the IOP, corneal thickness and biomechanical properties. Based on these data, it has the potential to measure the true IOP. It determines the influence of the biomechanical properties on conventional IOP measurements (figure 9b). Both, stiffness and viscosity of the cornea are reduced by ectasia and these can be analyzed simultaneously with the Corvis® ST. It also has the potential to quantify the effect of corneal crosslinking on the biomechanical properties.

### **Tonopen**

This is the portable version of Mackay Marg tonometer. The force that is required to keep the flat plate of plunger flush with a surrounding sleeve against the pressure of corneal deformation is measured. The effect of corneal rigidity is transmitted to sleeve. The IOP is recorded as wave front. Tonopen uses electronic gauge to flatten cornea (figure 10). The microprocessor inside averages several wave fronts & gives digital display of IOP. An audible click is produced with satisfactory wave front. It is useful for irregular corneas since the area of appplanation is small (1.5 mm diameter) and is not dependent on optical system. The Tono-Pen is able to record IOP through a bandage contact lens, which makes it useful in eyes with alkali or other chemical burns, chronic neurotrophic ulceration and other situations where a bandage contact lens is therapeutically indicated and where removing it for pressure measurement may cause problems.<sup>4</sup> The IOP readings match well in the normal range. However, it gives higher values in eyes with low IOP and lower values in eyes with high IOP when compared with GAT. Whereas the older model required calibration before every use, the new AVIA model does not require calibration.

### **Pneumatic tonometer**

The pneumotonometer was first developed by Durham et al and subsequently refined by Langham and McCarthy.<sup>5</sup> It is basically an appplanation tonometer but has some aspects of indentation tonometry.<sup>6</sup> This appplanates cornea with a probe that is supported by column of gas and, hence, the sensing device is air pressure (figure 11). Being non-optical, it is useful for diseased corneas. Its recordings are also similar to Mackay Marg tonometer. It can be used for continuous monitoring of IOP. It is not to be confused with air-puff tonometer which is another name for NCT.

### **Dynamic Contour Tonometer – Pascal**

The measuring head curvature of this device is similar to the curvature of the corneal surface. Therefore, it does not cause corneal flattening or

indentation when brought into contact with the corneal surface.<sup>7</sup> Thus, this instrument eliminates the impact of the tangent and any elastic deformation on the measured value (figure 12).

Requiring a contact period of 5-7 seconds, it also gives a diastolic and systolic IOP with the difference being called Ocular Pulse Amplitude (OPA). The instrument is mounted on slit lamp like GAT (figure 13 a). The probe has a radius of curvature of 10.5 mm, contact surface of 7 mm diameter and sensor diameter of 1.2 mm. The PASCAL's probe rests on cornea with a constant force of one gram. Its piezoelectric sensor measures IOP 100 times per second with resolution of 0.1 mm. The plunger is concave and contour matched to cornea and uses low appositional force thereby not causing any deformation of globe while measuring the IOP. The instrument measures IOP in both diastolic and systolic phases of cardiac cycle. The difference in the two is called 'Ocular Pulse Amplitude' (OPA) which is an indirect indicator of choroidal perfusion.

Its LCD screen displays:

1. Diastolic IOP mmHg
2. OPA mmHg
3. Quality score- Score of 1 & 2 are satisfactory and 4 & 5 to be discarded. Although the manufacturer's recommend the acceptance of score 3, most of users feel it should be discarded.

However, DCT has its own shortcomings, viz., it is more time consuming than GAT as 5 cardiac cycles need to be recorded and it doesn't seem as useful in diseased corneas or after corneal transplant. Recurrent cost of disposable tip is also an important consideration, not only in our country, but everywhere. The specific advantage of this tonometer is its role in post kerato-refractive surgery, where it is supposed to be more reliable than GAT as it is claimed to measure IOP independently of corneal structure and CCT.<sup>8</sup>

### Rebound Tonometer

These are hand held ballistic devices that measure the return bounce motion of an object impacting the cornea. The instrument is an electromechanical device consisting of two coils, a solenoid propelling and a sensing coil positioned around a central shaft containing a magnetized probe (figure 14 a). Application of a transient electrical current to the solenoid coil propels probe to cornea. This movement of magnetized probe induces voltage which is monitored by the sensor. On impact with cornea, the probe decelerates and rebounds and the microprocessor analyses deceleration of probe following the impact. This deceleration is less at low than high IOP, consequently, the higher the IOP, the shorter the duration of impact. Its clinical importance is realized for screening and in people who have

difficulties in positioning their head on the slit lamp (children, on wheelchair, obese, while performing certain special acts - figure 14 b).<sup>9</sup> Moreover, even topical anaesthesia is not required. The rebound tonometer, as might be expected, is highly influenced by corneal thickness and other biomechanical factors.<sup>10</sup> Although IOP readings are comparable with GAT in thin corneas, the tendency to overestimation of IOP in eyes with thick corneas exceeds that of both Goldmann and Tonopen.<sup>10</sup> On activation of the measurement button, it takes six readings and displays a mean value after discarding the aberrant values on its own.

### Transpalpebral Tonometer's

Theoretically, these tonometer's can circumvent corneal problems like oedema, astigmatism, variation in thickness, scleral rigidity etc. However, their doubtful accuracy has limited their use. Examples include TGDc-01 and IGD-02 (2003) and Phosphene tonometer (1998). Phosphene tonometry is a psychophysical test for self-tonometry. The pencil shaped instrument is pressed the Phosphene appears opposite to pressure applied. Drawbacks include, patients with field loss may not perceive phosphenes.<sup>11</sup>

### Continuous IOP monitoring (Sensimed Triggerfish®)

Various tonometers can be used for continuous IOP monitoring. A recent addition to this list is SENSIMED Triggerfish which can be used for 24 hour IOP recording including sleeping hours. It uses a sensor which is a soft hydrophilic single use contact lens, containing passive and active strain gauges embedded in the silicone to monitor fluctuations in diameter of the corneo-scleral junction (figure 15). Although the instrument does not measure IOP, the output signal sent wirelessly to the antenna is directly correlated to fluctuations in intraocular pressure. The adhesive antenna, worn around the eye, is connected to a portable recorder through a thin flexible data cable (figure 16). The patient wears the contact lens up to 24 hours and assumes normal activities including sleep periods. When the patient returns to his doctor, the data is transferred from the recorder to the practitioner's computer via Bluetooth technology for immediate analysis. Recently, John Flanagan, during his talk in 'World Glaucoma Congress, 2015' at Hong- Kong, commented that sclera based tonometry may be better tolerated than corneal based continuous monitoring systems by causing less inflammation.

### Special Situations

Although GAT is still considered the gold standard in average glaucoma clinics, some of the

tonometers are useful in certain special circumstances viz.

1. Under anaesthesia: Here GAT cannot be performed as the patient is supine. Therefore,
  - a. Perkins applanation tonometer (portable) is best for measuring IOP in eyes with average corneas.
  - b. Pneumatotonometer is best when the cornea is abnormal.
  - c. Tonopen is easy to use but does not provide the most accurate IOP estimate.
2. In corneal scarring/ edema/ post corneal transplant: Pneumatotonometer may be the best instrument. Tonopen may also be used especially when part of cornea is clear. This portion may be used to measure IOP by tonopen in any convenient posture.
3. In keratoprosthesis, no instrument is reliable. Hence, only digital palpation gives an estimate of IOP as being low, medium, or high.<sup>12</sup>
4. Pascal DCT is the best in post kerato-refractive surgery cases
5. Rebound tonometer is most suitable for pediatric glaucoma clinics and for research involving IOP measurement during special maneuvers

Although the value of intraocular pressure has not changed, digital tonometry has travelled two centuries to be replaced by sophisticated technologies for its estimation. Today's instruments are incredibly accurate and easy to use. However, the cost may be prohibitive. The use of right diagnostics at each step remains the key to success of any clinical practice.

#### Factors which can affect IOP readings

At the end, we would like to, briefly, enumerate the factors which can affect IOP readings. These can be divided into those factors which actually affect the IOP and the factors which affect measurement of IOP. Whereas the former include factors like obesity, posture, neck tie, valsalva, seasonal variation, general anesthesia, drugs, acidosis etc. and are beyond the scope of this article; the latter include factors affecting mires, central corneal thickness (CCT), corneal curvature and effect of bio-mechanical properties

Intra-observer Variability ranges from 2.2 to 2.5 mmHg for GAT to 3.2 mmHg for NCT. Inter-observer variability is estimated to be +/- 2.2 to 3.8 mmHg for GAT and +/- 5.1 mmHg for DCT. Goldmann tonometer is highly affected by observer's skill to identify perfect mires. Intraocular pressure estimation depends on centration of mires, thickness of fluorescein ring and applanation force. All forms of tonometry, currently available, are affected by Central Corneal thickness, although the extent varies. Higher CCT overestimates and lower CCT underestimates IOP, however, corneal edema underestimates IOP. Corneal irregularities & scarring distort the mires. IOP is wrongly estimated when

measured over contact lenses. Cornea with steeper curvature needs to be indented more requiring more force to produce standard area of contact Therefore, this overestimates IOP in GAT. IOP is underestimated following kerato-refractive surgeries including LASIK, LASEK, PRK and even hyperopic LASIK and RK which cause minimal changes in CCT, using routine procedures like GAT.

Last but not the least, the most important factors in the measurement errors of IOP are the inter and intra observer variability.<sup>13</sup> Thus, the importance of proper training and careful clinical examination cannot be replaced by any technological advancement.



**Fig 1: Corneal deformation in indentation tonometry (a); the instrument (b)**



**Fig 2: Corneal deformation in applanation tonometry**



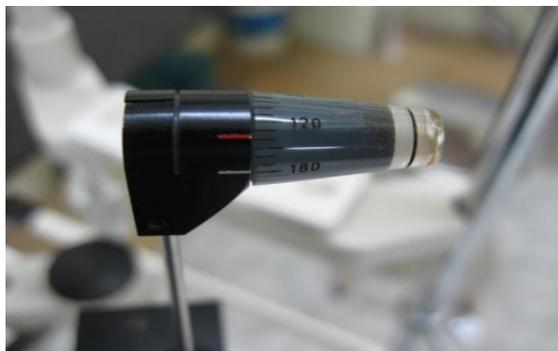


Fig 3: (a) The Goldmann applanation tonometer, (b) its probe

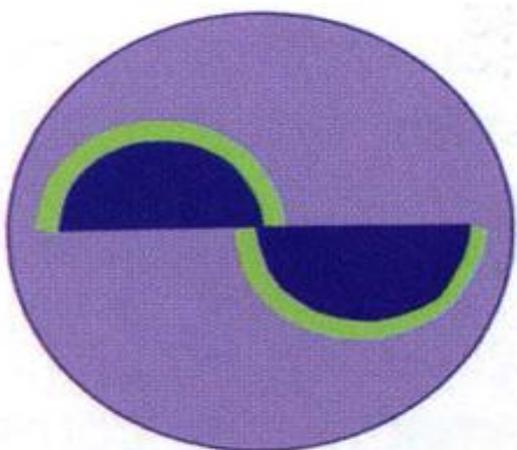


Fig 4: Well aligned mires in Goldmann applanation tonometer

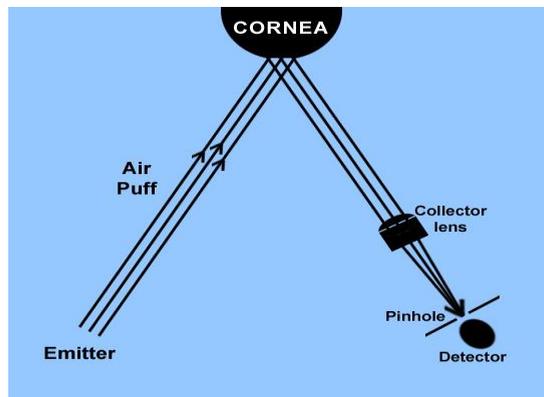
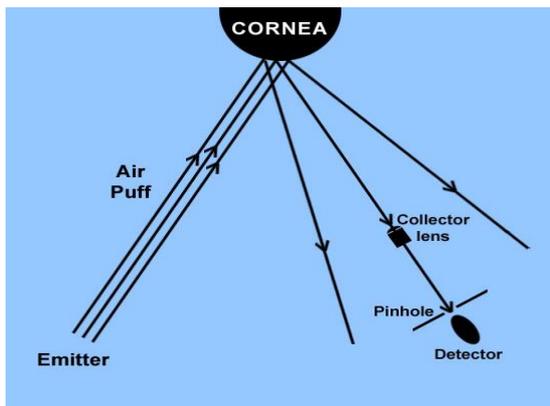


Fig 5: (a) Principle of Non-contact tonometer- emission of air puff, (b) flattened cornea and reception of air puff



Fig 6: Non- contact tonometer



Fig 7: The Ocular Response Analyzer (With permission from Reichert Corporation; USA)

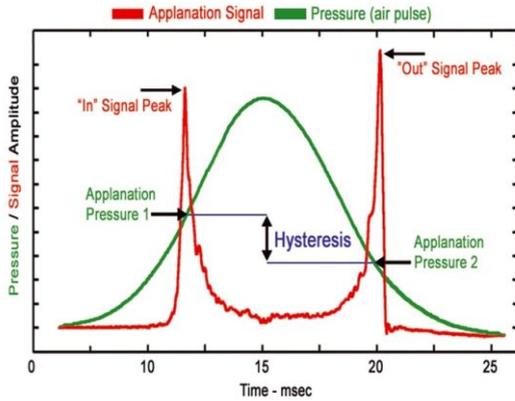


Fig 8: The signal plot from ORA (With permission from Reichert Corporation; USA)



Fig 11: Pneumatic tonometer (With permission from Reichert Corporation; USA)

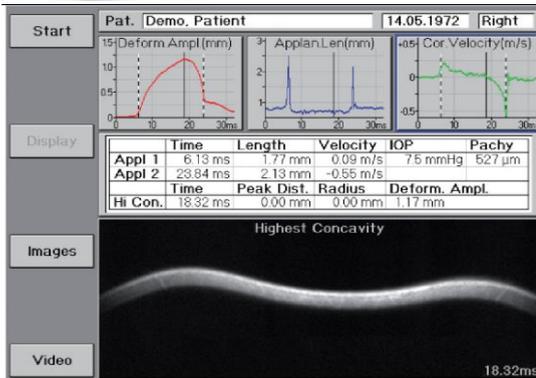


Fig 9: Corvis ST – mechanical model (a); display (b)

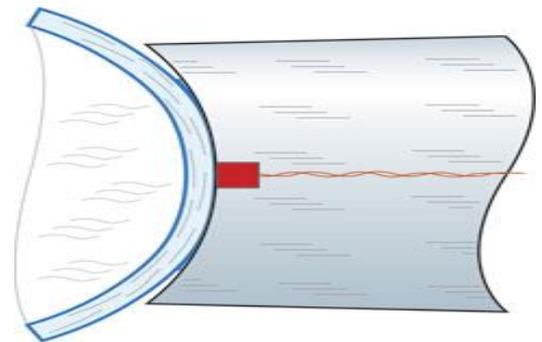


Fig 12: Principle of Contour Matching and the sensor in Pascal DCT

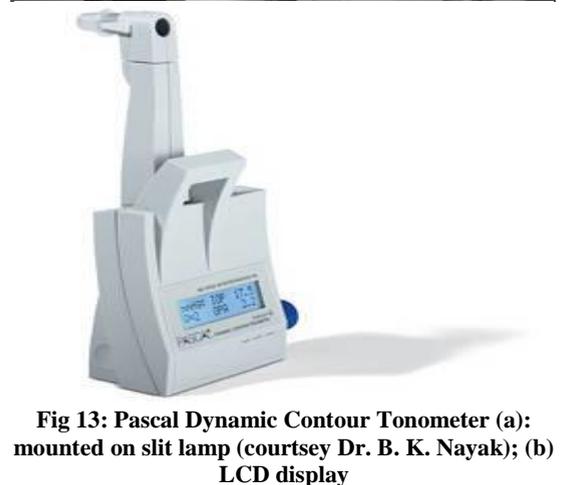


Fig 13: Pascal Dynamic Contour Tonometer (a): mounted on slit lamp (courtesy Dr. B. K. Nayak); (b) LCD display



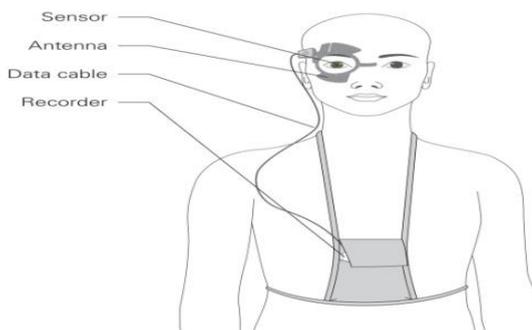
Fig 10: The Tonopen (With permission from Reichert Corporation; USA)



**Fig 14: (a) I care Rebound Tonometer; (b) IOP being measured while intra-abdominal pressure is raised (courtesy: Brig. Sagarika Patyal)**



**Fig 15: SENSIMED Triggerfish contact lens**



**Fig 16: SENSIMED Triggerfish continuous IOP monitoring system**

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