

# Review: Measurement Techniques for Intraocular Pressure

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## Abstract

The literature on intra-ocular pressure dynamics is reviewed, including tonometer design and calibration, the influence of corneal-scleral mechanics, and scleral rigidity factors. Drugs that influence the outflow facility of the trabecular meshwork (TM) are discussed. Transmural pressure drop across the lamina cribosa (LC) is an important parameter, in terms of quantifying potential glaucoma damage to the optic nerve.

**Keywords:** Intraocular pressure; Glaucoma; Tonometer; Ocular rigidity; Calibration

## Introduction

It is important to determine the intra-ocular pressure, the fluid pressure inside the eye, in order to evaluate for patients at risk from glaucoma, because of potential damage to the optic nerve [1,2]. Tonometers are calibrated to measure pressure in millimeters of

mercury [mmHg]. There are many different types of tonometers, including Schiotz, Goldmann, Perkins, Marg-MacKay, Air-Puff (American Optical), and the new “Triggerfish” wireless contact lens (Sensimed AG) [3-8]. Preliminary mechanics and development work in this area was presented by Friedenwald [9]. This list is certainly not exhaustive, as there are many new devices developed in recent years, including the Tono-Pen, ocular bounce, resonant tonography, and dynamic pascal tonometry [10].

Type	Accuracy	Year	Area	Cost	Reference
<b>Indentation</b>					
(1) Schiotz	± 2 mmHg	1915	3.0 mm	250 - 500	[4]
<b>Applanation</b>					
(2) Goldmann	± 1.9 mmHg	1955	3.05 mm	3,000 - 5,000	[3]
(3) Perkins [Portable Goldmann]	± 2 mmHg	1980	3.0 mm	1,380	[5]
[4] Marg-MacKay	± 1 mmHg	1960	1.0 mm	n.a.	[6,28]
[5] Tono-Pen [Portable Marg-Mackay]	± 2 mmHg	1988	2.0 mm	2,500 - 3,000	[29]
<b>Miscellaneous</b>					
[6] Air-Puff	± 1 mmHg	1975	n.a.	4,000 - 8,000	[7]
[7] Diaton Tonom. (transpalpebral)	± 2 mmHg	1995	3.0 mm	2,750	[30]
[8] Ocular Resonance (vibration)	± 4 mmHg	1965	4.0 mm	n.a.	[31-33]
[9] Sensimed AG (Wireless Contact)	± 3 mmHg	2012	14 mm	10,000 – 12,000	[8]

**Table 1:** Comparison of Tonometers.

By comparison, tonographs, a different type of device can be used to measure the outflow facility. Quigley [2] reviewed the world-wide prevalence and incidence of glaucoma. Wang et al. [11-13] discussed ROP (often associated with rapid juvenile myopia rates) and glaucoma related studies. Direct and remote intra-ocular pressure measuring techniques were reviewed by Downs [14], Nuyen et al. [15], Okaforet al. [16], Sit [17], Clement et al. [18] and Stamper [19].

Basically, there are two types of tonometry, indentation and applanation (Table 1). Indentation involves corneal buckling, with attendant volumetric change  $\Delta V$ , applanation involves corneal bending. Basic equations for corneal bending and buckling are listed here in Nomenclature. Various bio-mechanical factors contribute to the problem of tonometer design and calibration, including corneal-scleral mechanics [20,21], aqueous outflow, diurnal fluctuations [23] and amount of axial myopia [24-27]. Nuyen et al. [15] reported 24 h fluctuations of intra-ocular pressure, measured with an instrumented contact lens.

The cornea is involved in most I.O.P. measurement methods, and its bio-mechanical properties influence the measurement results. Corneal thickness does not always correlate with corneal hysteresis. In order to properly calibrate tonometers, an evaluation of the cornea properties required new special methods [34,35].

Accommodation affects I.O.P. dynamics. The ciliary body has two main functions: regulation of the lens optical power and producing fluid. The accommodation tension is responsible for an increasing intra-ocular liquid production [36]. Eyes with progressive myopia were characterized with evident pathology of the trabecular meshwork [37,38], which reduced the aqueous outflow. The eyes with progressive myopia are distinguished with an elevated I.O.P., which possibly is a cause of the myopic eyeball extension, development of axial myopia [39], and lower than normal scleral rigidity [27].

Pierscionek et al. [40] measured scleral rigidity in the range 0.0017 to 0.0022 where  $K$  = the ratio of loge (IOP) to the change in volume, using Friedenwald's definition. Coquart et al. [41] measured and modeled the normal-mode resonant frequencies of the pre-stressed corneo-scleral shell, a form of resonant tonometry, finding a correlation between resonant frequency and I.O.P. Woo et al. [42] measured non-linear stress-strain response of the cornea and sclera, finding that a tri-linear model worked best with the finite element technique Kobayashi et al. [43].

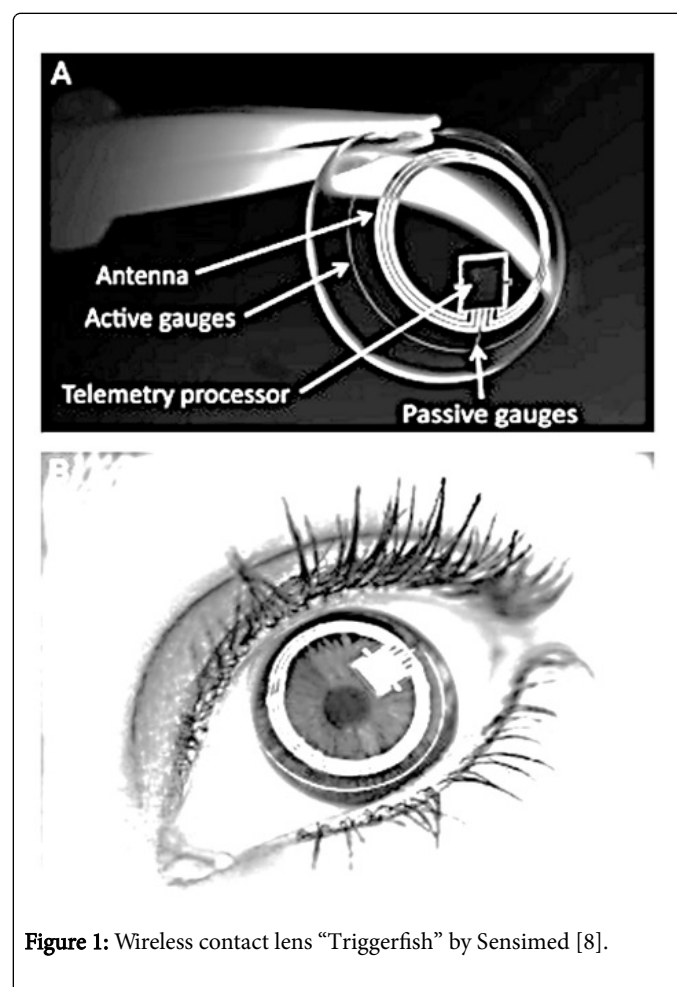
## Literature Review

Friedenwald [9] provides provided some of the first measurements of the important "ocular rigidity" parameter  $[\ln(\text{mmHg})/\text{mm}^3]$ , and how that relates to the calibration and measurement of intra-ocular pressure. Nash et al. [20] reviewed corneal mechanics, measuring the Young's modulus for cornea, an important parameter in terms of determining the effects of corneal bending and buckling. Ku et al. [21] measured the Young's modulus for sclera, including the effects of oscillating and reverse loads, similar to the brief impulse loading during tonometry.

Modern work on new devices would include the studies of Bao et al. [44] who reported the performance of the ocular response analyser, a device for evaluating corneal hysteresis, Raina et al. [45] and Feng et al. [46], evaluated the Air-Puff tonometer, and Ottobelli et al. [47] reported on ocular resonance tonography, to measure the aqueous flow-rate through the trabecular meshwork  $[\text{mm}^3/\text{min}]$ .

Ophthalmologists sometimes use a water drinking test to monitor the response of the system to excess fluid intake, Yassein et al. [48].

Using microfabricated strain gauges embedded in a contact lens, Zarbin et al. [8] reported measurements of circumferential changes in the area of the corneoscleral junction that indicated changes in IOP (Table 1 and Figure 1). Wireless powering and communication between the contact lens and the recording unit were achieved with a miniature microprocessor onboard the lens and a 9 mm loop antenna. This device, a miracle of modern electronics, allows continuous monitoring of fluctuations in the intra-ocular pressure, interrupted only during blinking. Transpalpebral tonometry is now possible [29], Table 1, allowing measurements through the lid, without anesthesia.



Collins [49] developed an implantable, remotely monitored pressure transducer, about the size of an aspirin tablet that was surgically inserted into the vitreous cavity, which directly and continuously measured the vitreous pressure, an important parameter in the study of glaucoma. Downs [14] reviewed the laboratory usage of similar remotely monitored intra-ocular pressure transducers. Injection of small volumes into the vitreous resulted in elevated I.O.P. [40,50].

Goyal et al. [51] used tonography to measure the aqueous outflow facility  $[\text{mm}^3/\text{mmHg}]$ , i.e. the flow "resistance" of the trabecular meshwork. Phillips et al. [52] used hollow rubber balls of various sizes to pre-calibrate tonometers. Coudrillier et al. [53] reviewed the effects of ageing on scleral collagen mechanical response, i.e. stiffness, an important factor with indentation tonometry. Girard et al. [54]

reviewed the practical clinical applications of ocular mechanics research. The pressure drop across the lamina cribrosa (LC) is an important parameter, in terms of quantifying the stress on LC fibers, Quigley [2], Hasnain [1].

Corneo-scleral stress-strain contributions to the overall mechanical response of the globe were measured in several studies [20,21,23,25,34,35], as they related to volumetric changes induced by indentation tonometry (Figure 2). Genest et al. [55,56] modeled the chick eye with a finite element model, which simulated glaucoma with internal pressure in the range 50 to 100 mmHg or greater. Uchio et al. [57], Ljubimova et al. [58] and Coquart et al. [41] used the finite element technique to model various aspects of ocular mechanics, including accommodation, impact, and vibration.

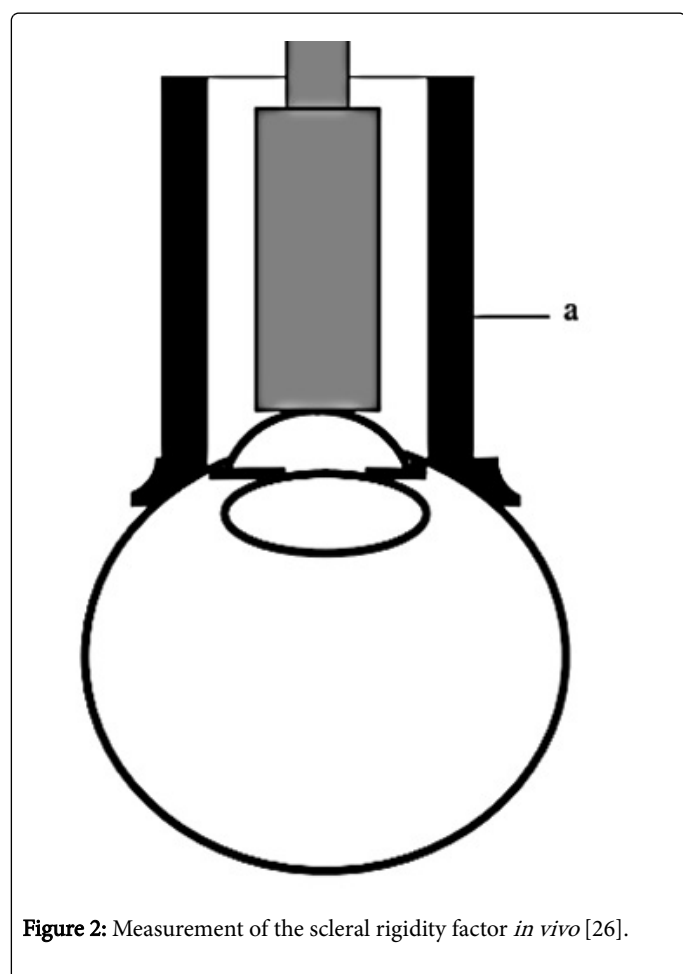


Figure 2: Measurement of the scleral rigidity factor *in vivo* [26].

Silver et al. [59] reported measurements of intra-ocular volume increase with pressure increase, finding a combined linear plus logarithmic equation, showing that both logarithmic (ocular rigidity) and linear (ocular stiffness) co-efficients are present. Pallikaris et al. [60] measured ocular rigidity in living human eyes, using injected manometry, finding that ocular rigidity increases with age, and decreases with axial length.

## Discussion

### Scleral rigidity

Another factor of clinical importance is the amount of axial myopia, because the scleral rigidity (Figure 2) is different for high myopes [23,61,62]. Ethier et al. [63] reviewed ocular mechanics, scleral rigidity, aqueous flow parameters, etc. Bellezza et al. [64], Roberts et al. [65], and Sigal et al. [66] calculated finite element stress-strain results for the lamina cribrosa (LC). Using A.P. ultrasound, Avetisov [50] and Sergienko et al. [26] measured the different mechanical properties of emmetropic and myopic eyes, reporting that the myopic eye has a lower scleral rigidity, as shown schematically in Figure 2.

### Clinical applications

Accommodation dynamics and intra-ocular pressure have been suggested as relevant to the development of axial myopia and high myopia. The drug Atropine, at various concentration levels and application rates, has been explored in several clinical studies, to reduce the progressive myopia rate [67]. Tonography devices measuring the outflow facility of the trabecular meshwork (TM) are beyond the scope of this report. Commonly used drugs, used routinely with glaucoma patients for reducing the intra-ocular pressure, include Pilocarpine and Timilol. Wang et al. [13] reviewed the development of Rho-kinase, as a means of reducing intra-ocular pressure.

### Conclusions

There are slight, but significant differences between various types of tonometers, some over-estimating and some under-estimating the intraocular pressure [68]. Therefore, as practiced by some ophthalmology and optometry clinics, to achieve an average and accurate results, two different instruments can be used for comparison. Generally speaking, scleral rigidity is only relevant with indentation tonometry, because the indented volume  $\Delta V$  [mm<sup>3</sup>] is larger than with applanation techniques. Moses et al. [69] presented an indirect graphical technique for calculating the scleral rigidity, using several different tonometer weights. Clinical tonometry has advanced to the point where reliable measurements can be taken through the lid, or through a contact lens, thus obviating the need for corneal anesthesia, an important convenience in the modern clinic. Lastly, at present, it seems that none of these instruments were designed specifically to measure the ocular or scleral rigidity (Figure 2), parameters that may prove useful in terms of estimating patient susceptibility to axial myopia.

### Nomenclature

dP = incremental increase in ocular pressure

I.O.P. = intra-ocular pressure [mmHg]

dV = incremental increase in ocular volume

K = ocular rigidity =  $d(\ln P)/dV$  [mm<sup>-3</sup>]

k = ocular stiffness =  $dP/dV$  [mmHg/mm<sup>3</sup>]

Q = aqueous inflow rate [mm<sup>3</sup>/min]

c = outflow facility of the trabecular meshwork [mm<sup>3</sup>/mmHg]

Goldmann Eq. I.O.P. =  $(1/c) \times (Q - U) + E.V.P.$

E.V.P. = episcleral venous pressure

$U$  = uveo-scleral outflow rate [ $\text{mm}^3/\text{min}$ ]  
 $R(t)$  = axial myopia [diopters] at age  $t$  [yrs]  
TM = trabecular meshwork  
ROP = retinopathy of prematurity  
LC = lamina cribosa ONH = optic nerve head  
 $w = \text{sqr} [3(1 - v^2)] P a / (E \times h^2)$ , corneal indentation,  $a$  = radius,  $h$  = thickness [70]  
 $P_{\text{crit}} = E * h^3 / (a \times \text{sqr} [3(1 - v^2)])$ , corneal buckling, (Timoshenko et al. [70])  
 $S_{\text{crit}} = P_{\text{crit}} R/2h$ , spherical buckling load for sclera (von Karman [22]),  $R$  = radius  
1 atm. = 760 mmHg = 29.92 inch-Hg = 14.7 lb/in<sup>2</sup> = 101.3 KPa = pressure conversions\

### Conflict of Interest Statement

The authors have no proprietary or financial conflicts of interest.

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