Review: Measurement Techniques for Intraocular Pressure

Peter R Greene1, Nikolai M Sergienko2 and Sean K Wang3
1BGKT Consulting Ltd., Bioengineering, Huntington, New York, USA
2Department of Ophthalmology, National Medical Academy of Postgraduate Education, Kiev, Ukraine
3Harvard Medical School, Boston, Massachusetts, USA

*Corresponding author: Peter R Greene, BGKT Consulting Ltd., Bioengineering, Huntington, New York, USA, Tel: +16319355666; E-mail: prgreeneBGKT@gmail.com

Received date: May 16, 2016; Accepted date: June 07, 2016; Published date: June 10, 2016

Copyright: © 2016 Greene PR, et al. This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.

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

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 ΔV, 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 corneoscleral 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 (mmHg)/mm], 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 [mm³/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, Zarin 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 [mm³/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. Coudriuller 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 cribosa (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 cribosa (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 Timolol. 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 ΔV [mm$^3$] 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

\[ dP = \text{incremental increase in ocular pressure} \]
\[ \text{I.O.P.} = \text{intra-ocular pressure [mmHg]} \]
\[ dV = \text{incremental increase in ocular volume} \]
\[ K = \text{ocular rigidity} = \frac{d (\ln P)}{dV} \text{[mm$^3$]} \]
\[ k = \text{ocular stiffness} = \frac{dP}{dV} \text{[mmHg/mm$^3$]} \]
\[ Q = \text{aqueous inflow rate [mm$^3$/min]} \]
\[ c = \text{outflow facility of the trabecular meshwork [mm$^3$/mmHg]} \]

Goldmann Eq. I.O.P. = \frac{1}{c} \times (Q - U) + E.V.P.

E.V.P. = episcleral venous pressure
8. Zarbin MA, Arlow T, Ritch R (2013) Regenerative nanomedicine for Henderson MT, Wang SK, Moshfeghi DM (2013) A new paradigm for
9. Myers KJ, Scott CA (1975)
12. Quigley HA (2011) Glaucoma. Lancet 377: 1367-1377.
15. Nuyen B, Mansouri K (2015) Fundamentals and Advances in Tonometry.
18. Clement CI, Bhatiyya S, Shaarawy T (2014) New perspectives on target intraocular pressure. Surv Ophthalmol 59: 615-626.
19. Stamper BL (2011) A history of intraocular pressure and its measurement. Optom Vis Sci 88: E16-28.
20. Nash IS, Greene PR, Foster CS (1982) Comparison of mechanical properties of keratoconus and normal corneas. Exp Eye Res 35: 413-424.
21. Ku DN, Greene PR (1981) Scleral creep in vitro resulting from cyclic pressure pulses: applications to myopia. Am J Optom Physiol Opt 58: 528-535.
22. Karman TV (1939) The buckling of spherical shells by external pressure. J Aeronaut Sci 7: 43-50.
23. Sergienko NM, Kondratenko JN (1997) Intra ocular pressure and anterior chamber angle in patients with myopia. XI th Congress of the European Soc of Ophthalmol Budapest 350.
24. Sergienko NM, Kondratenko InU (1989) Accommodative hyperemia of the ciliary body as one of the pathogenetic factors in myopia. Oftalmol Zh : 474-476.
25. Sergienko NM, Kondratenko InU (1986) Ophthalmotonus and the gonioscopic picture in progressive and stable myopia. Vestn Oftalmol 102: 20-23.
26. Sergienko NM, Kondratenko JN (1997) Intra ocular pressure and anterior chamber angle in patients with myopia. XI th Congress of the European Soc of Ophthalmol Budapest 350.
27. Sergienko NM, Kondratenko InU (1988) Hypothesis of the pathogenesis of myopia. Oftalmol Zh : 138-143.
28. Pierscionek BK, Aseyczyk-Widlicka M, Schachar RA (2007) The effect of changing intraocular pressure on the corneal and scleral curvatures in the fresh porcine eye. Br J Ophthalmol 91: 801-803.
29. Coquart L, Depeursinge C, Curnier A, Ohayon R (1992) A non-contact (“air puff”) tonometer: The authors have no proprietary or financial conflicts of interest.
30. References
1. Hasnain SS (2016) Pathogenesis of Orderly Loss of Nerve Fibers in Glaucoma. Optom open access I: 1-4.
2. Quigley HA (2011) Glaucoma. Lancet 377: 1367-1377.
3. Goldman H (1954) A new application tonometer. Bull Mem Soc Fr Ophtalmol 67: 474-477.
4. Cridland B (1917) The tonometer of schiotz. Br J Ophthalmol 1: 352-358.
5. Perkins ES (1965) Hand-held applanation tonometer. Br J Ophthalmol 49: 591-593.
6. Mackay RS, Marg E, Oechsl R (1960) Automatic tonometer with exact theory: various biological applications. Science 131:1668-1669.
7. Myers KL, Scott CA (1975) The non-contact (“air puff”) tonometer: variability and corneal staining. Am J Optom Physiol Opt 52: 36-46.
8. Zarbin MA, Arlow T, Ritch R (2013) Regenerative nanomedicine for vision restoration. Mayo Clinic Proc 88: 1480-1490.
9. Friedenwald JS (1937) Contribution to the theory and practice of tonometry. American Journal of Ophthalmology 20:985-1024.
10. Ozcura F, Yildirim N, Sahin A, Colak E (2015) Comparison of Goldman applanation tonometry, rebound tonometry and dynamic contour tonometry in normal and glaucomatous eyes. Int J Ophthalmol 8: 299-304.
11. Wang SK, Callaway NF, Wallenstein MB, Henderson MT, Leng T, et al. (2015) SUNDROP: six years of screening for retinopathy of prematurity with telemedicine. Can J Ophthalmol 50: 101-106.
12. Henderson MT, Wang SK, Mosheghi DM (2013) A new paradigm for incorporating the joint statement screening guidelines for retinopathy of prematurity into clinical practice: outcomes from a quaternary referral program. Ophthalmic Surg Lasers Imaging Retina 44:442-447.
13. Wang SK, Chang RT (2014) An emerging treatment option for glaucoma: Rho kinase inhibitors. Clin Ophthalmol 8: 883-890.
14. Downs JC (2015) IOP telemetry in the nonhuman primate. Exp Eye Res 141: 91-98.
15. Nuyen B, Mansouri K (2015) Fundamentals and Advances in Tonometry. Asia Pac J Ophthalmol (Phila) 4: 66-75.
16. Okafor KC, Brandt JD (2015) Measuring intraocular pressure. Curr Opin Ophthalmol 26: 103-109.
17. Sit AJ (2014) Intraocular pressure variations: causes and clinical significance. Can J Ophthalmol 49: 484-488.
18. Hasnain SS (2016) Pathogenesis of Orderly Loss of Nerve Fibers in Glaucoma. Optom open access I: 1-4.
