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MAJOR REVIEW

Self-tonometry in Glaucoma Management—Past, Present and Future

Steve Y.-W. Liang, MBBS,[1] Graham A. Lee, MD, MBBS, FRANZCO,[1,2,3] and David Shields, BSc[4]

[1]City Eye Centre, Brisbane, Queensland, Australia, [2]University of Queensland, Brisbane, Queensland, Australia, [3]Department of Ophthalmology, Royal Brisbane and Women's Hospital, Brisbane, Queensland, Australia; and [4]ViewMachine Corporation, Jacksonville, Florida, USA

Abstract. Glaucoma is the leading cause of irreversible blindness in the world. Diagnosis and management of glaucoma is significantly associated with intraocular pressure, but contemporary office-based measurements are not sufficient to discover diurnal changes and spikes, nor do they demonstrate the effect of medication and compliance. Patient-directed self-tonometry can be taken throughout the day and is therefore the subject of much discussion and research. In this article we review the history of self-tonometry devices and present technologies for the future. (**Surv Ophthalmol 54**:450–462, 2009. © 2009 Elsevier Inc. All rights reserved.)

Key words. glaucoma • intraocular pressure • self-tonometry • tonometer

I. Introduction

Glaucoma is the leading cause of irreversible blindness in the world and the second leading cause of blindness in the world after cataracts.[98] Numerous parameters have been studied over the last century to further the understanding and management of this disease, including the direct and indirect measurements of intraocular pressure (IOP), various forms of visual field testing, optic nerve and retinal nerve fiber layer estimation, central corneal thickness, the evaluation of the anterior chamber angle, and associated signs such as splinter hemorrhages. Intraocular pressure is the only modifiable factor and justifiably the primary target of glaucoma management.

The current approach is to measure the IOP at a routine office visit. We know, however, that the IOP varies over the course of a day and from day to day. It is also influenced by the cardiac cycle and blood pressure,[87] ocular manipulation, including ocular massage and tonometry, the use of topical pressure-lowering medications and local anesthetics, previous ocular surgery, posture, stress (which may be quantified by allostatic load) and other unquantifiable factors such as measurement technique. Many other factors may affect the IOP, including exercise, diet, sleep patterns, viral illness, sinus congestion, and playing a musical instrument. With self-tonometry the patient can take regular measurements through the day and overnight, if required, in a familiar environment without stress. It is possible then to chart the diurnal pattern of the patient's IOP, discover any fluctuations, as well as monitor the effect of medications and patient compliance.

This information can be used to direct therapy and investigate glaucoma suspects. Indeed, Hughes et al in 2003 reported that 24-hour IOP monitoring changed the clinical management of 79.3% of the

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29 patients in their study.[60] The enthusiastic and reliable patient could also be taught to self-medicate according to their measured IOP. This may increase patient compliance by giving power and control back to the patient, similar to self-monitoring of blood glucose levels for the diabetes or spirometry for asthma. It may reduce the number of routine visits, but also expedite emergency evaluation of an acute angle closure attack. Remote centers where ophthalmic expertise is limited could also benefit from the telemedicine application of self-tonometry. Self-tonometry may also further our understanding of glaucoma pathophysiology in ocular hypertension and normal-tension glaucoma.

II. History

The measurement of IOP has evolved over the last century from invasive manometry to various tonometric approaches. Albrecht von Graefe invented the first impression tonometer in 1862,[37] and this was followed by the Schiotz tonometer in 1906. The Goldmann applanation tonometer (GAT) was introduced in 1957 and has become the gold standard.[51]

A. CONTINUOUS INTRAOCULAR PRESSURE RECORDING

A complete record of IOP throughout the day, known as "phasing," can be obtained by hospitalizing the patient for regular measurements throughout the 24-hour cycle. However, this is an expensive and impractical exercise in a foreign environment for the patient. Other approaches have been considered. In 1958, Maurice suggested a continuous recording tonometer that was fixed to the head of the patient and continuously indented the cornea.[82] Nissen reported in 1977 and 1980 the use of a suction cup applanating tonometer that was able to take continuous measurements for an hour at a time.[90,91] A number of authors also reported their experience on continuous IOP recording with established tonometers.[47,81,92,112] Most of these devices were as impractical and expensive as hospitalization.

B. ASSISTED SELF-TONOMETRY

Assisted self-tonometry was suggested by Posner in 1965.[93] He educated the patient's family to take imprints on the "Applanometer," a modified Maklakoff tonometer, so that it could be reviewed by the ophthalmologist at a subsequent office visit. This idea evolved into the concept of "home tonometry" with the Schiotz tonometer under Jensen in 1973[61] and Alpar in 1983.[1] In 1991, Stewart et al trained family members and work colleagues to take IOP readings with the Pulsair-Keeler pneumatic tonometer; they reported 26 patients with good results.[113] Of interest, because the Pulsair-Keeler tonometer can be and was used by the patient as a self-tonometer in this study, for the first time home tonometry and self-tonometry overlapped.

C. SELF-TONOMETRY

The challenge of self-tonometry was taken up as early as 1967, when Collins reported the invention of a wireless passive intraocular sensor that used a pressure-sensitive capacitor to detect IOPs in 70 rabbits with good tolerance.[18] This work formed the basis for the current research into intraocular lens tonometers.

Between 1965 and 1990, Draeger et al modified and developed the GAT into an automatic hand-held electronic applanation tonometer that eventually became the Ocuton S hand-held tonometer.[26–30,33–36,40] In 1974, Greene and Gilman proposed a different approach using a soft contact lens that was embedded with a strain gauge to measure the angular deformation caused by IOP changes at the corneoscleral junction.[52] Although this was not commercially feasible because the contact lenses needed to be molded individually, it inspired the development of the Sensing Contact Lens by Leonardi et al in 2003.[75] Another contact lens tonometer design was suggested by Lee in 1988.[73] This involved applanation tonometry with a membrane on the back of a contact lens that was inflated by a pressure pump. This device was never realized, most likely because of the cumbersome arrangement of the pressure pump and attached tubing.

In 1976, Couvillon et al described a new continuous applanation tonometer.[21] This was a small titanium pressure sensor in a hydrogel ring that continually applanates the sclera under the lower eyelid. Unlike the corneal applanation tonometers, this device can be held in continuous applanation without a local anesthesia, corneal injury, or impaired vision. Active telemetric transmission of the pressure readings were done by radio frequency. Although canine trials had shown potential, the promised human trials were never reported. In 1977, Cooper and Beale described a similar sclera-applanating device that used the passive capacitor technology pioneered by Collins.[19] In 1979, the sensor was incorporated into a haptic contact lens that was held in the lower fornix and tested in the rabbit and dog.[20] This device did not proceed to human trials either, possibly because individual differences in scleral rigidity made commercialization impractical.

A different style of sclera-applanating pressure sensor was proposed by Wolbarsht et al in 1980,

modeled on the scleral buckle commonly used for retinal detachment repairs at the time.[125] A strain gauge is incorporated into the scleral buckle, and when the diameter of the orbit changes with the IOP, the relative strain difference is detected and transmitted. While results were encouraging, the device suffered from problems with biocompatibility, and its measurements were inaccurate because the eye expanded unevenly in response to increases in IOP. Furthermore, the surgery required to place the device is so disproportionately invasive that it makes the device impractical.

D. HUMAN TRIALS

It was not until 1983 that the first device designed for self-tonometry underwent human trials. The "Home-tonometer" was designed and investigated by Zeimer, and Wilensky and co-workers, between 1982 and 1987.[124,126–128] The device measures the pressure required to applanate the cornea using the same principles as the non-contact tonometer. The eye is anesthetized and aligned with the instrument by focusing on a target down a transparent probe. The probe is then pressurized, moving forward to contact and applanate the cornea. The applanation is detected opto-electronically by measuring the amount of reflected light from the probe-cornea interface. The pressure required to applanate the cornea is used to calculate the IOP. The studies were small, but showed that the device was well-tolerated and allowed analysis of diurnal variations.

The non-contact tonometer (NCT) itself was studied for its potential as a self-tonometer. The Pulsair-Keeler tonometer was a hand-held non-contact tonometer that used the change in optical properties of the cornea when indented by a puff of air to calculate the IOP. The patient holds the instrument 2 cm away from the cornea and visually lines up the fixation points in the measuring component. The tonometer automatically fires when it optically senses that the unit is correctly aligned. Boles Carenini et al studied self-tonometry using the Pulsair-Keeler tonometer in 90 eyes of 45 patients between the ages of 37 and 77.[7] Self-tonometry was achieved in 75% of the cases and the measurements were within 1 mm Hg of the GAT measurements in 73% of the cases. This result is encouraging, but not good enough for practical use. Furthermore, it was unclear from the report what undertaking was required to educate the patients to perform self-tonometry with this instrument.

III. Current Technology

As electronics and manufacturing technology progressed rapidly, new ideas and technical modifications spurred the development of a variety of self-tonometers.

A. PRESSURE PHOSPHENE TONOMETER

The Proview Eye Pressure Monitor (Bausch & Lomb, Rochester, NY) was invented by Fresco in 1997 (Fig. 1).[49,50] It is a spring compression device with a 3.06-mm diameter circular tip that is applied to the superonasal orbit over the upper eyelid while the eye is directed inferotemporally. As increasing pressure is applied to the eye, a visual sensation that has been variously described as like a solar eclipse or a dark circle surrounded by a bright halo is produced, and the measured IOP is read off the scale. The visual sensation is an entopic phenomenon that occurs with deformation of the eyeball and had been described by various authors since Alcmaeon of Croton circa 600 BCE. A good summary of this history was presented by Grusser and Hagner in 1990.[55] It is thought to be caused by changes in the bipolar cells or parts of the rods and cones anterior to the external limiting membrane.[10,54]

The attraction of the Proview Eye Pressure Monitor is that it is relatively inexpensive, simple to use, easy to maintain, does not need a local anesthetic, and is not affected by corneal aberrations. In practice, Fresco's initial proof-of-concept study in 192 eyes showed a good correlation with GAT between 10 and 28 mm Hg. As a result of the pressing need for a self-tonometer, as well as the simplicity and alternative nature of the concept, the Proview tonometer has generated much interest over the last 10 years. A number of studies have shown that the Proview tonometer can perform at IOPs outside the range of 10–20 mm Hg;[2,5,22,96,99,115] other studies, however, have demonstrated a tendency to overestimate IOPs less than 10 mm Hg and underestimate IOPs greater than 20 mm Hg.[9,50,56,71,76,89,108,109,115,123]

When the measured IOPs were between 10 and 20 mm Hg, between 74.9% and 86% of Proview readings are within 2 mm Hg difference with GAT and between 87% and 100% are within an acceptable 3 mm Hg difference with GAT.[17,50,76,115] Two studies showed that the Proview tonometer had good reproducibility, with one study showing that repeated intraobserver measurements were within 1.76 ± 1.76 mm Hg of each other[9] and the other showing that 95% of intraobserver readings were between 2.17 and –2.52 mm Hg of each other.[76] Between 81% and 92% of patients found the Proview tonometer easy to use[77,96,115] and 88% were willing to continue its use at home.[115] One study also showed that an average of only 17.9 ± 4.0 minutes were required to achieve competency in

Fig. 1. (Left and Right): The Proview Eye Pressure Monitor (Bausch & Lomb, Rochester, NY).

self-tonometry with the Proview tonometer.[115] Proview readings are independent of LASIK surgery and therefore central corneal thickness.[77,89,109] The LASIK studies also demonstrated good reproducibility of Proview readings pre- and post-surgery.

Many studies, however, showed a limited correlation with GAT.[2,4,5,11,14,16,17,22,23,57,62,77,85,86,88,96,99,104] These found that only 30–47% of Proview readings are within 2 mm Hg difference with GAT, and only 51–61% are within an acceptable 3 mm Hg difference with GAT.[22,77,96] In one study of 137 subjects, only 18% of those with IOPs greater than 21 mm Hg (4/22), were correctly identified.[2] A number of studies showed poor reproducibility, with one study showing only 69% of readings were within 2.2 ± 1.5 mm Hg of each other.[96] Critically, between 2.2% and 31% of patients were unable to detect the pressure phosphene with the Proview tonometer.[2,9,14,17,49,57,78,85]

In summary, there is no consensus on the effectiveness of the Proview tonometer. This could be addressed with a well-designed study in which there is a large sample size, a defined end-point for the perception of a phosphene, and extensive patient training in recognizing the defined end-point and the technique of using the tonometer. There needs to be randomization of measurements with Proview tonometry and GAT to minimize the effect of ocular manipulation, stratification of patients by age and glaucoma stage, as well as exclusion of invalid IOP measurements, such as IOPs lower than 8 mm Hg or higher than 40 mm Hg, as dictated by the physical limits of the instrument.

The flaws in the instrument and the concept itself are more difficult investigate. The threshold for phosphene elicitation may vary with different scleral and eyelid characteristics[104] as well as different levels of ambient light.[97] Patients may become desensitized to phosphene perception with multiple measurements.[99] The linear scale of the Proview tonometer may not reflect Hooke's law for the linear behavior of springs.[2] Sensitivity to pressure phosphene may differ at different stages of glaucoma and patients with advanced glaucoma may have lost visual capacity in the target inferotemporal visual field.[102] Finally, it is plausible that pressure phosphenes may not correspond to IOP at all.

B. OCUTON S

The Ocuton S (EPSa Elektronik & Präzisionsbau, Saalfeld, Germany) tonometer was developed from the work of Draeger et al over the last four decades.[8,25,27–36,38–46,53] Initially named the "Self-Tonometer," the Ocuton S tonometer is a hand-held electronic automatic applanation tonometer based on the same principles as the GAT (Fig. 2). After topical anesthesia, the patient positions the device 10 mm in front of the eye, balancing it on the forehead and cheeks, and visually lines up the eye with the internal fixation light. A polymethylmethacrylate prism is automatically advanced to contact and applanates the apex of the cornea such that the contact area has a specific diameter of 3.06 mm as determined by the relative reflections of an internal parallel beam of light at the prism-air versus the prism-corneal interface. With the measured applanating force, the tonometer calculates the IOP using the Imbert-Fick principle. The prism is cleaned and sterilized with an alcohol wipe and a built-in ultraviolet light.

Between 1999 and 2005, a number of studies compared the Ocuton S with GAT in self-tonometry.[67,68,80,103,116,117,119] They have small sample sizes and diverse outcomes, with the majority finding that Ocuton S readings are 1.7–6.3 mm Hg higher than GAT readings. The most supportive study found that 80% and 90% of the Ocuton S readings were within

Fig. 2. (Left and Right)*:* The Ocuton S tonometer (EPSa Elektronik & Präzisionsbau, Saalfeld, Germany). Reprinted with permission from EPSa Elektronik.

2 mm Hg and 3 mm Hg of GAT, respectively.[116] While taking multiple measurements per reading and excluding outlier values has been shown to decrease the difference between the Ocuton S readings and the GAT readings, Sacu et al showed that only 67% of the median of six consecutive successful Ocuton S readings fall within 3 mm Hg of GAT readings, with a 90% confidence interval of 56–77%.[103] It is also likely that the ocular massage caused by taking multiple measurements with the Ocuton S and GAT affects the accuracy of the IOP readings. The studies also vary as to the ease of self-tonometry with the Ocuton S. Two studies of 196 patients in total showed that between 41%[117] and 48%[119] could not perform self-tonometry with the Ocuton S despite training, whereas another two relatively smaller studies with 25 subjects in total reported 100% achievement with the self-tonometer after only brief training.[67,80] Further studies of the training duration and process are needed to assess whether proficiency or capability with the Ocuton S can be improved in normal and glaucoma patients.

The potential advantage of the Ocuton S self-tonometer is that it would allow the patient to detect or exclude spikes of IOP in day-to-day life. This would be of most utility in early disease when target IOPs have to be determined. Many patients, however, may not be able to use the device: patients with limited field, patients with tremor who would have difficulty in keeping the device in position, and patients who have difficulty in self-administering the local anesthetic drops. The use of a local anesthetic and cornea device that contacts the cornea in a "home" environment are of concern, being because of the risks of corneal abrasion, ulceration, and infection. Similar to GAT, the Ocuton S readings are also influenced by the central corneal thickness (CCT) and changes in the CCT throughout the day, although studies differ as to the significance of this variation.[68,80]

C. TONO-PEN

The Tono-Pen is the second most commonly used tonometer clinically (the first is GAT). It is a small, portable device that has been shown to correlate well with GAT except in the extremes of IOP measurements. Despite its widespread and obvious ease of use, the Tono-Pen has only been investigated once in the literature for self-tonometry. This was done by Kupin et al in 1993, who reported the successful use of the Tono-Pen No. 2 by a 52-year-old man over a period of 4 years.[69] This patient was able to monitor his own IOP and maintain it between 15 and 18 mm Hg by bleb-massage. Over a period of 12 months, the patient was able to lower his IOP significantly by 1.2 ± 0.7 mm Hg in the right eye and 2.0 ± 0.6 mm Hg in the left eye. The patient also reported more confidence with his glaucoma management. Although the authors report that 93% of the measurements were within 2 mm Hg of GAT, there was no indication of the method of validation.

The disadvantages of the Tono-Pen are that it is expensive to purchase and to maintain, and its operation requires the use of a local anesthetic. It also requires dexterity, making it unsuitable for many elderly patients.

IV. Future Technology

A. INTRAOCULAR LENS TONOMETER

The intraocular lens tonometer was first suggested by Collins in 1967.[18] In this landmark paper Collins introduced the idea of a wireless passive

intraocular sensor embedded into an artificial intraocular lens. The sensor consists of a capacitor whose two plates are pushed together when IOP is exerted on them. This alters the capacitance of the sensor and therefore its resonance frequency. The resonance frequency is then captured using the grid-dip technique with an external oscillator sweeping a range of frequencies and correlated to the IOP from a pre-determined graph.

It took another 20 years before this idea was revisited in a series of technical papers.[3,79,101,114] The authors suggested improvements to the Collins intraocular sensor using novel micromachining techniques of photolithography, fusion bonding, and wet etching to create a silicon membrane and substrate that act as the plates of the passive resonance capacitor. The new techniques and material attempt to address the problems of creep and different thermal expansion coefficients in the Collins sensor.

Since then, other authors have suggested further improvements and variations. Some authors have experimented with different materials, such as incorporation into a polymethylmethacrylate lens[94,95,106] and polydimethylsiloxane[105] (Fig. 3). Others modified the sensor to allow active transmission of data out of and energy into the sensor via radiofrequency[84,120–122] and transcutaneously.[48] The analog signal is converted into digital data in situ on an integrated microchip using standard complementary metal-oxide semiconductor (CMOS) processing. New technology allowed the development of the foldable sensor using flexible microcoil technology[118] (Fig. 4), calibration with reference and temperature sensors, and in situ microprocessing for erroneous measurements.[110,111] The possibility of using a piezoresistive sensor instead of a capacitor was raised.[15] The change in IOP would produce stress in the piezoresistive sensor, thereby creating a change in resistance in the circuit that can be detected. However, the piezoresistive sensor has questionable long-term stability and is susceptible to temperature effects.

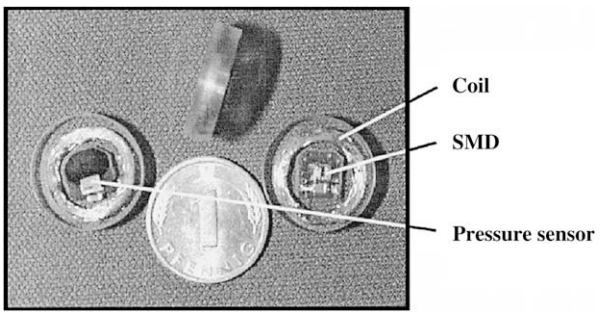

Fig. 3. Experimental intraocular lens tonometer encased in a polydimethylsiloxane intraocular lens. Reprinted from Schnakenberg et al[105] with permission of *Sensors and Actuators.*

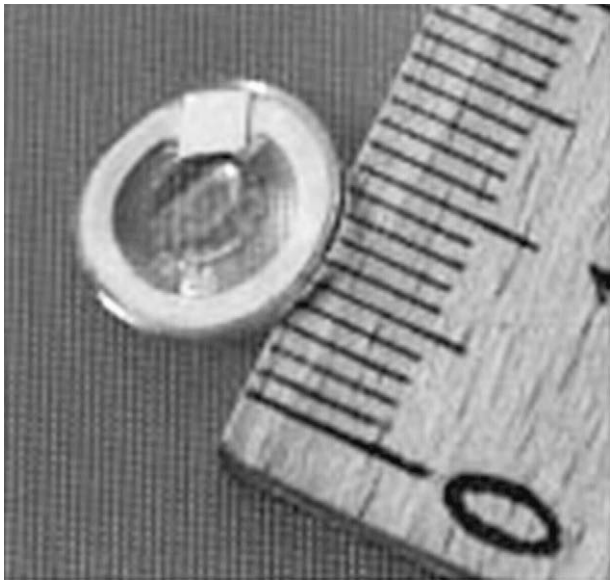

Fig. 4. Experimental intraocular lens tonometer incorporated a soft intraocular lens using flexible microcoil technology. Reprinted from Mokwa and Schnakenberg[84] with permission of IEEE.

A number of the aforementioned designs have been tested in animal models and cadaveric eyes;[18,58,84,122] however, none have yet proceeded to human trials. The advantage of this device is that it would allow continuous, direct measurement of the true IOP independent of the cornea. The main problems are the size of the implanted device, the range and magnitude of the transmission signal, long-term stability of the device, and the potential effect of the transmitted radiofrequency and energy on nearby tissues. An invasive procedure is required to insert the device and would also need to be optically functional.

B. SPIRAL-TUBE IRIS-SUPPORTED ANTERIOR-CHAMBER TONOMETER

In 2006, Chen et al pioneered an alternative design for an intraocular sensor fixed to the iris.[12,13] The sensor is based on the Bourdon tube so that as the external IOP varies against the sealed internal tube pressure, the sensor mechanically deforms, and the amount of deformation can be related to the IOP and read from the outside with a magnifier. The actual mechanical design of the tube can be either an Archimedian spiral or a serpentine tube (Fig. 5). The authors chose parylene (poly-para-xylene C) as the device material for its flexibility, chemical inertness, and biocompatibility. The tonometer is

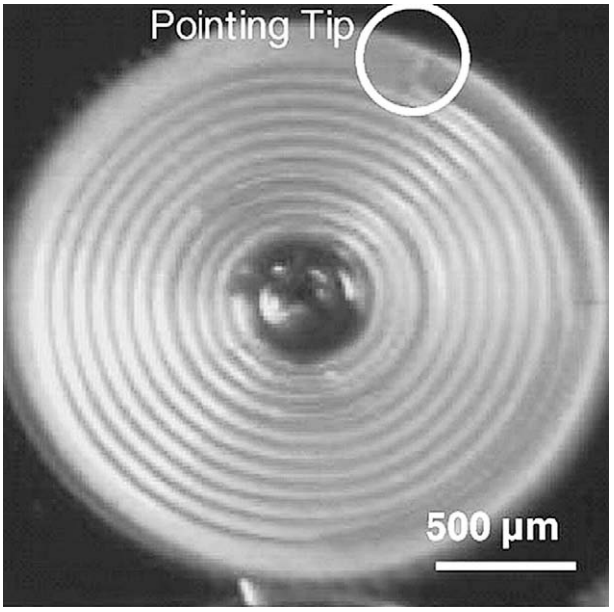

Fig. 5. Proposed spiral-tube iris-supported anterior chamber tonometer. Reprinted from Chen et al[13] with permission of IEEE.

inserted into the anterior chamber via a 19-gauge needle and attached to the iris by special anchors.

Compared to the intraocular lens tonometer, this novel design has the advantages of a less invasive deployment, ease of use, and not requiring electronics nor energy transfer. Like the intraocular lens tonometer, this device measures the true IOP independent of the cornea. Nevertheless, in addition to the usual risks associated with an invasive procedure, manipulation in the anterior chamber is also associated with the risks of endophthalmitis and cystoid macular edema. Furthermore, a device placed in the anterior chamber predisposes to corneal decompensation.

Apart from the discussed disadvantages, there are also a number of hurdles that must be overcome for this device to move on to animal studies. Firstly, it is not yet sensitive enough to detect small pressure variations. Its current size does not allow anterior chamber implantation and whether the iris could support its weight is unknown. Visual determination of the IOP is difficult for the visually impaired glaucoma patients and would also be affected by corneal aberrations and opacification.

C. SENSING CONTACT LENS

In 2003, Leonardi et al introduced the sensing contact lens.[6,74,75] Similar to the Greene and Gilman contact lens tonometer discussed in the History section, this was a soft contact lens embedded with strain gauges to measure the change in the cornea due to IOP variations (Fig. 6). However, instead of measuring the angular deformation at the corneoscleral junction, the sensing contact lens detects the deformation of the central cornea curvature. For a corneal radius of 7.8 mm, a change in IOP of 1 mm Hg produces a change of 3 mm in the central corneal curvature.[59,70] Two active gauges and two passive resistive platinum-titanium strain gauges are incorporated into a soft silicon contact lens in a Wheatstone bridge configuration. The active gauges are placed circumferentially to measure the change in corneal curvature while the passive gauges are placed radially to minimize the effect of corneal deformation and thereby act as the temperature reference measures. The current version is connected by a microflex cable to the controller. However, the aim is to create a wireless version of the device in the near future.

In 2004, Leonardi et al tested this device in six enucleated pig eyes, showing good sensitivity and correlation between IOPs of 17 and 29 mm Hg. Human trials followed in 2006 showing good sensitivity and tolerability in seven healthy subjects. However, it is unclear from the discussion how the measured IOP correlated with GAT; whether gravity at different head positions, blinking, ocular movements and corneal changes from prolonged contact lens wear had any impact on the measurements; whether there was any difficulty in keeping the contact lens on the subjects; and over what range of IOPs is the sensing contact lens accurate in human subjects. It is also unclear whether the sensing contact lens would need to be individually molded like the Greene and Gilman contact lens tonometer. There are also a number of issues to address, including the effect of electromagnetic forces and generated heat on the eye and risk to vision in the long term.

If all the aforementioned issues were successfully addressed, the advantage of the sensing contact lens is that it allows the non-invasive, continuous—albeit indirect—measurement of the IOP without the

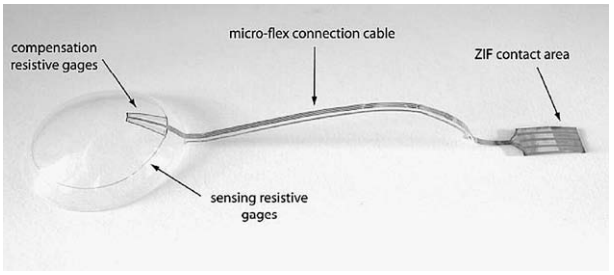

Fig. 6. Sensing contact lens. The communicating microflex cable is replaced with a wireless transponder in future designs. Reprinted from Leonardi et al[74] with permission of *Investigative Ophthalmology and Visual Science.*

need for a local anesthetic. The limitations are the same as with any contact lens use with the risk of corneal abrasion, ulcer, and infection.

D. CHOROIDAL INTRAOCULAR TONOMETER

An alternative intraocular tonometer was proposed by Rizq et al in 2001.[100] The choroidal intraocular tonometer indirectly measures the IOP at the choroidal surface in the posterior segment. A piezoresistive pressure sensor-transponder less than 1-mm long is inserted perpendicularly through a 2.5-mm diameter scleral hole opened by a trephine and positioned apposed to the choroidal surface. The endplate is sutured to the scleral surface. Radiofrequency transduction would power the sensor and allow measured pressures to be transmitted externally. Experiments were conducted on three cadaver eyes, showing good correlation between the choroidal intraocular tonometer and anterior chamber manometry between 10.3 and 47.1 mm Hg.

The advantage of this device over the other two IOP sensors is that it will not impede vision. Like the other two intraocular sensors, however, it is subject to the risks of invasive intraocular surgery and, due to its particular positioning, the risks of choroidal hemorrhage.

E. INTRASCLERAL HARMONICS-BASED PASSIVE TELEMETRIC TONOMETER

In 1996, Schuylenbergh and Puers suggested a variation to the intraocular lens tonometer.[107] This sensor is similar to the intraocular lens tonometer in design with the difference being that the passive sensor is read using the harmonics of the resonant frequency. It is positioned intrasclerally for proposed better long-term stability. The device is yet to be tested in animal models.

F. TIOLAT ICARE REBOUND TONOMETER

The Tiolat ICare rebound tonometer (Fig. 7) was developed and commercialized from a novel proposal by Kontiola et al in 1997.[63–66] It is a hand-held unit that works by measuring the deceleration of a magnetized probe in an electromagnetic field on the rebound off the cornea. This is correlated to the IOP with an effective range of 5–60 mm Hg. Although there has been no published literature on its efficacy as a self-tonometer, this device warrants a mention in this section of the review because it is currently marketed as having the capability of self-tonometry and mention of successful unpublished pilot studies were made by Kontiola and Puska in 2004.[64] The main advantages of this device are that it does not require a local anesthetic and that several IOP measurements can be conducted in rapid succession. Its limitation, however, is that it may be difficult to self-align the device in the correct measurement position in vision-impaired glaucoma patients and in patients with tremor and/or blepharospasm. Detry-Morel provides a good summary on the current literature comparing the ICare tonometer with GAT,[24] but further studies are required to prove its efficacy as a self-tonometer.

G. POTENTIAL SELF-TONOMETRIC ADAPTATION OF MODERN TONOMETERS

There are a number of commercially available tonometers that have the potential to be used as self-tonometers. The Reichert AT555 (Fig. 8; Reichert

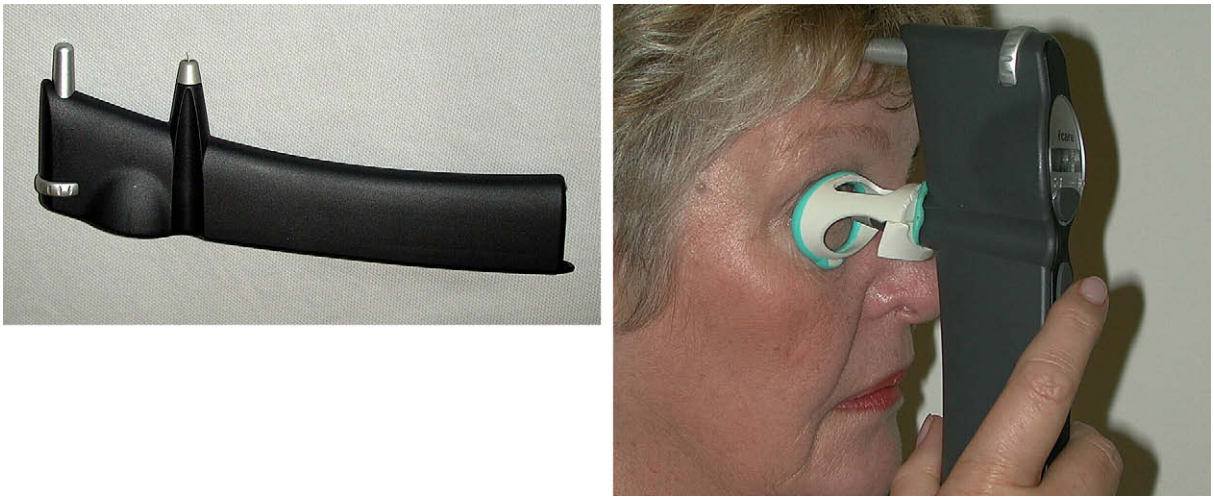

Fig. 7. (Left and Right)*:* The ICare rebound tonometer (Tiolat, Finland) and technique of self-measurement using a lid-holder and positioning device.

Fig. 8. (left and right). The AT555 (Reichert Inc., Depew, NY) and technique of self-measurement with screen view of output.

Inc., Depew, NY), the Reichert Ocular Response Analyser (Reichert Inc.), and the Nidek NT 4000 (Nidek Co. Ltd., Aichi, Japan) are all microprocessor-enabled non-contact tonometers that are capable of full automation. Although they are expensive and difficult to carry around because of their weight and connections to other hardware and electrical sources, they can be readily adapted for home-based self-tonometry. There is a group of about a dozen glaucoma patients who have been performing self-tonometry daily with the Reichert AT555, some for several years. Some of these patients have collected thousands of IOP measurements in a variety of circumstances. The positive feedback from these patients and the ideas that have come out of this informal group have encouraged us in regard to the possibilities for conducting worthwhile self-tonometry research with currently available tonometers. However, studies to prove the efficacy of any of these tonometers for self-tonometry are necessary; and it is also important to note that these devices are intrinsically incapable of measuring IOPs during sleep and during vigorous activity.

The PASCAL Dynamic Contour Tonometer (Ziemer Ophthalmic Systems AG, Port, Switzerland) is another tonometer that may be adapted for self-tonometry. It is a contact tonometer similar to GAT but measures corneal deformation through a solid-state pressure sensor rather than by optical properties of light. This theoretically allows for a microprocessor-automated measurement of the IOP, although the current configuration requires a separate operator. The PASCAL tonometer has the same disadvantages as the instruments just discussed. In addition, it requires the use of a local anesthetic with the associated risks of corneal abrasions and ulcerations.

V. Conclusion

A. THE FUTURE OF SELF-TONOMETRY?

We can foresee the self-tonometer becoming an important part of the delivery of care to glaucoma patients. Potentially, it will be able to send readings to a secure central database that automatically flags fluctuating IOPs and alerts the treating ophthalmologist electronically. This will provide great benefit to patients who live remote to their treating ophthalmologist and may be useful for population screening programs.[72,83,120]

B. IDEAL DEVICE?

The ideal device needs to be safe, reproducible, reliable and easy to use. It should be accurate over a wide range of IOPs, or alternatively, be able to be calibrated individually to correlate with GAT. A diagnostic device, in addition, needs to be minimally invasive, removable, and require minimal patient and/or doctor training. Such a device could be loaned to a patient, for example, to take diurnal measurements over a period of 1–2 weeks to help distinguish normal-tension glaucoma from primary open-angle glaucoma with fluctuation of IOP. In contrast, a long-term monitoring device is ideally implantable, biocompatible, low maintenance, and durable. This device could be useful in established glaucoma patients who appear to be progressing despite IOPs measured in the normal range during office hours. A single device is not capable of meeting all these criteria, and thus it is envisaged a range of self-tonometers will need to be developed.

There is much progress in technology required. Furthermore, commercialization of this technology

and its affordability are hurdles that are no less difficult to overcome. However, if "necessity is the mother of invention" then realization of these self-tonometers may be in the not-too-distant future.

VI. Method of Literature Search

The literature review for this article was performed using Medline and the IEEE database using the search terms *self-tonometry, Proview, pressure phosphene, Ocuton S, ICare*, and combinations of *self, intraocular pressure, glaucoma, tonometer* and *monitor.* All years were covered. Additional sources include articles cited in the reference lists of other articles and Google search of the above terms. All articles were judged to be of clinical significance. All non-English articles were considered with significant non-English articles translated in full and published English abstracts used for the other non-English articles.

References

1. Alpar JJ. The use of tonometry in the diagnosis and treatment of glaucoma. Glaucoma. 1983;5(3):130–2
2. Alvarez TL, Gollance SA, Thomas GA, et al. The Proview phosphene tonometer fails to measure ocular pressure accurately in clinical practice. Ophthalmology. 2004; 111(6):1077–85
3. Backlund Y, Rosengren L, Hok B, Svedbergh B. Passive silicone transensor intended for biomedical, remote pressure monitoring. Sensors Actuators;A21–3, 58–61.
4. Bartolone A, Chung I. A clinical comparison of Proview and Goldmann tonometry in children. Optom Vis Sci. 2004;81(Suppl):52
5. Baskaran M, Krishna KR, Ramesh SV, et al. Comparison of Proview phosphene tonometer with the Goldmann applanation tonometer in myopic and non-myopic eyes. Asian J Ophthalmol. 2006;8(2):57–61
6. Bertsch A, Leonardi M, Renaud P. The sensing contact lens. Med Device Technol. 2006;17(5):19–21
7. Boles Carenini B, Brogliatti B, Tonetto C, Renis E. The Pulsair-Keeler non-contact tonometer in self-tonometry: preliminary results. Int Ophthalmol. 1992;16(4–5):295–7
8. Bolla N, Savio E, Bellone A, et al. The Draeger autotonometer: its advantages and limits. Acta Ophthalmol Scand. 1998;227(Suppl):21–2
9. Brigatti L, Maguluri S. Reproducibility of self-measured intraocular pressure with the phosphene tonometer in patients with ocular hypertension and early to advanced glaucoma. J Glaucoma. 2005;14(1):36–9
10. Brindley GS. The site of electrical excitation of the human eye. J Physiol. 1955;127(1):189–200
11. Castells D, Fredrickson S, Theesfeld M, Stalzer B. Proview pressure phosphene tonometry: a comparison of accuracy with Goldmann tonometry. Optom Vis Sci. 2003;80(Suppl): 251
12. Chen PJ, Rodger DC, Humayun MS, Tai YC. Unpowered spiral-tube parylene pressure sensor for intraocular pressure sensing. Sensors Actuators A: Physical. 2006;127(2): 276–82
13. Chen PJ, Rodger DC, Meng E, et al. Implantable unpowered parylene MEMS intraocular pressure sensor. Technical Digest, IEEE Engineering in Medicine and Biology Society Special Topic Conference on Microtechnologies in Medicine and Biology. May 9–12, 2006;256–9
14. Chew GS, Sanderson GF, Molteno AC. The pressure phosphene tonometer—a clinical evaluation. Eye. 2005; 19(6):683–5
15. Chomiak R. An approach to designing an implantable intraocular pressure sensor. IEEE Proceedings of 29th Annual Bioengineering Conference. March 22–23, 2003:154–155
16. Choudhari NS, Sekhar GC, Nutheti R, Thomas R. Precision and accuracy of Proview tonometer: clinical implications for self-tonometry. J Glaucoma. 2005;14(6):515
17. Chung I, Bartolone A, Swanson WH, Thau AP. A clinical evaluation of proview pressure phosphene tonometry in children. Optom Vis Sci.. 2006;83(11):817–22
18. Collins CC. Miniature passive pressure transensor for implanting in the eye. IEEE Trans Biomed Eng. 1967; 14(2):74–83
19. Cooper RL, Beale D. Radiotelemetry of intraocular pressure in vitro. Invest Ophthalmol Vis Sci. 1977;16(2): 168–71
20. Cooper RL, Beale DG, Constable IJ. Passive radiotelemetry of intraocular pressure in vivo: calibration and validation of continual scleral guard-ring applanation transensors in the dog and rabbit. Invest Ophthalmol Vis Sci. 1979;18(9): 930–938
21. Couvillon LA, Baker CD, Grover TP, Konigsberg E. Telemetry monitoring of intraocular pressure. Biotelemetry. 1976;3:123–6
22. Danesh-Meyer HV, Niederer R, Gaskin BJ, Gamble G. Comparison of the Proview pressure phosphene tonometer performed by the patient and examiner with the Goldmann applanation tonometer. Clin Experiment Ophthalmol. 2004;32(1):29–32
23. Daniels K, Wilson C. Independent clinical comparability of the Proview eye pressure monitor versus the Goldmann applanation tonometer. Optom Vis Sci. 2003;80(Suppl): 133
24. Detry-Morel M. Update in tonometry. Phosphene and rebound tonometries, self-tonometry and technologies for the future. Bull Soc Belge Ophtalmol. 2007;303:87–95
25. Deutsch C, Draeger J, Groenhoff S. [2 years self-tonometry. Acceptance and results]. Ophthalmologe. 1992;89(6):489–92
26. Draeger J. Uber ein lageunabhangiges Applanationstonometer. Klin Monatsbl Augenheilkd. 1965;149:905–11
27. Draeger J. [A new hand applanation tonometer for application on recumbent and sitting patients]. Ber Zusammenkunft Dtsch Ophthalmol Ges. 1966;67:391–3
28. Draeger J. [On a position-independent applanation tonometer]. Klin Monatsbl Augenheilkd. 1966;149(6):905–11
29. Draeger J. Simple hand applanation tonometer for use on the seated as well as on the supine patient. Am J Ophthalmol. 1966;62(6):1208–10
30. Draeger J. Principle and clinical application of a portable applanation tonometer. Invest Ophthalmol. 1967;6(2): 132–4
31. Draeger J. [Principles of measurements in tonometry at the time of Albrecht von Graefes to D2 mission and self-tonometry]. Klin Monatsbl Augenheilkd. 1993;202(1):2–7
32. Draeger J. [Intraocular pressure self-monitoring in glaucoma patients]. Klin Monatsbl Augenheilkd. 1998;213(1): A9
33. Draeger J, Becker F. [Results with a new aplanation tonometer]. Bibl Ophthalmol. 1967;71:169–203
34. Draeger J, Groenhoff S. [Self-tonometry—technical possibilities and clinical significance]. Fortschr Ophthalmol. 1990;87(6):688–91
35. Draeger J, Groenhoff S, Hock B, Klemm M. [Optimizing the automatic self-tonometer by an acoustic control signal and changed fixation optics]. Ophthalmologe. 1993;90(1): 54–7
36. Draeger J, Hechler B, Levedag S, Wirt H. [Automatic measurement of intraocular pressure with an electronic sensor tonometer]. Klin Monatsbl Augenheilkd. 1987; 190(6):539–41

37. Draeger J, Kaefer I. [A contribution to the history of tonometry. The first impression tonometer (A. v. Graefe, 1862)]. Klin Monatsblatter Augenheilkd Augenarztl Fortbild. 1959;135:846–52
38. Draeger J, Michelson G, Rumberger E. Continuous assessment of intraocular pressure—telematic transmission, even under flight—or space mission conditions. Eur J Med Res. 2000;5(1):2–4
39. Draeger J, Rumberger E. [New diagnostic possibilities by a fully automatic applanation tonometer for the ophthalmologist. From the Goldmann principle to automated tonometry]. Ophthalmologe. 2000;97(8):571–3
40. Draeger J, Rumberger E, Dauper J, Deutsch C. Microprocessor controlled tonometry. Eye. 1989;3(6):738–42
41. Draeger J, Schwartz R, Deutsch C, Groenhoff S. [Clinical and experimental results with a new fully automatic self-tonometer]. Fortschr Ophthalmol. 1991;88(3):304–7
42. Draeger J, Schwartz R, Groenhoff S, Stern C. Self-tonometry under microgravity conditions. Clin Investig. 1993;71(9):700–3
43. Draeger J, Schwartz R, Groenhoff S, Stern C. [Self tonometry during the German 1993 Spacelab D2 mission]. Ophthalmologe. 1994;91(5):697–9
44. Draeger J, Schwartz R, Groenhoff S, Stern C. Self-tonometry under microgravity conditions. Aviat Space Environ Med. 1995;66(6):568–70
45. Draeger J, Wiezorrek R, Hock B, Gerhard E, Klemm M. [Physical technical calibration of a new self-tonometer]. Ophthalmologe. 1993;90(1):51–3
46. Draeger J, Winter R. [Entwicklung und Andwendung eines neuen automatischen Selbsttonometers]. Spektrum Augenheilkd. 1998;121:7–9
47. Durham DG, Bigliano RP, Masino JA. Pneumatic applanation tonometer. Trans Am Acad Ophthalmol Otolaryngol. 1965;69(6):1029–47
48. Eggers T, Draeger J, Hille K, et al. Wireless intra-ocular pressure monitoring system integrated into an artificial lens. 1st Annual International Conference on Microtechnologies in Medicine and Biology. 2000;1: 466–469
49. Fresco BB. Pressure phosphene tonometry. Invest Ophthalmol Vis Sci.. 1997;38(Suppl):S1056
50. Fresco BB. A new tonometer—the pressure phosphene tonometer: clinical comparison with Goldman tonometry. Ophthalmology. 1998;105(11):2123–6
51. Goldmann H, Schmidt T. [Applanation tonometry]. Ophthalmologica. 1957;134(4):221–42
52. Greene ME, Gilman BG. Intraocular pressure measurement with instrumented contact lenses. Invest Ophthalmol. 1974;13(4):299–302
53. Groenhoff S, Draeger J, Deutsch C, et al. Self-tonometry: technical aspects of calibration and clinical application. Int Ophthalmol. 1992;16(4–5):299–303
54. Grusser OJ, Grusser-Cornehls U, Hagner M, Przybyszewski AW. Purkyne's description of pressure phosphenes and modern neurophysiological studies on the generation of phosphenes by eyeball deformation. Physiol Bohemoslov. 1989;38(4): 289–309
55. Grusser OJ, Hagner M. On the history of deformation phosphenes and the idea of internal light generated in the eye for the purpose of vision. Doc Ophthalmol. 1990;74(1–2):57–85
56. Gunvant P, Baskaran M, Ramani K, Lingham V. Comparison of the Proview tonometer with the Goldmann applanation tonometer. Optom Vis Sci. 2003;80(Suppl): 226
57. Herse P, Hans A, Hall J, et al. The Proview Eye Pressure Monitor: influence of clinical factors on accuracy and agreement with the Goldmann tonometer. Ophthalmic Physiol Opt. 2005;25(5):416–20
58. Hille K, Draeger J, Eggers T, Stegmaier P. [Technical construction, calibration and results with a new intraocular pressure sensor with telemetric transmission]. Klin Monatsbl Augenheilkd. 2001;218(5):376–80
59. Hjortdal JO, Jensen PK. In vitro measurement of corneal strain, thickness, and curvature using digital image processing. Acta Ophthalmol Scand. 1995;73(1):5–11
60. Hughes E, Spry P, Diamond J. 24-hour monitoring of intraocular pressure in glaucoma management: a retrospective review. J Glaucoma. 2003;12(3):232–6
61. Jensen AD, Maumenee AE. Home tonometry. Am J Ophthalmol. 1973;76(6):929–32
62. Kinnaird C, Bartels Z, Pedarsani N, Zetlmeisl K. Accuracy of the Proview eye pressure monitor in comparison to the Goldmann tonometer in serial tonometry in a veteran population. Optom Vis Sci. 2003;80(Suppl):133
63. Kontiola A. A new electromechanical method for measuring intraocular pressure. Doc Ophthalmol. 1997;93(3): 265–76
64. Kontiola A, Puska P. Measuring intraocular pressure with the Pulsair 3000 and Rebound tonometers in elderly patients without an anesthetic. Graefes Arch Clin Exp Ophthalmol. 2004;242(1):3–7
65. Kontiola AI. A new induction-based impact method for measuring intraocular pressure. Acta Ophthalmol Scand. 2000;78(2):142–5
66. Kontiola AI, Goldblum D, Mittag T, Danias J. The induction/impact tonometer: a new instrument to measure intraocular pressure in the rat. Exp Eye Res.. 2001; 73(6):781–5
67. Kothy P, Nagymihaly A, Hollo G. The evaluation of tonometry and self-tonometry with Ocuton tonometers. Med Sci Monit. 2003;9(1). PI1–4.
68. Kothy P, Vargha P, Hollo G. Ocuton-S self tonometry vs. Goldmann tonometry; a diurnal comparison study. Acta Ophthalmol Scand. 2001;79(3):294–7
69. Kupin TH, Shin DH, Juzych MS, et al. Use of a Tono-Pen for long-term home tonometry. Am J Ophthalmol. 1993; 116(5):643–4
70. Lam AK, Douthwaite WA. The effect of an artificially elevated intraocular pressure on the central corneal curvature. Ophthalmic Physiol Opt. 1997;17(1):18–24
71. Lam DS, Leung DY, Chiu TY, et al. Pressure phosphene self-tonometry: a comparison with Goldmann tonometry in glaucoma patients. Invest Ophthalmol Vis Sci.. 2004;45(9): 3131–6
72. Lammer R, Groh ME, Michelson G. [Telematic-assisted self-tonometry (TAS)]. Ophthalmologe. 2004;101(8):813–8
73. Lee DA. A theoretical design for a contact lens tonometer. Med Hypotheses. 1988;26(1):25–9
74. Leonardi M, Leuenberger P, Bertrand D, et al. First steps toward noninvasive intraocular pressure monitoring with a sensing contact lens. Invest Ophthalmol Vis Sci.. 2004; 45(9):3113–7
75. Leonardi M, Leunberger P, Bertrand D, Renaud P. A soft contact lens with a MEMS strain gauge embedded for intraocular pressure monitoring. Transducers '03: The 12th International Conference on Solid State Sensors. Boston, Actuators and Microsystems, June 8–12, 2003; 2:1043–6.
76. Leung DY, Rao SK, Lam DS. Pressure phosphene self-tonometry in a patient with Posner-Schlossman syndrome. Clin Experiment Ophthalmol. 2006;34(6):513–5
77. Li J, Herndon LW, Asrani SG, et al. Clinical comparison of the Proview eye pressure monitor with the Goldmann applanation tonometer and the Tonopen. Arch Ophthalmol. 2004;122(8):1117–21
78. Lievens CW, Gunvant P, Newman J, et al. Effect of Proview self-tonometry on pharmaceutical compliance. Clin Exp Optom. 2006;89(6):381–5
79. Linden Y. Hok B. Ejdesjo L. et al. Development of a micromachined transensor for monitoring of intraocular pressure. Trans World Congr on Med Phys & Biomed Eng; August 6–12, 1988:367
80. Marchini G, Babighian S, Specchia L, Perfetti S. Evaluation of the new Ocuton S tonometer. Acta Ophthalmol Scand. 2002;80(2):167–71
81. Matsumuto T, Nagata R, Saishin M, et al. Measurement by holographic interferometry of the deformation of the eye

accompanying changes in intraocular pressure. Appl Optics. 1978;17. 3638–539.
82. Maurice DM. A recording tonometer. Br J Ophthalmol. 1958;42(6):321–35
83. Michelson G, Striebel W, Prihoda W, Schmidt V. Telemedicine in the control of intra-ocular pressure. J Telemed Telecare. 2000;6(Suppl):S126–8
84. Mokwa W, Schnakenberg U. Micro-transponder systems for medical application. IEEE Transactions on Instrumentation and Measurement. 2001;50(6):1551–4
85. Moreno Montanes J, Sadaba LM, Heras H. [Intraocular pressure measurement using the Proview tonometer]. Arch Soc Esp Oftalmol. 2005;80(2):79–83
86. Morledge-Hampton SJ, Kwon RO, Krishna R, et al. Comparison of Proview phosphene tonometry with Goldmann applanation tonometry. Can J Ophthalmol. 2006; 41(6):722–6
87. Moses RA, Arnzen RJ. Instantaneous tonometry. Arch Ophthalmol. 1983;101(2):249–52
88. Naruse S, Mori K, Kinoshita S. Evaluation of the pressure phosphene tonometer as a self-tonometer. Ophthalmic Physiol Opt. 2005;25(5):421–8
89. Naruse S, Mori K, Kojo M, et al. Evaluation of intraocular pressure change after laser in situ keratomileusis using the pressure phosphene tonometer. J Cataract Refract Surg. 2004;30(2):390–7
90. Nissen OI. Continuous recording of the intraocular pressure in human and rabbit eyes with a simple applanating suction cup. Acta Ophthalmol (Copenh). 1977;55(5): 750–60
91. Nissen OI. Bilateral recording of human intraocular pressure with an improved applanating suction cup tonograph. Acta Ophthalmol (Copenh). 1980;58(3):377–87
92. Ohnesorge FK, Soyka H, van Zwieten PA. Continuous determination of intraocular pressure in the rat. Exp Eye Res.. 1968;7(1):70–4
93. Posner A. Home use of the Applanometer as an aid in the management of glaucoma. Eye Ear Nose Throat Mon. 1965;44:64–6
94. Puers R. Capacitive sensors: when and how to use them. Sensors Actuators A: Physical. 1993;37–38:93–105
95. Puers R. Linking sensors with telemetry: impact on the system design. Transducers '95. The 8th International Conference on Solid-State Sensors and Actuators, and Eurosensors IX, Stockholm, Sweden. June 9–25, 1995;1:47–50
96. Rai S, Moster MR, Kesen M, et al. Level of disagreement between Proview phosphene tonometer and Goldmann applanation tonometer intraocular pressure readings. J Glaucoma. 2005;14(2):120–3
97. Reichardt C, Snider M, Bergenske P. The effect of ambient illumination and dark adaptation on the force required to perceive a pressure phosphene. Optom Vis Sci. 2003; 80(Suppl):130
98. Resnikoff S, Pascolini D, Etya'ale D, et al. Global data on visual impairment in the year 2002. Bull World Health Organ. 2004;82(11):844–51
99. Rietveld E, van den Bremer DA, Volker-Dieben HJ. Clinical evaluation of the pressure phosphene tonometer in patients with glaucoma. Br J Ophthalmol. 2005;89(5): 537–9
100. Rizq RN, Choi WH, Eilers D, et al. Intraocular pressure measurement at the choroid surface: a feasibility study with implications for implantable microsystems. Br J Ophthalmol. 2001;85(7):868–71
101. Rosengren L, Backlund V, Sjostrom T, et al. A system for wireless intra-ocular pressure measurements using a silicon micromachined sensor. J Micromech Microeng. 1992;2: 202–4
102. Rumsey J, Sowka J, Reich L. Pressure phosphene measurement in advanced glaucoma. Optom Vis Sci. 2003; 80(Suppl):132
103. Sacu S, Vass C, Schemper M, Rainer G. Self-tonometry with the Ocuton S: evaluation of accuracy in glaucoma patients. Acta Ophthalmol Scand. 2004;82(4):405–9
104. Sawamura M, Comer G, Nakawama E, Kim H. The impact of eyelids on the agreement between the Proview tonometer and the Goldmann applanation tonometer: ethnic variables. Optom Vis Sci. 2003;80(Suppl):134
105. Schnakenberg U, Walter P, Vom Bogel G, et al. Initial investigations on a system for measuring intraocular pressure. Sensors Actuators. 2000;A85:287–91
106. Schuylenbergh KV, Peeters E, Puers B, et al. An implantable telemetric tonometer for direct intraocular pressure measurements. Abstr 1st Eur Conf Biomed Eng, Nice, France, February 17–20, 1991:194–5
107. Schuylenbergh KV, Puers R. Passive Telemetry by Harmonics Detection. 18th Annual International Conference of the IEEE Engineering in Medicine and Biology Society, Amsterdam. October 31–November 3, 1996:299–300
108. Sehi M, Flanagan JG. The reliability and repeatability of the Proview Eye Pressure Monitor during diurnal measurement of the intraocular pressure. Optom Vis Sci. 2002; 79(Suppl):72
109. Shemesh G, Man O, Michaeli A, et al. Pressure phosphene tonometry versus Goldmann applanation tonometry for measuring intraocular pressure before and after LASIK. J Refract Surg. 2007;23(4):405–9
110. Stangel K, Kolnsberg S, Hammerschmidt D, et al. A programmable intraocular CMOS pressure sensor system implant. Proceedings of the 26th European Solid-state Circuits Conference, Stockholm, Sweden, September 19–21, 2000
111. Stangel K, Kolnsberg S, Hammerschmidt D, et al. A Programmable Intraocular CMOS Pressure Sensor System Implant. IEEE J Solid-State Circuits. 2001;36(7):1094–100
112. Stepanik J. [The Mackay-Marg-tonometer. VII. The continuous registration of the intraocular pressure (author's transl)]. Albrecht Von Graefes Arch Klin Exp Ophthalmol. 1976;198(2):171–7
113. Stewart WC, Cascairo MA, Banta R. The use of a new portable noncontact tonometer in home tonometry. Ann Ophthalmol. 1991;23(10):377–82
114. Svedbergh B, Backlund Y, Hok B, Rosengren L. The IOP-IOL. A probe into the eye. Acta Ophthalmol (Copenh). 1992;70(2):266–8
115. Tai MC, Chen PL, Wu JN, Lu DW. Clinical evaluation of the intraocular pressure in patients with glaucoma or ocular hypertension by a self-assessable tonometer. J Ocul Pharmacol Ther. 2005;21(1):55–61
116. Theisen R, Scherer V, Ruprecht KW. [Self-measurement of intraocular pressure]. J Fr Ophtalmol. 2001;24(4):378–81
117. Theofylaktopoulos I, Diestelhorst M, Krieglstein GK. Self-tonometry with the Ocuton S versus Goldmann tonometry. Graefes Arch Clin Exp Ophthalmol. 1999;237(9):720–4
118. Ullerich S, Mokwa W, vom Bogel G, Schnakenberg U. Foldable microcoils for a transponder system measuring intraocular pressure. Proceedings Sensors. 2001;1:319–24
119. Vogt R, Duncker GI. [Usability of self-tonometry under ambulatory conditions to obtain daily profiles of intraocular pressure at home]. Klin Monatsbl Augenheilkd. 2005; 222(10):814–21
120. Walter P. Intraocular pressure sensor: where are we—where will we go? Graefes Arch Clin Exp Ophthalmol. 2002; 240(5):335–6
121. Walter P. [Medical aspects of active implants in the eye]. Biomed Tech (Berl). 2002;47(Suppl):158–60
122. Walter P, Schnakenberg U, vom Bogel G, et al. Development of a completely encapsulated intraocular pressure sensor. Ophthalmic Res.. 2000;32(6):278–84
123. Wang WH, Patel P. Utilizing the Proview pressure phosphene tonometer as a screening device in community outreach. Optom Vis Sci.. 2004;81(Suppl):89
124. Wilensky JT, Gieser DK, Mori MT, et al. Self-tonometry to manage patients with glaucoma and apparently controlled intraocular pressure. Arch Ophthalmol. 1987;105(8): 1072–1075
125. Wolbarsht ML, Wortman J, Schwartz B, Cook D. A scleral buckle pressure gauge for continuous monitoring of intraocular pressure. Int Ophthalmol. 1980;3(1):11–7

126. Zeimer RC, Wilensky JT. An instrument for self-measurement of intraocular pressure. IEEE Trans Biomed Eng. 1982;29(3):178–83
127. Zeimer RC, Wilensky JT, Gieser DK, et al. Evaluation of a self tonometer for home use. Arch Ophthalmol. 1983; 101(11):1791–3
128. Zeimer RC, Wilensky JT, Gieser DK, et al. Application of a self-tonometer to home tonometry. Arch Ophthalmol. 1986;104(1):49–53

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Reprint address: Professor Graham Lee, Level 10, 135 Wickham Terrace, Brisbane, QLD 4000, Australia. e-mail: eye@cityeye.com.au.

Outline