

Intraocular pressure measurement after penetrating keratoplasty: minified Goldmann applanation tonometer, pneumatonometer, and Tono-Pen versus manometry

Mitchel J Ménage, Paul L Kaufman, Mary Ann Croft, Stuart P Landay

Abstract

The accuracy of intraocular pressure measurement with the minified Goldmann applanation tonometer, the pneumatonometer, and the Tono-Pen tonometer were compared in post-mortem human eyes which had undergone penetrating keratoplasty. Enucleated post-mortem human eyes underwent same sized (7.75 mm) or 0.5 mm oversized (8.25 mm) autologous penetrating keratoplasty. Intraocular pressure was then set and measured manometrically while being determined successively with each tonometer over the range of 0-65 mm Hg. Linear regression analysis comparing tonometric and manometric readings showed: (1) minified Goldmann applanation tonometer - slope 0.985 and 0.944, intercept 1.64 and 2.55 mm Hg, correlation coefficient 0.99 and 0.99 in same sized and oversized grafted eyes respectively; (2) pneumatonometer - slope 1.008 and 0.990, intercept 3.37 and 3.69 mm Hg, correlation coefficient 0.99 and 0.98; (3) Tono-Pen - slope 1.061 and 1.002, intercept 5.01 and 4.06 mm Hg, correlation coefficient 0.97 and 0.98. We concluded that the minified Goldmann applanation tonometer is as accurate or more accurate than the pneumatonometer and the Tono-Pen in post-mortem post-keratoplasty human eyes, and may be an economical, convenient alternative to the latter two instruments in clinical practice.

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The measurement of intraocular pressure after penetrating keratoplasty is reported to be difficult with the Goldmann applanation tonometer because of inaccuracy induced by the sutures interfering with the tip of the instrument, corneal surface irregularity, and corneal oedema.¹ Several authors have shown that there is a marked tendency to high intraocular pressure in the immediate postoperative period, particularly after aphakic or pseudophakic graft surgery.¹⁻³ Some patients show a late postoperative chronic elevation of intraocular pressure,³⁻⁵ particularly if there is a preoperative history of glaucoma.³ Goldmann applanation tonometry is most problematic in the immediate postoperative period and in some cases can remain a long term difficulty. Since the advent of the Mackay-Marg tonometer⁶ and its more modern version, the Tono-Pen,⁷ measurement of intraocular pressure after penetrating keratoplasty is reported to be more reliable.⁸⁻¹⁰ Others have investigated the use

of the pneumatonometer¹¹ in irregular or recently grafted eyes.¹²

The accuracy of a minified version of the Goldmann applanation tonometer in normal cynomolgus monkey and human eyes has been described.¹³ In this instrument the front 4 mm of a standard Goldmann applanating prism is reduced in diameter from 7.0 mm to 4.00 mm on a lathe, without changing the endpoint of intraocular pressure measurement, which is the applanation of a circle of cornea 3.06 mm in diameter. The authors suggested that the minified Goldmann applanation tonometer would permit applanation of the central graft tissue, without interference from the sutures or irregular interface tissue, in eyes which have undergone penetrating keratoplasty.

The pneumatonometer, developed by Langham and co-workers,¹¹ consists of a hollow plunger in a porous sleeve propelled by gas and using a gas bearing. The tip is 4.4 mm in diameter and covered with a thin silicone rubber membrane. When the tip is applied to the cornea the membrane occludes multiple small orifices, impeding the outflow of gas and propelling the plunger toward the eye with greater force until equilibrium is reached. At equilibrium the pressure in the flow system is proportional to the intraocular pressure and is measured electronically and displayed either on a liquid crystal panel (Modular One; Mentor O & O, Inc, Norwell, MA, USA) or as a pen recording (Model 30 R; Mentor O & O). The pneumatonometer was claimed to be an applanation tonometer by Langham but this has been disputed by other investigators.¹⁴

The Tono-Pen (Mentor O & O) is a hand held, self-contained instrument which operates on the same principle as the Mackay-Marg tonometer. It consists of a 1.2 mm central plunger attached to a micro-strain gauge transducer, surrounded by a stationary, nearly flush 3.2 mm annulus. A disposable tip cover is used to avoid contamination. The force exerted on the plunger is transmitted as a voltage wave that is analysed by a microprocessor for acceptability. Three to six accepted samples are averaged and the mean shown on a liquid crystal display along with a coefficient of variation (standard deviation divided by the mean) indicator.

Both the pneumatonometer and the Tono-Pen are in current clinical use for intraocular pressure measurement after penetrating keratoplasty.

We investigated the accuracy of the minified Goldmann applanation tonometer, pneumatonometer and Tono-Pen in measuring intraocular

Department of
Ophthalmology and
Visual Sciences,
University of Wisconsin,
Clinical Science Center,
Madison, WI, USA

M J Ménage*
P L Kaufman
M A Croft
S P Landay

*Current address:
General Infirmary at Leeds,
Great George Street, Leeds
LS1 3EX, UK.

Correspondence to:
Dr Paul L Kaufman,
Department of
Ophthalmology and Visual
Sciences, University of
Wisconsin, Clinical Science
Center, 600 Highland
Avenue, Madison, WI
53792-3220, USA.

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pressure characteristics in postmortem human eyes which had received same sized and oversized penetrating corneal grafts.

Materials and methods

The study used postmortem human eyes considered unsuitable for human transplant for various reasons. All experiments were carried out within 48 hours of death. Seven eyes underwent same sized penetrating keratoplasty using a 7.75 mm hand-held trephine, the button being rotated 90° and sutured back into place. Seven pairs of eyes underwent a 0.5 mm oversized penetrating keratoplasty using a 7.75 mm trephine for the recipient eye and an 8.25 mm trephine to cut the donor tissue from the paired eye. In all cases the donor tissue was secured with 16 10/0 deep stromal nylon sutures in the usual manner. Sutures were not buried but the knots were pulled to the recipient side of the interface. The anterior chambers were reformed using balanced salt solution and if necessary any interface leaks treated by replacement or additional sutures.

Each eye was mounted on a custom built plastic eye holder and secured in position, with the cornea facing horizontally, by pins passed through the optic nerve remnant. The anterior chamber was cannulated through the limbus with a branched 26 gauge needle, one arm of which was connected via rigid polyethylene tubing to a vertically adjustable test tube reservoir of degassed mock aqueous humour (Bárány's solution),¹⁵ the other arm to a pressure transducer, amplifier, and pen recorder. The pressure drop across the needle has previously been calculated to be 0.17 mm Hg at 24 mm Hg.¹⁶ A small amount of cyanoacrylate glue was used to seal the entry wound of the needle at the limbus. The transducer was calibrated to 0 mm Hg, 30 mm Hg, and 60 mm Hg using test tube reservoirs of water before each experiment.

The eye was placed at the calibrated 0 mm Hg height, the test tube reservoir raised to a height corresponding to 20 mm Hg, and the intraocular pressure allowed to stabilise. The central graft tissue thickness was measured using an optical pachymeter (Haag-Streit) and the corneal curvature at the steepest and flattest meridians measured using a keratometer (Bausch & Lomb, Inc, Rochester, NY, USA).

The intraocular pressure was then measured using the minified Goldmann applanation tonometer (mounted on a standard Goldmann applanation apparatus on a Haag-Streit slit-lamp), the pneumatonometer (Modular One), and the Tono-Pen (XL). The instruments were always used in that order and all measurements at all pressures were carried out with one instrument before using another. The manometric pressure was raised in approximately 12 arbitrary increments between 0 mm Hg and 65 mm Hg, with measurements at each level after 60 seconds of stabilisation. The test tube reservoir was open to the eye throughout the experiment.

If the epithelium became oedematous and friable during the experiment, it was carefully scraped from the central graft tissue with a blade. This occurred in five of the seven same sized

grafts and three of the seven oversized grafts, always early in the minified Goldmann tonometer measurement series.

Before each experiment, calibration of the minified Goldmann applanation tonometer was tested with the standard metal calibration rod in the usual manner. The scale wheel was dialled to 20 mm Hg before and after each intraocular pressure measurement and was masked with a paper strip before determination of each applanation end point. The planed 4 mm diameter tip was placed precisely within the graft interface on the surface of the graft tissue. To correct for any inaccuracy caused by graft astigmatism, the intraocular pressure was measured with the mires oriented both horizontally and vertically for each manometric pressure and the mean of the readings used for comparison.¹⁷ 'Half and Half' coffee creamer (Borden, Inc, Columbus, Ohio; milk, cream, non-fat dry milk, disodium phosphate, sodium citrate) was used in the tear film instead of fluorescein to generate the mires, since the tendency of fluorescein to infiltrate the corneal epithelium with repeated measurements¹⁸ made end point determination very difficult. The effect of this substitution on intraocular pressure readings with the Goldmann applanation tonometer should be minimal. The 'Half and Half' was applied directly to the tip of the prism with an eye dropper and cleaned off with alcohol between each measurement.

The pneumatonometer and the Tono-Pen were both supplied by the manufacturer for our experiments. The pneumatonometer was calibrated with the manufacturer's standard test apparatus, which artificially mimics an intraocular pressure of 20 mm Hg. The plastic tip was placed on the graft tissue within the interface and the digital readout of the intraocular pressure recorded. The surface of the pneumatonometer tip was cleaned with alcohol and dried thoroughly after each measurement.

The calibration procedure for the Tono-Pen was carried out at the beginning of each experiment. The tip of the instrument was applied to the centre of the graft tissue. The latex tip cover was replaced after every second intraocular pressure measurement. The instrument will accept a series of three to six readings and automatically displays the mean intraocular pressure and a coefficient of variation indicator. We only accepted values with a coefficient of variation $\leq 5\%$.

Results

Details are summarised for the same sized grafts in Table 1 and for the oversized grafts in Table 2. As would be expected¹⁹ the mean keratometer readings from the same sized grafts were significantly flatter than the oversized grafts ($p=0.002$ unpaired two tailed t test).

The results for the minified Goldmann applanation tonometer, pneumatonometer, and Tono-Pen are summarised in Figures 1, 2, and 3 respectively. There were a total of 81 intraocular pressure measurements in the seven same sized penetrating keratoplasty eyes and 87 in the seven oversized penetrating keratoplasty eyes with the minified Goldmann applanation tonometer, 84

Table 1 Details of same sized penetrating keratoplasty eyes

Donor no	Age (years)	Time from death to experiment (hours)	Graft thickness (mm)	Keratometry (dioptries)		
				Flattest	Steepest	Mean
1	52	21	0.76	36.0	41.5	38.8
2	52	24	0.80	36.3	39.5	37.9
3	71	24	0.90	36.5	41.0	38.8
4	71	45	0.85	36.0	40.5	38.3
5	57	14	0.70	38.5	42.0	40.3
6	57	34	0.75	39.5	42.5	41.0
7	73	29	0.75	39.5	48.0	43.8
Mean	62	27	0.79	37.5	42.1	39.8
SD	9	10	0.07	1.6	2.8	2.1

Table 2 Details of oversized penetrating keratoplasty eyes

Donor no	Age (years)	Time from death to experiment (hours)	Graft thickness (mm)	Keratometry (dioptries)		
				Flattest	Steepest	Mean
1	75	33	0.85	39.5	49.0	44.3
2	55	30	0.75	40.5	42.5	41.5
3	76	7	0.80	42.5	48.5	45.5
4	67	25	0.70	41.5	46.0	43.8
5	70	9	0.70	39.0	45.5	42.3
6	64	29	0.80	41.5	45.3	43.4
7	81	33	0.70	41.0	44.5	42.8
Mean	70	24	0.76	40.8	45.9	43.3
SD	9	11	0.06	1.2	2.3	1.3

and 91 with the pneumatonometer, and 85 and 91 with the Tono-Pen. Linear regression analyses of the relations between the measured intraocular pressures and actual manometric intraocular pressures are summarised in each figure.

From Figure 1 it can be seen that the minified Goldmann applanation tonometer gave a very

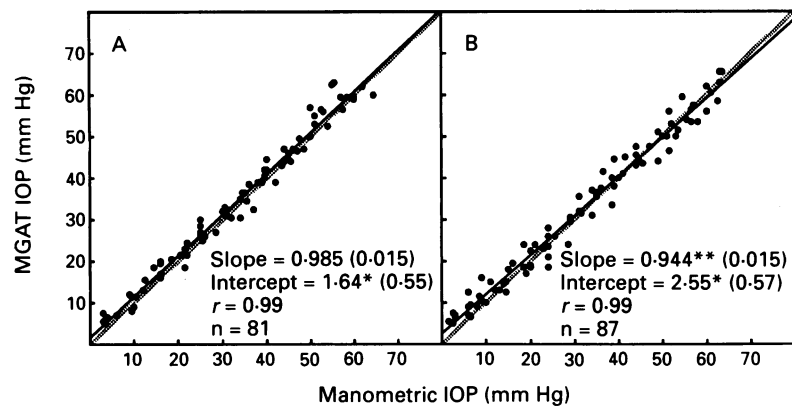


Figure 1 Manometric (x) versus minified Goldmann tonometric (MGAT; y) intraocular pressure (IOP) measurements in enucleated postmortem human eyes following same size (A) or 0.5 mm oversized (B) penetrating keratoplasty. Broken line, $y=x$; solid line, least squares regression of MGAT measurements on manometric IOP. **Slope significantly different from 1.0, $p<0.001$. *Intercept significantly different from 0.0, $p<0.004$.

reliable measurement of the intraocular pressure after penetrating keratoplasty in both the same sized and oversized penetrating keratoplasty eyes. The slopes are very close to one with a low intercept and a high correlation coefficient.

From Figures 2 and 3 it can be seen that although both the pneumatonometer and the Tono-Pen gave a reasonable estimate of the manometric intraocular pressure with high correlation coefficients, there was a tendency for both instruments to overread in a linear fashion throughout the range of measurements and this was most pronounced for the Tono-Pen measurements in the eyes with same sized penetrating keratoplasty.

Because of the possibility that the overestimation of intraocular pressure of the pneumatonometer and Tono-Pen could be due to a calibration fault we also tested a second model of each instrument.

The second pneumatonometer (Model 30 R) had been serviced recently by the manufacturer and was used to measure the intraocular pressure in three of the same sized grafted eyes. Results of a total of 38 separate measurements are graphically summarised in Figure 2C with linear regression analysis. Comparison of Figure 2C with Figure 2A shows that the second instrument also tended to overread, although this effect diminished with increasing pressure.

The second Tono-Pen was in clinical use and was used to measure the intraocular pressure in three of the oversized grafted eyes. The results of 39 separate measurements are graphically summarised in Figure 3C with linear regression analysis. Comparison of Figure 3C with Figure 3B shows a very similar overread of intraocular pressure throughout the range of measurements.

Removal of the corneal epithelium changed the slope or intercept in a few instances, but did not alter the overall findings (Table 3).

Discussion

We found the minified Goldmann applanation tonometer to be very accurate in the measurement of the intraocular pressure in both same sized and oversized grafted postmortem human eyes. Minified Goldmann applanation tonometer values reflected manometric intraocular pressure more closely and uniformly across the entire experimental range than the values of the

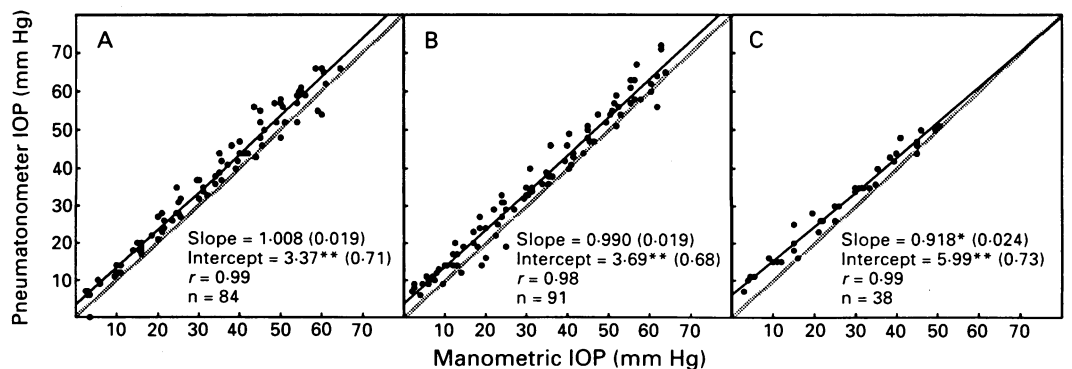


Figure 2 Manometric (x) versus pneumatonometer (y) intraocular pressure (IOP) measurements in enucleated postmortem human eyes following same size (A, pneumatonometer 1; C, pneumatonometer 2) or 0.5 mm oversized (B, pneumatonometer 1) penetrating keratoplasty. Broken line, $y=x$; solid line, least squares linear regression of pneumatonometric measurements on manometric IOP. *Slope significantly different from 1.0, $p<0.005$. **Intercept significantly different from 0.0, $p<0.0009$.

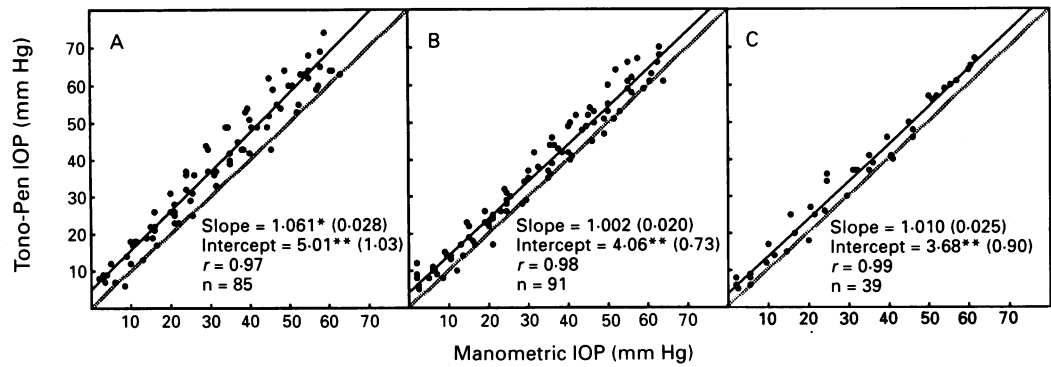


Figure 3 Manometric (x) versus Tono-Pen (y) intraocular pressure (IOP) measurements in enucleated postmortem human eyes following same size (A, Tono-Pen 1) or 0.5 mm oversized (B, Tono-Pen 1; C, Tono-Pen 2) penetrating keratoplasty. Broken line, $y=x$; solid line, least squares regression of Tono-Pen measurements on manometric IOP. *Slope significantly different from 1.0, $p<0.05$. **Intercept significantly different from 0.0, $p<0.0009$.

pneumatometer or Tono-Pen. This was still true when we tested second units of the other instruments.

The much reduced diameter of the tip of the minified Goldmann applanation tonometer allows accurate placement in the centre of the graft tissue, where there is the least irregularity and very little interference with the mires from the sutures or the interface area. The graft diameters we used were large and the minified Goldmann applanation tonometer might be more difficult to use in very small grafts. The more viscous 'Half and Half' also provided slightly broader and more regular mires than ordinary fluorescein.

The minified Goldmann applanation tonometer was certainly the most difficult of the three instruments to use, requiring considerable practice by an operator already very experienced in the use of a conventional Goldmann applanation tonometer. By trial and error we found the best mires were formed by applying the 'Half and Half' direct to the tip of the prism with an eye dropper and cleaning the tip with alcohol between each measurement.

Previous authors have suggested that in the presence of corneal oedema Goldmann applanation tonometry is grossly inaccurate, markedly underestimating the true intraocular pressure.^{18 20 21} Moses¹⁸ found an underestimation of intraocular pressure in an enucleated human eye 33 hours post mortem and attributed the inaccuracy to corneal thickening, although only eight measurements in one eye are shown. Goldmann and Schmidt,²² however, found it accurate in postmortem human eyes with slight corneal oedema. Kaufman²¹ postulated that the inaccuracy is caused by the oedematous corneal

epithelium being easier to appanate, giving a falsely low estimate of the intraocular pressure. Several of the eyes used in our experiments were 33 or more hours post mortem and there was unquestionably corneal oedema of the graft tissue as judged from the appearance and the elevated pachymetry measurements. One explanation for our improved results was that we removed the corneal epithelium if it became friable and tattered with repeated measurement, providing a smooth surface for the determination of the applanation end point. This occurred in eight of the 14 eyes studied (five of seven same sized and three of seven oversized grafts). Since epithelial removal was always done early in the minified Goldmann measurement series, and since the Goldmann measurements always preceded the pneumatometer and Tono-Pen measurements, it seemed unlikely that epithelial removal would bias our measurements in favour of the Goldmann apparatus in these eyes. Indeed, although there were some statistically significant differences between slopes or intercepts with and without the corneal epithelium present in a few of the tonometer/graft size subcategories, the overall conclusion was unchanged. A smooth corneal surface is more important for precise measurement with the Goldmann tonometer than with the other two, and in a clinical situation the removal of corneal epithelium after penetrating keratoplasty would normally be precluded, as it would be detrimental to healing. However, in a clinical situation dozens of measurements would not be made within a few minutes, so the epithelium would be far less likely to become so oedematous, friable, or tattered. Although a severely oedematous or irregular corneal graft might compromise measurements with the

Table 3 Regression analysis of tonometry data in same sized and oversized corneal grafts with epithelium intact and removed

	MGAT				Pneumatometer No 1				Tono-Pen No 1			
	Same sized		Oversized		Same sized		Oversized		Same sized		Oversized	
	Intact	Removed	Intact	Removed	Intact	Removed	Intact	Removed	Intact	Removed	Intact	Removed
Slope	0.996	0.983	0.974 ^f	0.909 ^d	0.901 ^{d,s}	1.049 ^b	1.028 ^f	0.942 ^b	1.042	1.069 ^b	1.017	0.998
SEM	0.019	0.020	0.016	0.024	0.023	0.021	0.022	0.028	0.071	0.027	0.026	0.025
Intercept	1.52 ^b	1.65 ^b	2.55 ^d	2.38 ^b	4.68 ^d	2.90 ^d	3.33 ^d	4.17 ^d	4.60 ^a	5.17 ^d	4.94 ^{d,c}	2.59 ^f
SEM	0.63	0.73	0.59	0.90	0.83	0.76	0.80	1.05	2.58	1.00	0.93	0.95
r	1.00	0.99	0.99	0.99	0.99	0.99	0.99	0.98	0.95	0.99	0.99	0.99
n	23	58	52	35	25	59	52	39	25	60	51	40

Slope significantly different from 1.0 or intercept significantly different from 0.0 by the two tailed paired t test: ^a $p<0.10$; ^b $p<0.05$; ^c $p<0.01$; ^d $p<0.001$. Significantly different from slope or intercept for eyes with corneal epithelium removed, by the two tailed two sample t test: ^e $p<0.10$; ^f $p<0.05$; ^g $p<0.001$.

minified Goldmann tonometer, the instrument is probably suitable for many, if not most, post-keratoplasty eyes.

We performed and reported keratometry measurements only to define our material. The measurements were not used to guide tonometer orientation or in data analysis, but could be used for the former.^{17 18}

Since modern ophthalmic offices are already equipped with conventional slit-lamp mounted Goldmann applanation tonometers, the lathed minified Goldmann applanation tonometer prism is easily the cheapest of the three instruments. When mounted on a slit-lamp, the minified Goldmann applanation tonometer is less portable than the pneumatonometer and, particularly, the Tono-Pen, and unlike the latter instruments would not allow the intraocular pressure measurement in any position other than at the slit-lamp – for example, lying flat. This problem would be overcome by mounting the minified Goldmann applanation tonometer prism on a Perkins hand held applanation tonometer²³ or by using a Draeger unit with minified tip.²⁴

Both the pneumatonometer and the Tono-Pen tended to overestimate the intraocular pressure in our grafted postmortem eyes, and this was confirmed for a second unit of each instrument. The pneumatonometer can be difficult to use in recently grafted living eyes¹² and overestimates the intraocular pressure in manometric experiments in postmortem eyes.²⁵ In some previous studies, the instrument overestimated low intraocular pressures and underestimated high pressures,^{14 26} or showed a tendency to overestimate intraocular pressure throughout the range tested, when compared with standard Goldmann applanation tonometry.²⁷

The Tono-Pen is a modern development of the Mackay-Marg tonometer, which is no longer commercially available. The Tono-Pen is reported to be as accurate as the Mackay-Marg tonometer in measuring intraocular pressure after keratoplasty,¹⁰ and the Mackay-Marg has been shown previously to be accurate after penetrating keratoplasty^{18 9} or in the presence of corneal irregularity or oedema.^{20 21 28}

The Tono-Pen has been directly compared with the Goldmann applanation tonometer in postmortem^{25 26 29} and living human eyes,^{7 26 30–32} and tended to overestimate low intraocular pressures and underestimate high pressures in all but two studies. A comparative study in post-mortem human eyes reported accurate measurement throughout the range of intraocular pressures.²⁵ However, this was based on a mean of five separate pressure measurements at only five manometric pressures between 10 and 50 mm Hg. A recent study comparing the Tono-Pen with the Goldmann applanation tonometer in normal and grafted human eyes reported significant overestimation of intraocular pressure by the Tono-Pen throughout the range of intraocular pressures, when compared with the Goldmann applanation tonometer readings.³² This was more pronounced in the eyes which had undergone penetrating keratoplasty.

Our study also showed a linear overestimation of intraocular pressure after penetrating kerato-

plasty by both of the Tono-Pen units, throughout the range of manometric pressures tested. It seems unlikely that both units of the instrument would be incorrectly calibrated.

Clinicians should be aware of the 3–6 mm Hg average overestimation of intraocular pressure after penetrating keratoplasty by the Tono-Pen and the pneumatonometer.

We used an open stopcock manometric system to evaluate the accuracy of the instruments, since intraocular pressure remains stable throughout the measurement. Closed stopcock manometry would have mimicked in vivo conditions more closely but is technically more difficult, since intraocular pressure begins to fall as soon as the stopcock is closed, and rises when the tonometer is placed in the eye.^{13 25} This is a particular problem when repeated measurements at one manometric pressure are required – for instance, two for the minified Goldmann applanation tonometer and as many as six for the Tono-Pen. These confounding effects can be managed with some effort,¹³ which did not seem warranted here since the magnitudes and measurement consequences of aqueous humour displacement by all three tonometers are already known.^{13 14 33}

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