Tonometry in Adults and Children

A Manometric Evaluation of Pneumatonometry, Applanation, and TonoPen In Vitro and In Vivo

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Objective: The purpose of the study was to determine the accuracy of applanation tonometry, pneumatonometry, and TonoPen tonometry in adults and children and the effect of age on tonometer error.

Design: The design was divided into four parts: part 1 was prospective and cross-sectional, and parts 2 through 4 were prospective, cross-sectional, and masked.

Participants: This study contained 72 patients representing 74 data points.

Intervention: Tonometry with simultaneous manometry was performed.

Main Outcome Measures: Intraocular pressure (IOP) and the tonometric estimate of IOP were obtained.

Results: The normal pediatric IOP follows the line Ta = 0.71 age(years) + 10 up to age 10. Applanation tonometry under anesthesia differs from pneumatonometry by an average of −8.6 mmHg and is age related by the equation Ta = Tpn + 2.6 log(age) − 10.3. The TonoPen was the most accurate instrument for enucleated eyes, and the pneumatonometer was the most accurate in anesthetized living eyes.

Conclusions: Applanation tonometry markedly underestimated IOP in young eyes. TonoPen tonometry performed well with enucleated eyes but was not adequately accurate for clinical use. The pneumatonometer performed the best clinically and the best overall. *Ophthalmology 1998;105:1173–1181*

Information on the normal values of intraocular pressure (IOP) in children is limited and confusing. There is evidence that the IOP in children begins below the normal adult average and then gradually increases with age, but this is not universally accepted. There also is a report that this age-related increase is not found with pneumatonometry.[1] In that article, the authors found a large difference in IOP readings when they compared Perkins applanation tonometry against pneumatonometry in eyes of children. The difference diminished as the age of the child increased, but they were unable to resolve the question of which, if either, tonometer was more accurate. Because the measurement of IOP is a critical factor in the management of pediatric glaucoma, we thought that a manometric investigation was justified to determine the true accuracy of tonometry in children. The current study was designed to evaluate the effect of patient age on the accuracy of applanation, pneumatonometry, and TonoPen tonometry using a manometer as the "gold standard" of IOP measurement.

Methods

Three independent parts have been incorporated to address a variety of clinical situations, with a fourth laboratory part included for verification. The TonoPen tonometer was not included in the original protocol but was added to parts 3 and 4 because of requests from reviewers of the pilot study (Eisenberg et al. Invest Ophthalmol Vis Sci [Suppl] 1996;37:S813). All four parts and pilot were approved by the hospital human investigational review board. All four parts proceeded simultaneously and independently. For clarity, pressure results by tonometry will be designated as an "estimate" of IOP. Only manometric pressures will be considered IOP.

Statistical Analysis

Linear regression, stepped linear regression, multiple linear regression, and residual analysis were computed with Statistica for Macintosh (Stat Soft, Tulsa, OK). Power calculations and *t* tests were done with MathCad 4.0 for Windows (MathSoft, Cambridge, MA).

Part 1: Goldmann versus Pneuma in Clinic

The first part was designed to replicate the findings of Jaafar and Kazi[1] and generate an independent data set. All tonometry was performed by two of the authors (DLE and BGS). Inclusion

criterion was all patients presenting to the Pediatric Ophthalmology and Strabismus service between November 1995 and July 1996. Exclusion criteria were known or suspected glaucoma, congenital anomalies, trauma, surgery, current steroid use, inability to cooperate for both tonometries, or refusal. Applanation tonometry (Ta) was performed by standard technique with Fluress (Akorn, Inc, Abita Springs, LA) using a Haag–Streit-mounted Goldmann tonometer. Pneumatonometry (Tpn) was performed with a factory-calibrated pneumatonometer (Model 30 Classic; Mentor, Norwell, MA) after instillation of topical anesthetic. Values of Tpn with standard deviations greater than 0.6 mmHg were rejected and the measurement was repeated. The Ta always preceded Tpn as cooperation usually was more difficult for Ta. In addition, because prior work has reported Ta to estimate a lower IOP than Tpn,[1] performing Ta first creates a bias in the opposite direction (i.e., Tpn should be lower than Ta). The mean of both eyes was used as a single data point when two eyes were available[2] to provide a better sample of the effect of age on tonometry. Stepped linear regression analysis was used to assess age-related changes. Linear regression was used to compare Ta with Tpn.

Part 2: Perkins versus Pneuma under Anesthesia

The second part was designed to compare tonometric results with the patient under anesthesia, as would be a usual component of an examination under anesthesia (EUA). All tonometry was performed by one of the authors (CAM). Inclusion criterion was all patients undergoing strabismus surgery or EUA between November 1995 and July 1996. Exclusion criteria were known or suspected glaucoma, congenital anomalies, trauma, surgery, current steroid use, inability to perform both tonometries, or refusal. Applanation tonometry (Ta) was performed with a Perkins tonometer (Clement Clarke, Inc, Columbus, OH) using a 0.25% fluorescein mixture[3] made by diluting 2% fluorescein with balanced salt solution (BSS). A cobalt blue light from a portable slit lamp was used as an accessory light source because the standard illumination was too dim.[4] The Perkins tonometer calibration was verified with a precision laboratory scale (AE163; Mettler Instrument Corp, Highstown, NJ) by the following technique: The tonometer was mounted on a laboratory equipment stand to mimic the position of use for a supine patient. The prism end was leveled with a bubble level and the height adjusted above the scale so that the prism tip was flush against the plate with less than 0.1 g of force applied when the dial was at zero. The dial then was increased by 5 mmHg up to 50 mmHg, and the grams force applied was recorded. This was done three separate times. Pneumatonometry (Tpn) was performed with the pneumatonometer as described in part 1. Values of Tpn with standard deviations greater than 0.6 mmHg were rejected and the measurement was repeated. All tonometry was performed after induction of general anesthesia and was supervised by two of the authors (DLE, BGS). The tonometrist and supervisor were masked as to the results of all tonometries. Readings were shown to the supervisor and accepted into the data only after the tonometrist and supervisor declared them to be technically valid. The tonometrist remained masked until all tonometry had been completed.

Two readings from each eye were obtained with each instrument. The mean of both eyes was used as a single data point when two eyes were available. Regression and distribution analyses were performed.

Part 3: Perkins versus Pneuma versus TonoPen In Vitro

The third part used enucleated human whole eyes to examine the tonometric estimate isolated from cardiac, respiratory, and autonomic input and provided independent data to compare with those of part 4. A closed stopcock technique was used to approximate the normal state of the eye. All tonometry was performed by one of the authors (DLE). The Perkins tonometer was the same as used in parts 1 and 2. A second Model 30 Classic pneumatonometer (Mentor, Norwell, MA) was used. Two TonoPens (Mentor, Norwell, MA) were used: one commercially purchased and the other factory modified for gas sterilization (description below). Both were TonoPen XL models.

Inclusion criteria were eyes from children younger than 13 years of age. Adult eyes were requested as control eyes. Exclusion criteria were time greater than 24 hours postmortem, corneal clouding or edema by biomicroscopy, sepsis at time of death, prior surgery, or any indication that the eye was abnormal.

System. Using a surgical microscope, a 27-g needle was inserted at the limbus, through the pupil, and into the posterior chamber. The lens was not disrupted. The entry site was sealed with cyanoacrylate adhesive. The globe was supported in a firm sponge "orbit." Constant pressure perfusion at 10 mmHg with Bárány's solution at 25° C was done for 15 minutes to inflate and hydrate the eyes. A gauge pressure transducer (PX800-001GV; Omega Engineering, Stamford, CT) was connected to the infusion line and monitored by computer (Macintosh IIci, Apple Computer, Inc, Cupertino, CA). Custom software (Lab-View 3.1, National Instruments, Inc, Austin, TX) was written to operate the analog–digital card (MB MIO 16XL; National Instruments, Inc) and log the data. A millimeters of mercury/volt calibration curve was generated with a water manometer. The system was accurate to ±0.01 mmHg.

Procedure. Manometric IOP was set to one of three target pressure ranges (low, medium, or high) before each tonometry. The low range was 10 to 15 mmHg, the medium range was 18 to 25 mmHg, and the high range was 28 to 35 mmHg. A very low range, below 10 mmHg, was tested on some eyes. A target range was chosen to provide a degree of randomness while also decreasing the technical difficulty of IOP adjustment.

Protocol. For each reading, the manometer was filled to a randomly determined pressure range. Readings were taken with the computer to verify the range and stability of pressure. The stopcock then was closed, and a computer reading was taken immediately. Tonometry was performed. A second computer reading was taken immediately after the tonometry. The mean of the computer readings, before and after, was used as the manometric pressure. A separate software program that recorded continuous manometry during tonometry showed the validity of this technique (Fig 1). All Ta was done first to enable the best-quality mires. The Tpn series then was done followed by the TonoPen (Tt) series. The TonoPen self-calibration was performed before use. TonoPen readings with greater than 5% variability were rejected. Perkins and pneumatonometry rejection criteria were the same as described in part 2 above. When a tonometry reading was rejected, the corresponding manometry values also were discarded and that pressure range was repeated. This procedure was repeated until valid readings were obtained for all three pressure ranges for all tonometers. A wrist rest was used for all tonometries.

Part 4: Perkins versus Pneuma versus TonoPen versus Manometer In Vivo

This fourth part was designed to verify tonometer accuracy in the living human eye (i.e., in situ and in vivo). All pediatric
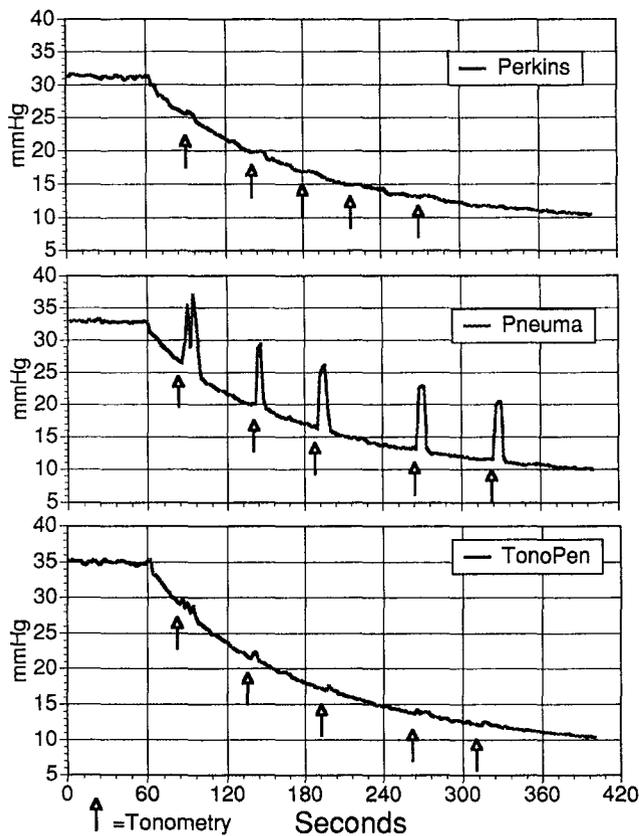
Figure 1. Dynamic tonometry during manometry. An enucleated adult globe was pressurized for 1 minute. The stopcock was closed and the pressure-decay curve was followed by continuous computerized manometry while five tonometric readings were taken (arrows). The indentation effect of the pneumatonometer clearly is seen (middle graph) compared to that of Perkins and TonoPen tonometry. The overall decay curve was not influenced by any form of tonometry.

tonometry was performed by one of the authors (CAM). All adult tonometry was performed by one of the authors (JSS). The Perkins tonometer was the same as described previously (parts 1–3). The pneumatonometer was the same unit used in part 3. The TonoPen XL, modified by the manufacturer (Mentor, Norwell, MA), had a separate, detachable battery pack to enable gas sterilization but otherwise was identical to commercially available units.

Sterilization. The Perkins tonometer was gas sterilized with batteries and cobalt filters removed. The pneumatonometer handpiece was gas sterilized with the tip installed. Tips were changed after two sterilizations because they appeared to become stiff with additional sterilization. The TonoPen unit without the battery pack was gas sterilized along with shields. Shields were not resterilized.

System Components. A sterile pressure transducer (Transpac II and connector #42574; Abbott Laboratories, North Chicago, IL) was calibrated with a water manometer to generate a millimeters of mercury/volt calibration curve. The transducer was tested at random during the course of the study to verify agreement with the initial calibration. The transducer system was accurate to ±1 mmHg. Pressure readings from the transducer were recorded continuously by a computer (MacIIsi, Apple Computers, Cupertino, CA) with a National Instruments analog–digital board (NB-MIO16XL; National Instruments)

and custom software (LabView 3.1). A bottle of BSS Plus (Alcon Laboratories, Inc, Fort Worth, TX) was suspended from an adjustable pole. It was connected to a four-way valve via a one-way valve. The four-way valve was positioned open for the bottle, transducer, and eye. The fourth port was left unconnected and used to bleed air and depressurize the system.

Inclusion criteria were pediatric ophthalmology service patients and glaucoma service patients who were undergoing a procedure that routinely involved a paracentesis wound. Exclusion criteria were prior surgery, anterior segment abnormality, corneal irregularity or scarring, or refusal.

Surgical Procedure. Informed consent was obtained from all participants or legal guardians or both. All pediatric participants were placed under general anesthesia. All adult participants received retrobulbar and van Lint injections with a mixture of 2% lidocaine and 0.75% Marcaine (Winthrop Pharmaceutical, New York, NY) with 150 U of hyaluronidase. After sterile preparation, a clear corneal paracentesis wound was created with a 20-g corneal stiletto blade (Visitec #5220; Visitec, Sarasota, FL). A 20-g tapered oval anterior chamber maintainer (Visitec #5149 Blumenthal) then was placed near the limbus with the infusion line attached. A manometric reading was obtained by the computer. This reading was used as the zero pressure, and all succeeding pressures were adjusted by this value. The anterior chamber maintainer then was inserted into the paracentesis. The surgeon selected the paracentesis site and infusion fluid. The eye then was pressurized, and the system was tested for leakage by monitoring the IOP with the infusion line closed. Direct observation under the operating microscope was performed simultaneously. If leaks were detected by either method, the anterior chamber maintainer was repositioned and the system retested until the pressure was maintained and no leakage was noted.

Tonometry Procedure. The infusion bottle was adjusted to a target manometric pressure range of low, medium, or high in random order, using the same ranges as described in part 3. The one-way valve then was closed. A manometry reading was determined by computer, immediately followed by a tonometry reading. The infusion was restarted and the process was repeated. Three different pressures were obtained with each instrument. Each measurement series was completed before changing to the next tonometer. The order of tonometers was the same as in part 3 (Ta, Tpn, Tt). Sterile 0.25% fluorescein mixture was made from sterile 2% fluorescein and BSS as described in part 3. Because corneal staining had been identified in the pilot study, the fluorescein mixture was applied to the tonometer tip only. Copious irrigation with BSS followed each tonometry to maintain epithelial integrity. The tonometrists were masked to both the target range and the tonometric results. The same rejection options as those in part 2 were available, and, as in part 3, the corresponding manometry value also was rejected. Tonometric technique was supervised by one of the authors (DLE or BGS). Delay in obtaining the tonometry was an additional reason for rejection. This process was repeated until valid manometry–tonometry pairs were obtained for all three target ranges for each tonometer. After the tonometries, the surgeries proceeded as usual. A small comparison study of Perkins tonometry by two of the authors (CAM, JSS) was done to exclude technical bias. Power calculations determined a sample size of eight eyes for 80% power to discriminate a difference of 3.1 mmHg. Eight eyes of four volunteers had Perkins tonometry performed in the supine position by an author (CAM), followed 20 minutes later by another author (JSS). The order of volunteers was randomized and both authors were masked as to the results. A one-tailed *t* test for paired data was used with
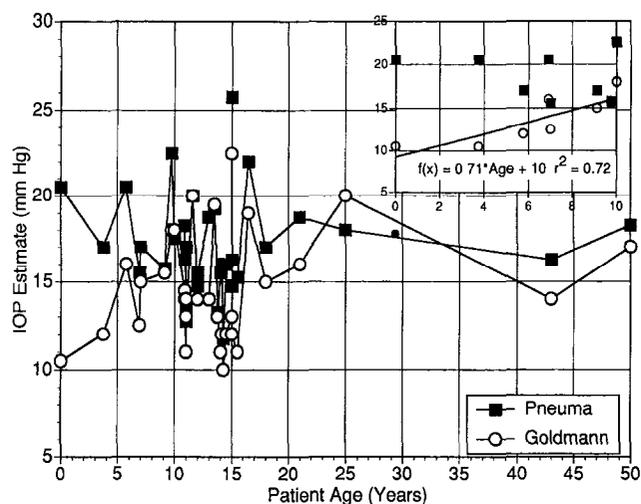
Figure 2. Goldmann vs. Pneuma by age in clinic. This is a paired plot of all data from awake patients in clinic. Each patient is represented by an open circle (Goldmann) and a solid square (Pneuma). Estimates from the tonometers are seen to diverge in the younger age group. The inset (upper right) is an enlarged view of the patients younger than 10 years of age. The regression is a linear least-squares best fit. Tonometry for the zero age point was the only Perkins measurement included and was performed supine 13 hours after birth.

the null hypothesis that one author (CAM) does not report lower pressures than another author (JSS).

Results of Part 1: Goldmann versus Pneuma in Clinic

Eighteen males and 15 females participated. Mean age was 14.5 years, with a range of 0 to 50 years. All data are shown in Figure 2.

Goldmann Results

Stepwise regression found a significant linear response up to age 10 years by the following equation: Expected normal Ta = 0.71 age + 10 mmHg (Fig 3). Beyond age 10 years, the linear fit worsened. The mean Ta value for patients older than 10 years of age was 14.6 ± 3.3 mmHg.

Pneumatonometer Results

No age-related effects were found for any segment of age ranges. Mean IOP was 16.8 ± 3.0 mmHg. This was 2.2 mmHg higher than the mean Goldmann value ($P < 0.001$). Comparison of Ta with Tpn for all ages showed a significant correlation of Ta = 0.78 Tpn + 1, and for age older than 10 years, Ta = 0.94 Tpn − 1.2. The slope of the latter did not differ from 1.0; therefore, Ta = Tpn − 1.2.

Results of Part 2: Perkins versus Pneuma under Anesthesia

Fourteen males and 11 females participated. Mean age was 14.0 years, with a range of 0 to 68 years. The Perkins calibration

was found to be accurate and linear from 0 to 5 g (grams = 0.100dial + 0.004, $r^2 = 1.000$). The intercept was not significantly different from zero.

Paired Estimates

Comparison of Ta with Tpn showed a mean difference (Ta − Tpn) of −8.6 ± 0.5 mmHg (mean ± standard error) (paired $t = -17.3$, $P < 0.0001$) (Fig 4). The difference of the estimates (Ta − Tpn) varied by age according to the following relationship: Ta − Tpn = 2.6 log(age) − 10.3 ($r^2 = 0.60$, $P < 0.0001$).

Results of Part 3: Perkins versus Pneuma versus TonoPen in Enucleated Human Eyes

Demographics of eyes obtained are presented in Table 1. All results were analyzed with multiple linear regression using patient age and tonometry estimate as independent variables and manometric IOP as the dependent variable. Slope and intercept were compared to zero. All values are reported as millimeters of mercury ± standard error (probability value). For clarity, the multiple regression (age and estimate on IOP) has been graphed separately, but all slopes, intercepts, and probability values reported are from the multiple regression results. Figures 5 and 6 present the age effects and IOP effects, respectively, on the error of the tonometry estimate for all three instruments.

Perkins Results

There was initial underestimation of −7.6 ± 2.1 ($P < 0.0008$) and gradually decreasing error with increasing age, 0.040 ± 0.019 ($P = 0.045$) (Fig 7). There was no association between the manometric IOP and Perkins error. Using the regression to predict manometric IOP (±standard error of estimate) from the Ta estimate (in millimeters of mercury) and age (in years) yields
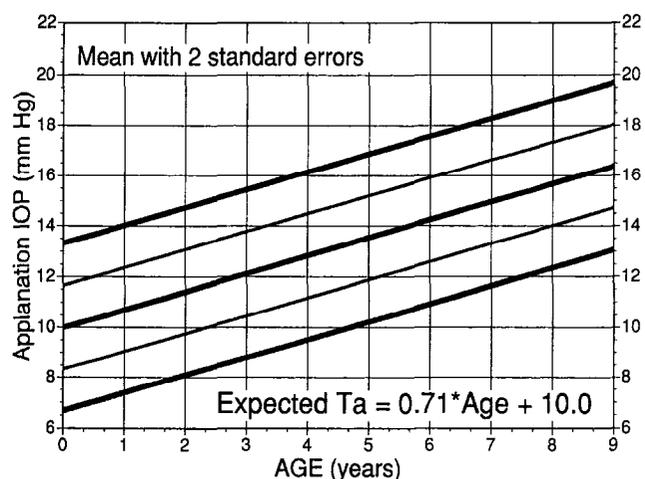

Figure 3. Age-adjusted normal applanation intraocular pressure in clinic. This presents the least-squares best-fit linear regression of patient age and Goldmann intraocular pressure in clinic. Each line represents one standard error of the estimate so that upper and lower bold lines enclose the 95% confidence interval of the regression estimate by patient age.
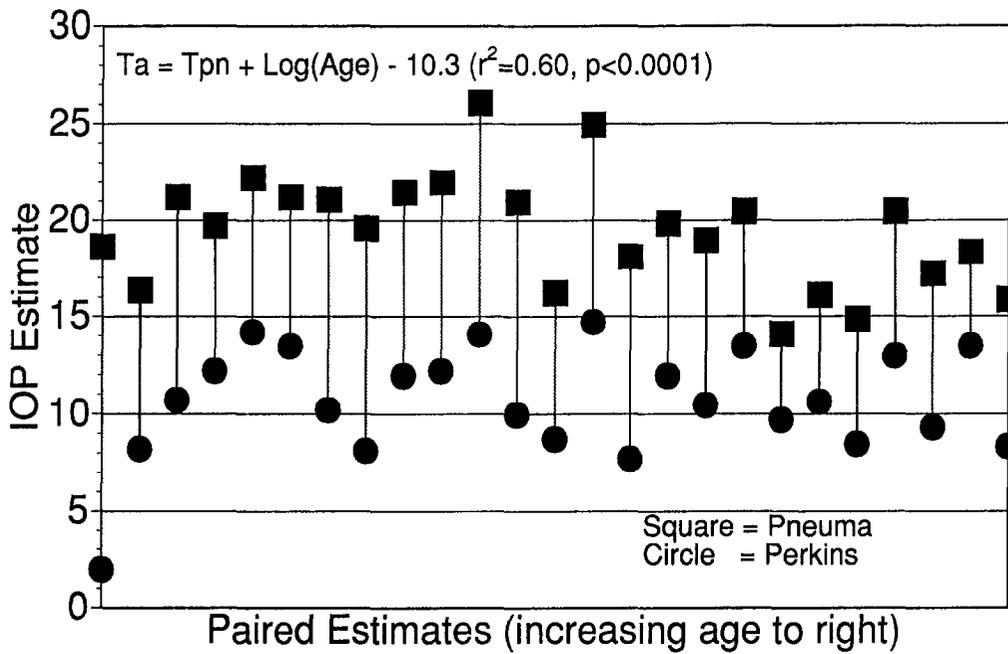
Figure 4. Pairwise intraocular pressure (IOP) under anesthesia, Pneuma vs. Perkins. This presents the pairwise view of IOP estimates under light sedation. Pairs are rank ordered by increasing age from left to right. In all cases, the Pneuma (solid squares) reported a higher IOP for the same eye than did the Perkins (solid circles). The difference decreased as age increased by a log–linear relationship.

the following equation: IOP ($\pm$5.0) = 0.89 Ta − 0.08 age + 11.0 mmHg.

Pneumatonomer Results

There was initial overestimation of +5.6 $\pm$ 1.1 ($P < 0.0001$) and gradually decreasing error with age, −0.053 $\pm$ 0.011 ($P < 0.0001$) (Fig 8). There was no association with IOP. Predicting manometric IOP from Tpn and age yields the following: IOP ($\pm$3.1) = 0.90 Tpn + 0.049 age − 2.8.

TonoPen Results

There was no difference from zero at intercept and no association with age (Fig 9). The TonoPen underestimated IOP by greater amounts as IOP increased, −0.10 $\pm$ 0.05 ($P = 0.049$).

Results of Part 4: Intraoperative Perkins versus Pneuma versus TonoPen versus Manometer

Demographics of patients tested are presented in Table 2. Figures 10 and 11 present the age effects and IOP effects, respectively, on the error of the tonometric estimate for all three instruments. All surgeries were completed as planned without

complications. The Perkins comparative study found no significant underestimation of IOP by one author (CAM) versus another author (JSS) by t test for paired data.

Perkins Results

There was initial underestimation of −3.7 $\pm$ 2.4 ($P < 0.0001$) and decreasing error as age increased, 0.067 $\pm$ 0.023 ($P = 0.006$) (Fig 12). There was increasing underestimation with higher IOP, −0.21 $\pm$ 0.01 ($P = 0.036$). Manometric IOP inter-

Table 1. Demographics: Human Enucleated Eyes

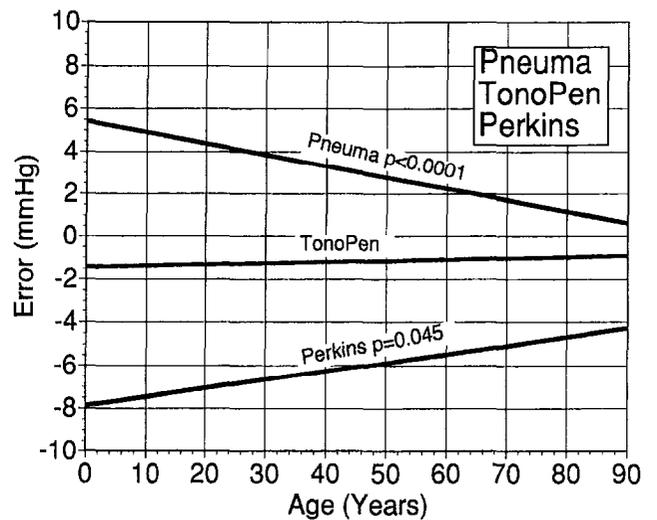| Patient No.	Age (yrs)	Gender	Eye
1	0	M	OU
2	0.01	F	OU
3	3	M	OU
4	82	M	OU
5	82.1	F	OU

Figure 5. Error by age in enucleated human eyes. This presents the influence of patient age on the estimate of intraocular pressure (IOP) in enucleated eyes. All slopes and intercepts were derived from multilinear regression of age and tonometry on manometry. The IOP effects are not shown. The TonoPen shows no influence of patient age on the estimate of IOP. The Pneuma and Perkins estimates were influenced by age.
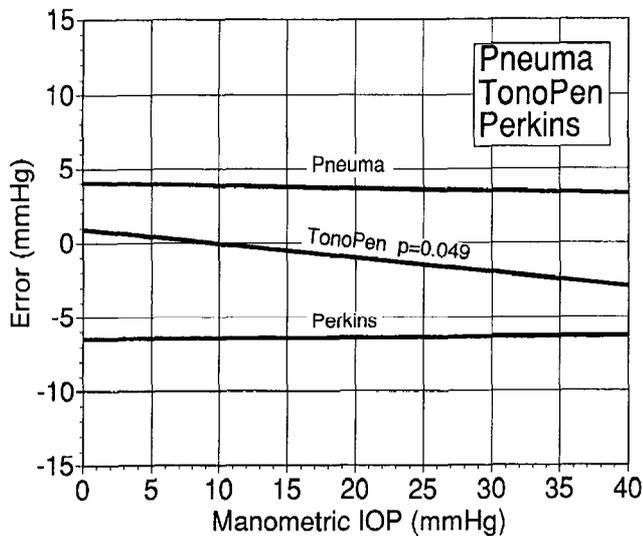
Figure 6. Error by intraocular pressure (IOP) in enucleated human eyes. This presents the influence of actual IOP on the tonometric estimate of IOP in enucleated eyes. All slopes and intercepts were derived from multilinear regression of age and tonometry on manometry Age effects are not shown. The TonoPen shows a slightly decreasing estimation with increasing manometric IOP. The Pneuma and Perkins estimates maintained a consistent error throughout the pressure range tested

cept did not differ from zero. Predicting manometric IOP from Ta and age yields the following: IOP ($\pm$4.7) = 0.85 Ta − 0.065 age + 10.7 mmHg.

Pneumatonometer Results

No age associations were found (Fig 13). There was an initial overestimation of 7.6 $\pm$ 2.1 (P = 0.0009) at low IOP and a gradual underestimation with increasing IOP, −0.36 $\pm$ 0.08 (P

Figure 8. Pneumatonometry in enucleated human eyes This is the raw pneumatonometer data from enucleated human eyes. Each line represents 2 mmHg deviation from manometric intraocular pressure Note the relatively tight fit in all age groups, but the estimates in newborn eyes (open squares) tended to overestimate actual intraocular pressures.

< 0.0001), resulting in an underestimation at higher IOP and a nodal point of 21.9 mmHg in which the estimate equaled the IOP.

TonoPen Results

No age effects were found (Fig 14). At low IOP, there was overestimation beginning at 5.2 $\pm$ 1.7 (P = 0.01), a negative slope resulting in increasing underestimation with increasing IOP, −0.50 $\pm$ 0.06 (P < 0.0001), and a nodal point of 11.8 mmHg. After two sterilizations, the liquid crystal display (LCD) panel on the TonoPen became dim and difficult to read. It was returned to the manufacturer for repair and evaluation. The manufacturer reported that the internal electronics were undis-
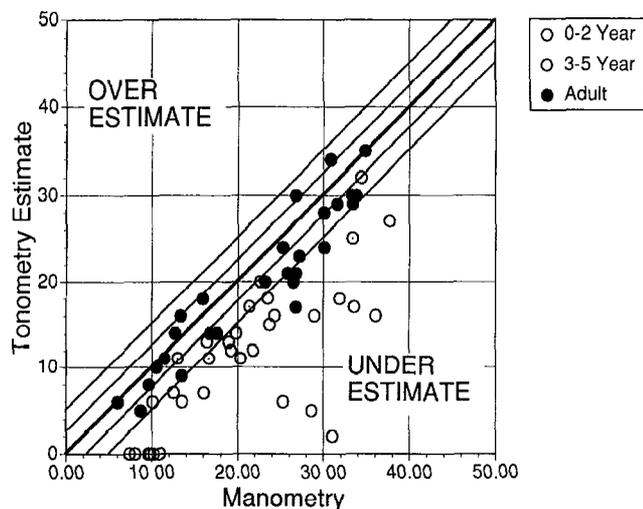

Figure 7. Perkins tonometry in enucleated human eyes. This is the raw Perkins data from enucleated human eyes. Each line represents 2 mmHg deviation from manometric intraocular pressure. Note that in general, the estimates for the newborn eyes (open circles) were well below the 4 mmHg line and, in some cases, up to 30 mmHg in error. The Perkins estimates in adult control eyes reasonably represent manometric pressures.
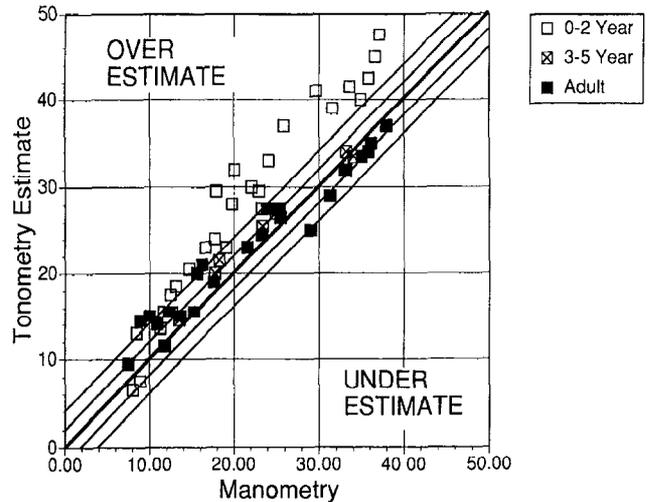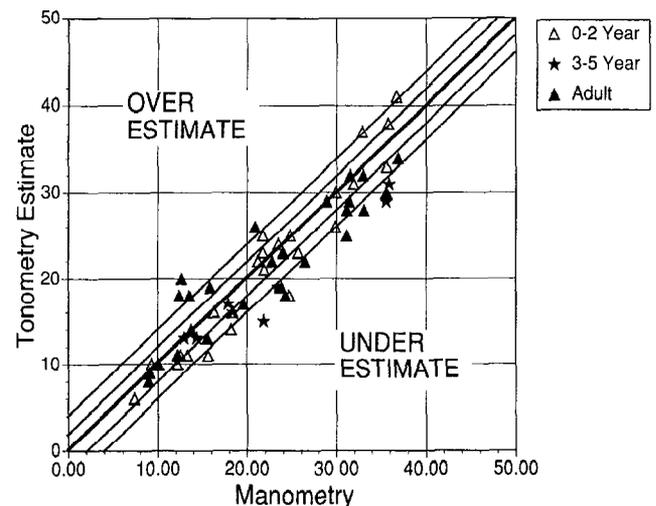

Figure 9. TonoPen in enucleated human eyes. This is the raw TonoPen data from enucleated human eyes. Each line represents 2 mmHg deviation from manometric intraocular pressure. There is good overall agreement with the manometer but no consistent pattern of error.

Table 2. Demographics: Intraoperative Manometry

Patient No.	Age (yrs)	Gender	Eye
1	0.1	F	OS
2	0.23	M	OS
3	0.75	M	OD
3	1	M	OS
4	1.75	F	OD
5	4.9	F	OS
5	5	F	OD
6	50.2	F	OD
7	68	F	OD
8	78.3	F	OS
9	85	M	OD

turbed and the unit was functioning properly, but the LCD panel was sensitive to heat and gas. The panel was replaced by the manufacturer.

Conclusions

Mean applanation tonometry estimates in young children begin well below average adult values and increase with age. Estimates equivalent to adult values were achieved by 10 years of age in this study. Our data provided the following age-adjusted regression equation for patients younger than 10 years of age: expected normal Ta = 0.71 age + 10 mmHg.

Pneumatonometry estimates of IOP in clinics were not affected by patient age. Pneumatonometric estimates were statistically different from applanation estimates and the conversion Ta = Tpn − 1.2 mmHg was able to compare estimates for patients older than 10 years of age.

With the patient under anesthesia, there was a significant

Figure 11. Error by intraocular pressure (IOP)—intraoperative manometry. This presents the influence of actual IOP on the tonometric estimate of IOP in live patients under anesthesia. All slopes and intercepts were derived from multilinear regression of age and tonometry on manometry. Age effects are not shown. All tonometers were influenced by IOP such that increases in IOP produced less of an increase in the tonometric estimate.

difference in the estimate of IOP by Perkins and pneumatic tonometry irrespective of age. This difference changed by a log–linear relationship to age. The following conversion may be clinically useful for comparing measurements between the two instruments for examinations under anesthesia:

Perkins = 2.6 log(age) + pneuma − 10.3 mmHg

Applanation tonometry underestimated manometric IOP in an age- and IOP-dependent manner in living eyes. The magnitude of error increased with decreasing patient age.
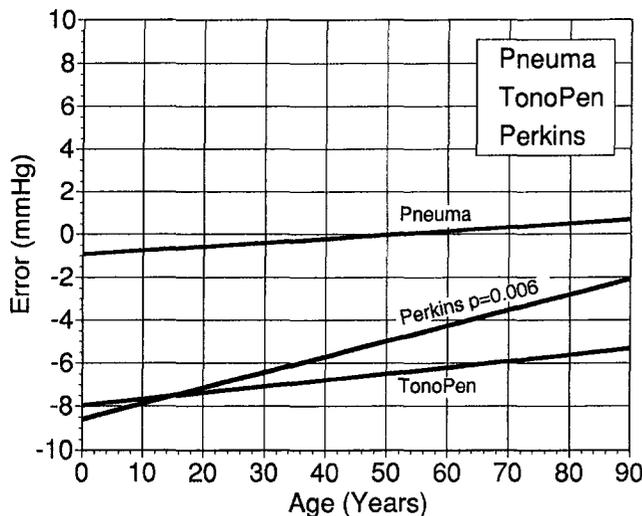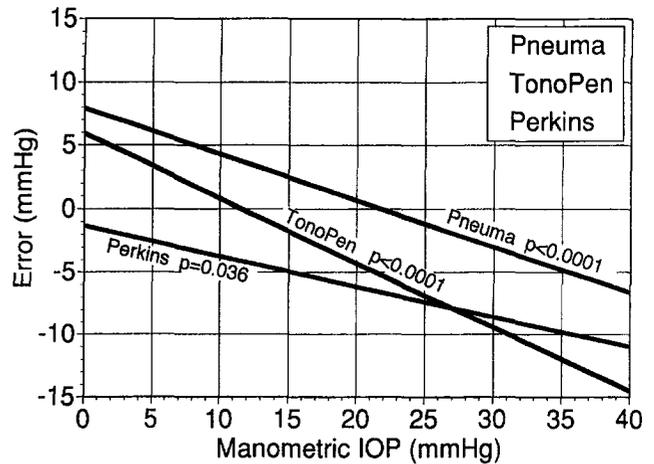

Figure 10. Error by age—intraoperative manometry This presents the influence of patient age on the estimate of intraocular pressure (IOP) in live patients under anesthesia. All slopes and intercepts were derived from multilinear regression of age and tonometry on manometry. The IOP effects are not shown. The pneumatonometer and TonoPen show no influence of patient age on the estimate of IOP. The Perkins estimates were influenced by age.
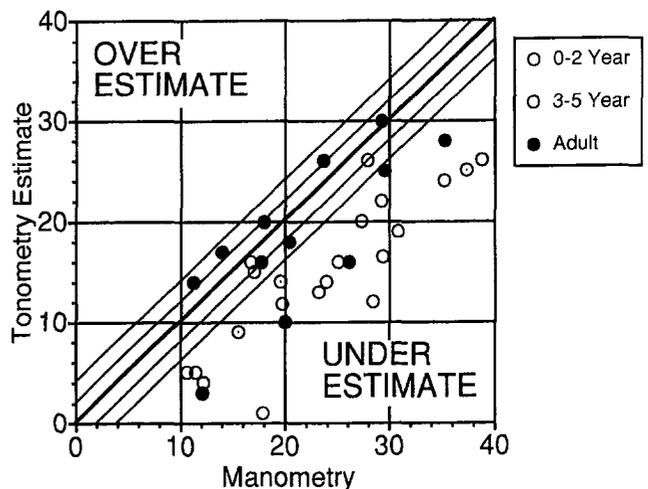

Figure 12. Intraoperative Perkins tonometry. This is the raw Perkins data from live patients under anesthesia. Each line represents 2 mmHg deviation from manometric intraocular pressure. Note the consistent underestimation of intraocular pressure in the young eyes (open circles), including two errors of nearly 20 mmHg underestimation. Three of four of the adult (solid circles) underestimated points were from the same patient.
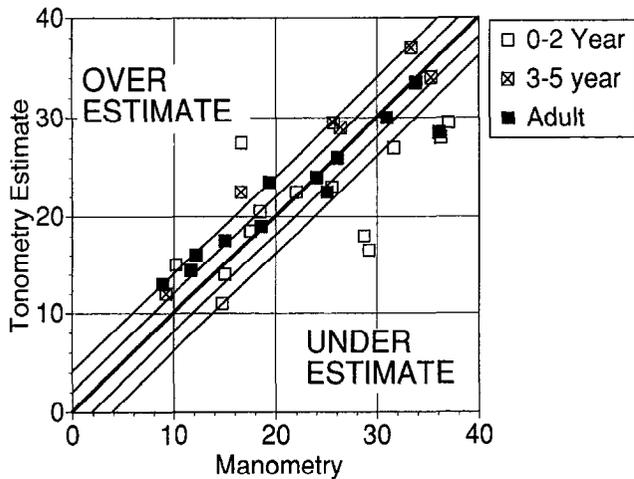
Figure 13. Intraoperative pneumatonometry. This is the raw pneumatonometer data from live patients under anesthesia. Each line represents 2 mmHg deviation from manometric intraocular pressure. There is relatively good agreement with the manometer. There are two underestimates of 10 mmHg in the young eye (open squares) group.

Pneumatonometry slightly overestimated IOP intraoperatively at low IOP with a nodal point at 22 mmHg, then it slightly underestimated the higher IOP. Pneumatonometry estimates were not affected by patient age and came closest to manometric IOP.

The TonoPen was the most accurate instrument in the laboratory setting, but the intraoperative performance of the TonoPen was the worst of the instruments tested. The TonoPen produced large underestimations as IOP increased in any age group.

Discussion

Lower than "normal" tonometric results in infants and children have been reported in several studies using the Perkins or TonoPen tonometer or both.[1,5,6] Clinical studies with the Schiotz[7] and pneumatonometer[1] indicate a high normal or normal value compared to adults. But few studies include age as a variable and instead group all children together. There is good evidence that this is not a valid method. Independent studies using the Keeler Pulsair[8] and Perkins with patient's awake[1] or under anesthesia[9] have shown an age-related increase in the tonometric estimate in children. We also have shown this age effect with the Perkins and Goldmann tonometers. The pneumatonometer, in contrast, has been shown to be without an age effect.[1] This study agrees with that finding. But Tpn has been shown to report higher estimates than that of the Goldmann[10,11] by 0.45 to 1.70 and 1.6 mmHg. Our finding of an average 1.2 mmHg above the mean Goldmann estimates in adult eyes is consistent with these reports.

Manometric comparisons of tonometers have been done with enucleated adult eyes.[12–15] We have replicated these studies in part 3, and our results are in good agreement for the Perkins and the TonoPen. We found Tpn to be more accurate than was reported by Moses and

Grodzki[14] and more similar to that reported by Langham and McCarthy.[13] The different pneumatonometers used in each of these studies may account for the variable results. In addition, we have shown that young eyes are not equivalent to adult eyes for all tonometers. The pneumatonometer has been shown to provide accurate values in young enucleated human eyes (2 and 8 weeks old),[13] identical to those of adult eye readings. Our youngest enucleated eyes were much younger (1 and 4 days old) and showed a slight overestimation of IOP, potentially from compression and indentation of such small globes.

Manometric evaluations intraoperatively provide the most compelling evidence of the age and IOP effect on the estimate of applanation tonometry. We were unable to find a previous report of live simultaneous manometry and tonometry in children. The Perkins estimates in live eyes were similar to those in enucleated eyes, with nearly identical multiregression estimates of IOP (0.89 Ta − 0.080 age + 11.0 for enucleated eyes and 0.85 Ta − 0.065 age + 10.7 intraoperatively). The pneumatonometer also produced similar readings to the enucleated results. The age effect found for the pneumatonometer in the enucleated eyes was not found in live eyes. This may have been because of the use of newborn enucleated eyes compared to the 1-, 3-, and 9-month-old live eyes. The small indentation effect in adult pneumatonometry[14] probably is exaggerated in the very small newborn eyes. The TonoPen had good correlation to manometry in enucleated eyes but had a prominently flat slope intraoperatively. This markedly disparate performance was unexpected and should be investigated further. The flat slope found intraoperatively indicates that large actual change in IOP would produce a relatively small change in TonoPen readings. Of great concern is that our results represent a best-case scenario: an experienced ophthalmologist performing supervised tonometry on an anesthetized eye of
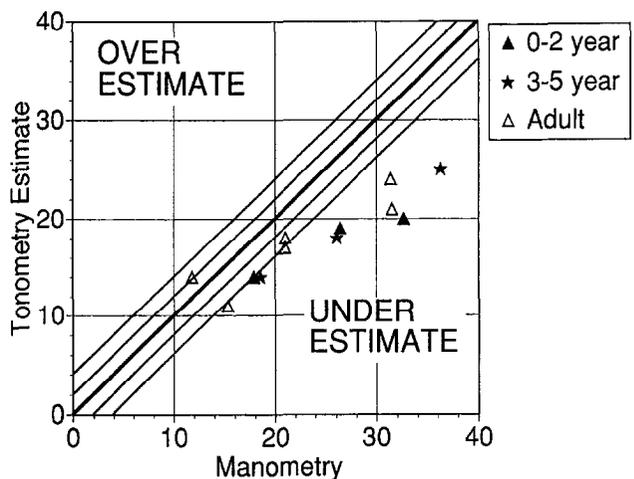

Figure 14. Intraoperative Perkins TonoPen. This is the raw TonoPen data from live patients under anesthesia. Each line represents 2 mmHg deviation from manometric intraocular pressure. Note the flat slope that produces increasingly greater underestimations with increasing actual intraocular pressure in all age groups.

a perfectly cooperative patient. It is difficult to imagine quality of results obtained in the typical busy clinic.

This study was limited by the small sample sizes, and therefore the regression equations should not be used as absolute references. However, the overall good agreement with prior literature and the internal agreement between parts 1 through 4 provide support for definitive conclusions about the performance of the tonometers.

We believe that the "increasing" IOP in childhood is an artifact of applanation tonometry and does not represent a true developmental increase in IOP. The normal IOP in children is most likely similar to adult values, as estimated by the pneumatonometer. We propose that an age-adjusted normal curve (Fig 3), similar to growth curves, be used for interpretation of applanation estimates (Ta) up to 10 years of age. Pneumatonometry was unaffected by age and may be the best instrument for the long-term monitoring of IOP, especially in children. Pneumatonometry does produce a significantly higher estimation of IOP compared to applanation. Therefore, normal values of IOP by applanation should not be used for interpretation of Tpn estimates. The TonoPen did not perform adequately for clinical use. It may be best to limit this instrument to laboratory evaluations. Caution is urged when evaluating tonometers against each other as complimentary errors will not be found. As shown in Figures 10 and 11, a comparison of TonoPen to Perkins would have found good correlation because both have similar error with respect to age and IOP. Manometry clearly is the gold standard.

In summary, the clinical implications of our findings may necessitate a change in pediatric glaucoma evaluation. There appears to be significant underestimation of IOP in the pediatric age group with use of applanation tonometry; the pneumatonometer provides a better representation of the true IOP. In persons 10 years of age and older, either pneumatonometry or applanation tonometry appears to provide an accurate estimate of the actual IOP. Unfortunately, the TonoPen did not give consistent readings and tended to overestimate low IOPs and underestimate high IOPs.

Based on our findings, we recommend the use of the pneumatonometer in individuals in any age group, especially for the diagnosis and management of pediatric glau-

coma. We reserve applanation tonometry for those persons 10 years of age and older. We are unable to recommend the TonoPen for clinical use at this time.

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