Published in final edited form as:

J AAPOS. 2012 June ; 16(3): 242–248. doi:10.1016/j.jaapos.2011.12.150.

Comparison of Tono-Pen and Goldmann applanation tonometers for measurement of intraocular pressure in healthy children

Yasmin S. Bradfield, MD^a, Brett M. Kaminski, MPH^b, Michael X. Repka, MD, MBA^c, and Michele Melia, ScM^{b,*} on behalf of the Pediatric Eye Disease Investigator Group

^aDepartment of Ophthalmology & Visual Sciences, University of Wisconsin, Madison ^bJaeb Center for Health Research, Tampa, Florida ^cJohns Hopkins University School of Medicine, Baltimore, Maryland

Abstract

Purpose—To assess the agreement of intraocular pressure (IOP) measured with the Tono-Pen and the Goldmann applanation tonometer (GAT) in normal children and adolescents.

Methods—A total of 439 subjects from birth to <18 years of age without anterior segment anomalies or glaucoma had their IOP measured with the two instruments by separate, masked examiners in the office or under general anesthesia.

Results—On average, the Tono-Pen measured values slightly lower than the GAT for IOP <11 mm Hg and slightly higher than the GAT for IOP >11 mm Hg in the office setting. Using the average of GAT and Tono-Pen IOPs to estimate the true IOP, the average difference (GAT–Tono-Pen) was 0.4 mm Hg at IOP of 10 mm Hg and –3.0 mm Hg at IOP of 20 mm Hg. The 95% limits of agreement on the average difference between instruments were ± 6.4 mm Hg in the office setting and ± 6.8 mm Hg under general anesthesia. Larger differences between instruments were found with younger age. Standard error of measurement with the Tono-Pen was 1.44 mm Hg and 1.82 mm Hg for the office and anesthesia settings, respectively. Thicker corneas were associated with higher IOP with both the GAT and the Tono-Pen.

Conclusions—In normal children, average differences between IOP measured by Tono-Pen and GAT were small, although there was substantial test–retest variability. Younger age was associated with larger average differences, as was higher IOP in the office setting.

Comprehensive eye care of children and adolescents may require measurement of intraocular pressure (IOP). The World Glaucoma Congress wrote that “the question of whether one tonometer is superior to the others in pediatric patients is unresolved.”¹ Studies in adults have reported differences in the IOP measurements obtained with the Tono-Pen (Reichert, Inc, Depew, NY) and Goldmann applanation tonometer (GAT).^{2,3} The difference varies with IOP. There have been few comparison studies conducted in children. When compared to simultaneous manometry, applanation tonometry was found to consistently

© 2012 American Association for Pediatric Ophthalmology and Strabismus. Published by Mosby, Inc. All rights reserved.

Correspondence: Pediatric Eye Disease Investigator Group, Jaeb Center for Health Research, 15310 Amberly Drive, Suite 350 Tampa, FL 33647 (pedig@jaeb.org).

*Additional authors are listed at the end of this article. Members of the Pediatric Eye Disease Investigator Group are provided in e-Supplement 1, available at www.jaapos.org.

Publisher's Disclaimer: This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final citable form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

underestimate IOP in young eyes, while the Tono-Pen was inconsistent.⁴ Conversely, Bordon and colleagues⁵ reported good agreement between the Tono-Pen and handheld GAT in pediatric patients.

The GAT is the gold standard for IOP measurement in adults.^{5–7} The instrument chosen to measure IOP in children is determined by several factors. The Tono-Pen is favored over the GAT in younger children who are unable to cooperate for slit-lamp mounted applanation. It may also be used successfully in sleeping supine toddlers or cradled infants in the office setting. The Tono-Pen may be better tolerated than the GAT by children who are apprehensive of having the GAT touch their eye. The GAT is chosen for older and more cooperative children. In a surgical setting, use of Tono-Pen or handheld GAT is determined by instrument availability or examiner preference.

The primary objective of this study was to assess the agreement between GAT and Tono-Pen in children. Secondary objectives were to identify factors that influence the agreement between GAT and Tono-Pen, to assess the correlation between IOP measured with the GAT and central corneal thickness (CCT), and to estimate the precision of Tono-Pen IOP measurements in children in an office setting and under general anesthesia.

Subjects and Methods

This ancillary study was performed in conjunction with a study of central corneal thickness (CCT) in children.⁸ The study was supported through a cooperative agreement with the National Eye Institute of the National Institutes of Health, Department of Health and Human Services, and was conducted by the Pediatric Eye Disease Investigator Group (PEDIG). The protocol and Health Insurance Portability and Accountability Act (HIPAA)–compliant informed consent forms were approved by the institutional review boards for participating sites, and a parent or guardian of each study subject gave written informed consent. The protocol is available on the PEDIG website (www.PEDIG.net; accessed September 22, 2011) and is summarized below.

Major eligibility criteria included age from date of birth to <18 years, ability to have CCT measurements taken in the office or under general anesthesia, cycloplegic refraction performed upon enrollment or within 6 months prior to enrollment, healthy corneas, and absence of systemic conditions that would influence CCT or IOP measurements. Acceptable ocular conditions included strabismus, nasolacrimal duct obstruction, and refractive error. Exclusion criteria included anterior segment dysgenesis, congenital cataract, contact lens use, periocular steroid use within 3 months of enrollment or current systemic steroid use, uveitis, corneal structural abnormality, microphthalmia, Marfan syndrome, glaucoma, history of intraocular or refractive surgery, optic nerve abnormality, and history of prematurity (birth at <37 weeks postmenstrual age). All eligible subjects received an anterior segment examination prior to enrollment to eliminate those with exclusion criteria.

All subjects in the primary study of CCT were required to have IOP measurements using the Tono-Pen. Of the 36 sites that participated in the primary study, 12 also participated in this ancillary study. These sites had a slit-lamp-mounted and/or handheld GAT and performed additional IOP measurements on the same eye using one of the GAT instruments. This examination could be performed in the office or while the subject was under general anesthesia. The Tono-Pen calibration was confirmed each day prior to the initial subject recording, and only measurements with 95% or higher confidence were recorded. IOP was measured after instillation of fluorescein combined with a topical anesthetic in the office setting. Subjects under general anesthesia had IOP measured within 2 minutes of induction, if possible. The testing order for the instruments was randomized using a list provided to

each site. The measurements were performed by two separate certified study examiners who were masked to the other examiner's measurements, with one taking two single Tono-Pen measurements and the other taking two single GAT measurements. For both instruments, a third IOP measurement was required whenever the first two measurements differed by 2 mm Hg and when measurements were obtained under general anesthesia. Examiners were not masked to their previous measurements. All measurements were taken in the right eye only.

Cycloplegic retinoscopy, if not available from an examination up to 6 months prior to enrollment, was performed using cyclopentolate 1% or 2%, or (Cyclomydril; Alcon Laboratories, Fort Worth, TX) with the choice at investigator's discretion.

A standardized data form was completed for each subject, including age, ethnicity, race, and time in minutes from general anesthesia induction to IOP measurement (if applicable). The examiner recorded his or her degree of confidence in the IOP measurement as "good," "poor," or "could not obtain." Possible reasons for poor confidence included subject behaviors expected to impact accuracy of IOP measurement, such as eye squeezing, or crying.

Instrument agreement analyses were conducted on data from subjects with both GAT and Tono-Pen measurements (N = 439). IOP measurements with poor reported examiner confidence (N = 4) or procedural deviations (N = 74) were excluded from analyses. Procedural deviations included having the same tester take GAT and Tono-Pen measurements (N = 28) and not obtaining the required number of IOP measurements (N = 46). Measurements taken more than 2 minutes after induction of general anesthesia (N = 13) also were excluded because general anesthesia has been reported to lower IOP measurements within a few minutes of induction.^{9,10}

Means of nonexcluded Tono-Pen measurements and GAT measurements, with up to three of each, were computed and agreement was assessed using Bland-Altman plots and by calculating limits of agreement.¹¹ The limits of agreement represent the range in which 95% of the differences between measurements by the two instruments occur. Separate analyses were performed for slit-lamp-mounted GAT in the office setting and handheld GAT under general anesthesia. In comparing the Tono-Pen to GAT mounted on slit-lamp, the difference between instruments was significantly related to the IOP measurement, so the differences were regressed on the average of the two methods to derive limits of agreement that were a linear function of the average of the two methods. The absolute residuals from this model were regressed versus the mean test-retest IOP to determine whether the measurement error depended on the IOP. A sensitivity analysis was performed assessing agreement between the median of measurements rather than the means. Linear regression was used to evaluate whether other factors, including age, sex, ethnicity, ocular diagnosis, refractive error, and CCT were related to the difference between instruments, after adjusting for the IOP measurement (average of GAT and Tono-Pen). The association of slit-lamp-mounted GAT IOP with CCT also was evaluated using regression, adjusting for age, racial/ethnic group, sex, and examination setting.

Tono-Pen precision analyses included subjects with two or more Tono-Pen measurements in at least one setting (N = 2,011). For the office setting, only the first two measurements were used for analysis. Tono-Pen IOP measurements with poor reported examiner confidence (N = 22) were excluded from analyses. Due to lack of masking of retest measurements and subjectivity of GAT IOP determination, precision of GAT measurements was not estimated. Standard error of measurement and the Bland-Altman coefficient of repeatability in each setting were calculated using repeated measures analysis of variance.¹¹ The coefficient of

repeatability provides the estimated limits within which 95% of test–retest differences are expected to fall ($= 1.96 \times 2 \times \text{standard error of measurement}$). Coefficients of repeatability also were calculated for individual examiners who performed Tono-Pen test–retest measurements for more than 20 subjects in the same setting.

Linear regression analysis, stratified by setting, was used to determine whether Tono-Pen test–retest differences were related to IOP, age, refractive error, central corneal thickness, and examiner. Test–retest differences were compared for subjects examined in the office versus under general anesthesia using a linear mixed model that accounted for multiple correlated differences in subjects examined under general anesthesia.

Results

Comparison of GAT and Tono-Pen Measurements

Of the 439 subjects measured using the GAT and meeting inclusion criteria for the analysis, 372 were measured using the slit-lamp-mounted GAT in an office setting, 21 using the handheld GAT in the office setting, and 46 using the handheld GAT under general anesthesia. Characteristics of these subjects are provided in e-Supplement 2 (available at jaapos.org). Forty-six subjects (100%) under general anesthesia had three measurements taken with both handheld GAT and Tono-Pen as required by protocol. In the office setting, three measurements were taken for 163 subjects (44%) with Tono-Pen and 37 (10%) with GAT because the first two measurements differed by ≥ 2 mm Hg. Two subjects had GAT IOP >21 mm Hg and 22 had Tono-Pen IOP >21 mm Hg.

The mean difference and limits of agreement between the Tono-Pen and the slit-lamp mounted GAT in the office setting varied as a function of the IOP measurement ($P < 0.001$), estimated using the average of the Tono-Pen and GAT measurements (Figure 1, Table 1). For example, the average difference (GAT–Tono-Pen) was 0.4 mm Hg for IOP of 10 mm Hg (the 3rd percentile of IOP) and -3.0 mm Hg for IOP of 20 mm Hg (the 98th percentile of IOP). Hence, the Tono-Pen measurements were similar to or slightly higher than the GAT measurements when IOP was between 10 and 20 mm Hg, a range that included 95% of IOPs in the study population. Tono-Pen measurements trended slightly lower than GAT when estimated IOP was less than 11 mm Hg and trended slightly higher than GAT when IOP was greater than 11 mm Hg. The 95% limits of agreement on the average difference were ± 6.4 mm Hg in the office setting and ± 6.8 mm Hg under general anesthesia, and did not vary with the IOP. Thus, in the office setting, the average difference depends on the IOP, but the spread of individual differences about the average, that is, the limits of agreement, does not. The general anesthesia cohort did not show a similar trend but rather showed that the Tono-Pen measurements were slightly higher than handheld GAT measurements by an average of 1.6 mm Hg across the range of IOP, with 95% of GAT–Tono-Pen differences falling within -8.4 and $+5.2$ mm Hg (Figure 2, Table 1). The comparison of instruments using the median measurement produced similar results.

Of age, race/ethnicity, sex, ocular diagnosis, CCT, and spherical equivalent refractive error, only age was associated with instrument agreement. Larger differences between instruments in which Tono-Pen measured higher than GAT were found with younger age for both the Tono-Pen compared with slit-lamp-mounted GAT in an office setting, and Tono-Pen compared with handheld GAT under general anesthesia (Table 2).

Correlation between GAT IOP and CCT

There was a statistically significant association between central corneal thickness and IOP determined with GAT (Figure 3); however, variability in CCT in this study population accounted for only 0.16% of the variability in IOP. Among normal subjects with IOP

ranging from 6 to 23 mm Hg, GAT IOP was 1.9 mm Hg higher for every 100 μ m increase in CCT ($P < 0.0001$; Figure 3). A similar relationship between IOP and CCT was found after excluding subjects with IOP higher than 21 mm Hg.

Precision of Tono-Pen Measurements

Table 3 summarizes the standard errors of measurement and coefficients of repeatability obtained by setting. The overall standard error of measurement was 1.44 and 1.82 mm Hg for office and general anesthesia settings, respectively. Magnitude of the measurement error increased with increasing IOP in the office and under general anesthesia ($P < 0.0001$ and $P = 0.01$; Table 3), while measurement error as a proportion of the IOP measurement decreased with increasing IOP ($P < 0.0001$ for both in office and under anesthesia). Combining data for all examiners, the coefficients of repeatability were 3.99 and 5.05 for the office and general anesthesia settings, respectively. Coefficients of repeatability for individual examiners with test–retest measurements for more than 20 subjects ranged from 1.9 to 7.1 mm Hg ($N = 25$ examiners, median = 3.7) for the Tono-Pen in the office setting, and were 4.4 and 4.8 mm Hg for 2 examiners using Tono-Pen in subjects under anesthesia. Most examiners used only one instrument in a particular setting. Only one examiner used Tono-Pen in more than 20 subjects in both the office setting and under general anesthesia, so we were unable to compare intra-examiner reliability between settings.

The magnitude of the Tono-Pen test–retest differences was not associated with age, refractive error, or CCT in either exam setting. There was an association with examiner in both settings ($P < 0.001$ and $P = 0.048$, for office and under anesthesia settings, respectively), with some examiners reporting more repeatable measurements than others.

Discussion

In this study of children and adolescents less than 18 years of age, the difference between measurements taken with the Tono-Pen and slit-lamp-mounted GAT was dependent on IOP. In an office setting, Tono-Pen measurements tended to be slightly lower than slit-lamp mounted GAT when IOP was less than 11 mm Hg and slightly higher than GAT when IOP was greater than 11 mm Hg. This trend was not seen for measurements under general anesthesia; however, our sample size for that analysis was small. Tono-Pen measurements were consistently slightly higher on average than handheld GAT under general anesthesia. Better agreement was found among older children in both settings.

Prior reports in adults have had varied findings. Minckler found Tono-Pen-measured IOP on average 1.7 mm Hg higher than GAT within a GAT IOP range of 6–24 mm Hg.¹² No difference was noted with intraocular pressures above 24 mm Hg. Frenkel and colleagues³ reported that the Tono-Pen-measured IOP was within 3 mm Hg of GAT in 77% of subjects. In addition, the Tono-Pen recorded lower IOP than GAT for IOPs of ≥ 21 mm Hg, while measuring higher IOP than GAT for intraocular pressures < 11 mm Hg. However, the authors compared GAT/Tono-Pen differences to the GAT measurement rather than to the GAT/Tono-Pen average. Such a statistical analysis would be biased toward finding an association between the two procedures.¹³

A recent study found that the Tono-Pen overestimated IOP relative to GAT in normal adult eyes.¹⁴ Another study compared the Tono-Pen to the GAT in 103 adults.⁷ The latter reported the 95% limits of agreement for the difference between methods (Tono-Pen minus GAT) to be -6 to $+8$ mm Hg, similar to the limits of agreement (-5 to $+8$ mm Hg) in our study for the anesthesia cohort and the office cohort at their average IOP of 15 mm Hg. The GAT itself has been reported to have inter-observer limits of agreement of ± 4 mm Hg.^{15, 16}

There are few data analyzing the accuracy of these instruments in children. Eisenberg and colleagues⁴ performed manometry through an incision in 5 children and 4 adults who were scheduled to undergo intraocular surgery, and compared handheld GAT and Tono-Pen IOP measurements with manometric readings. Both the GAT and the Tono-Pen underestimated IOP across all manometric IOP ranges in the 5 children. Including all 9 subjects, Tono-Pen was most accurate at a manometric IOP of 11.8 mm Hg, and was less accurate above this pressure.

A subject's seated or recumbent position affects Tono-Pen measurements. Viestenz and colleagues¹⁷ found that the Tono-Pen measured IOP 0.8 mm Hg higher when the subject was recumbent rather than seated. It was also noted to be 0.5 mm Hg higher than the Drager applanation tonometer used with the recumbent subject. It is possible that the higher measurements we observed with the Tono-Pen compared to handheld GAT in subjects under general anesthesia were influenced by the subjects' supine position affecting the two instruments differently vis-à-vis readings taken of seated subjects. IOP measurements may also have been affected by other factors, such as eye position or facial mask pressure.

In a secondary analysis we considered the relationship between GAT-measured IOP and CCT. GAT-measured IOP was 1.9 mm Hg higher for every 100 μ m increase in CCT. In an earlier publication we found Tono-Pen-measured IOP was 1.5 mm Hg higher for every 100 μ m increase in CCT.⁸ This accords with the results of a prior small pediatric study by Muir and colleagues.¹⁸ This small difference in the effect of CCT may be secondary to the larger corneal surface area contacted by the GAT device. In addition, Tono-Pen measurements may be less dependent than GAT on the biomechanical properties of the cornea.¹⁹ In adults, GAT was more affected by increasing subject age than Tono-Pen, possibly from increased corneal stiffness with age.^{19,20}

Our study has several limitations. It was designed so that measurements could be obtained without interruption of clinic or surgical facility operations; owing to these constraints, investigators obtaining retest measurements were not masked to their prior measurements. This could have biased our findings to greater precision and may also have biased GAT measurements toward normal values. Owing to the subjectivity of GAT measurement from the lack of masking, we did not estimate GAT precision. Second, the number of subjects tested with the handheld GAT under general anesthesia was small. Third, owing to the limited availability of the newer handheld Icare tonometer (Tiolat Oy, Helsinki, Finland) among study sites, it was not evaluated as an alternative option for pediatric IOP measurements. Lastly, this study enrolled only normal subjects. It is unknown whether this data can be extrapolated to children with glaucoma or ocular hypertension.

In children and adolescents with normal eyes, average differences between IOP measured with the Tono-Pen and GAT were small; however, there was substantial variability that is reflected by the 95% limits of agreement of ± 6.4 mm Hg in the office setting and ± 6.8 mm Hg under anesthesia. Younger age was associated with larger differences between these two instruments. Tono-Pen precision was greater in the office than under general anesthesia. Given the variability of measurements we advise clinicians to take two or three measurements with the Tono-Pen. In the office setting, a second instrument is recommended if any measurement is 20 mm Hg or higher, which is the IOP where the average difference between instruments is 3 mm Hg.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

Supported by the National Eye Institute of the National Institutes of Health, Department of Health and Human Services EY011751 and EY018810. The sponsor or funding organization had no role in the design or conduct of this research.

Appendix

Additional Authors

In alphabetical order: Bradley V. Davitt, MD,^a David A. Johnson, MD, PhD,^b Raymond T. Kraker, MSPH,^c Ruth E. Manny, OD, PhD,^d Noelle S. Matta,^e Susan Schloff, MD,^f Katherine K. Weise, OD, MBA,^g

Author affiliations: ^aCardinal Glennon Children's Medical Center, Saint Louis University, St. Louis, Missouri; ^bEye Associates of Wilmington, Wilmington, North Carolina; ^cJaeb Center for Health Research, Tampa, Florida; ^dUniversity of Houston College of Optometry, Houston, Texas; ^eFamily Eye Group, Lancaster, Pennsylvania; ^fAssociated Eye Care, Saint Paul, Minnesota; ^gUniversity of Alabama at Birmingham School of Optometry, Birmingham, Alabama

References

1. Garway-Heath, DF.; Kotecha, A.; Lerner, F., et al. WGA Consensus Series 4: Intraocular Pressure. Amsterdam: Kugler Publications; 2007. Measurement of intraocular pressure; p. 17-54.
2. Iester M, Mermoud A, Achache F, Roy S. New Tonopen XL: comparison with the Goldmann tonometer. *Eye*. 2001; 15:52–58. [PubMed: 11318296]
3. Frenkel RE, Hong YJ, Shin DH. Comparison of the Tono-Pen to the Goldmann applanation tonometer. *Arch Ophthalmol*. 1988; 106:750–753. [PubMed: 3369998]
4. Eisenberg DL, Sherman BG, McKeown CA, Schuman JS. Tonometry in adults and children. A manometric evaluation of pneumatonometry, applanation, and TonoPen in vitro and in vivo. *Ophthalmology*. 1998; 105:1173–1181. [PubMed: 9663218]
5. Bordon AF, Katsumi O, Hirose T. Tonometry in pediatric patients: A comparative study among Tono-pen, Perkins, and Schiotz tonometers. *J Pediatr Ophthalmol Strabismus*. 1995; 32:373–377. [PubMed: 8587021]
6. Kass MA. Standardizing the measurement of intraocular pressure for clinical research: Guidelines from the Eye Care Technology Forum. *Ophthalmology*. 1996; 103:183–185. [PubMed: 8628552]
7. van der Jagt LH, Jansonius NM. Three portable tonometers, the TGDc-01, the ICARE and the Tonopen XL, compared with each other and with Goldmann applanation tonometry. *Ophthalmic Physiol Opt*. 2005; 25:429–435. [PubMed: 16101949]
8. Pediatric Eye Disease Investigator Group. Central corneal thickness in children. *Arch Ophthalmol*. 2011; 129:1132–1138. [PubMed: 21911662]
9. Blumberg D, Congdon N, Jampel H, et al. The effects of sevoflurane and ketamine on intraocular pressure in children during examination under anesthesia. *Am J Ophthalmol*. 2007; 143:494–499. [PubMed: 17317393]
10. Ausinsch B, Munson ES, Levy NS. Intraocular pressure in children with glaucoma during halothane anesthesia. *Ann Ophthalmol*. 1977; 9:1391–1394. [PubMed: 337879]
11. Bland JM, Altman DG. Measuring agreement in method comparison studies. *Stat Methods Med Res*. 1999; 8:135–160. [PubMed: 10501650]
12. Minckler DS, Baerveldt G, Heuer DK, Quillen-Thomas B, Walonker AF, Weiner J. Clinical evaluation of the Oculab Tono-Pen. *Am J Ophthalmol*. 1987; 104:168–173. [PubMed: 3618714]
13. Bland JM, Altman DG. Comparing methods of measurement: why plotting difference against standard method is misleading. *Lancet*. 1995; 346:1085–1087. [PubMed: 7564793]

14. Mollan SP, Wolffsohn JS, Nessim M, et al. Accuracy of Goldmann, ocular response analyser, Pascal and TonoPen XL tonometry in keratoconic and normal eyes. *Br J Ophthalmol*. 2008; 92:1661–1665. [PubMed: 18757471]
15. Dielemans I, Vingerling JR, Hofman A, Grobbee DE, de Jong PT. Reliability of intraocular pressure measurement with the Goldmann applanation tonometer in epidemiological studies. *Graefes Arch Clin Exp Ophthalmol*. 1994; 232:141–144. [PubMed: 8188062]
16. Motolko MA, Feldman F, Hyde M, Hudy D. Sources of variability in the results of applanation tonometry. *Can J Ophthalmol*. 1982; 17:93–95. [PubMed: 7116219]
17. Viestenz A, Lausen B, Junemann AM, Mardin CY. [Comparison of precision of Tonopen XL with the Goldmann and Draeger applanation tonometer in a sitting and recumbent position - a clinical study on 251 eyes]. *Klin Monatsbl Augenheilkd*. 2002; 219:785–790. [PubMed: 12494368]
18. Muir KW, Duncan L, Enyedi LB, Freedman SF. Central corneal thickness in children: Racial differences (black vs. white) and correlation with measured intraocular pressure. *J Glaucoma*. 2006; 15:520–523. [PubMed: 17106365]
19. Tonnu PA, Ho T, Newson T, et al. The influence of central corneal thickness and age on intraocular pressure measured by pneumotonometry, non-contact tonometry, the Tono-Pen XL, Goldmann applanation tonometry. *Br J Ophthalmol*. 2005; 89:851–854. [PubMed: 15965165]
20. Daxer A, Misof K, Grabner B, Ettl A, Fratzl P. Collagen fibrils in the human corneal stroma: structure and aging. *Invest Ophthalmol Vis Sci*. 1998; 39:644–648. [PubMed: 9501878]

FIG 1.

Difference between Tono-Pen and slit-lamp-mounted Goldmann applanation tonometer (GAT) by average intraocular pressure (IOP) in subjects measured in an office setting. The middle line gives the estimated mean GAT–Tono-Pen difference as a function of the average of the Tono-Pen and GAT measurements (x). The upper and lower lines are the 95% limits of agreement for the difference. The Tono-Pen underestimated IOP relative to GAT for IOP <11 mm Hg and overestimated IOP relative to GAT for IOPs >11 mm Hg.

FIG 2.

Difference between Tono-Pen and handheld Goldmann applanation tonometer (GAT) by average intraocular pressure (IOP) in subjects measured under general anesthesia. The middle line gives the estimated mean GAT–Tono-Pen difference in IOP. The upper and lower lines are the 95% limits of agreement for the difference. On average, the Tono-Pen overestimated the IOP relative to the handheld GAT by 1.6 mm Hg across the range of IOP studied, with 95% of GAT–Tono-Pen differences falling within –8.4 and +5.2 mm Hg.

FIG 3.

Goldmann applanation tonometer (GAT) determined intraocular pressure (IOP) by central corneal thickness (CCT). Slope (β) of the regression line is 0.019. Partial coefficient of determination (R^2) for CCT is 0.04. The IOP determined by the GAT was 1.9 mm Hg higher for every 100 micrometer increase in CCT ($P < 0.0001$).

Table 1

Distribution of Goldmann applanation tonometer minus Tono-Pen differences by intraocular pressure

GAT minus Tonopen difference, mm Hg	Intraocular pressure, mm Hg office setting (slit-lamp-mounted GAT/Tonopen average)						
	<12 N (%)	12 to <14 N (%)	14 to <16 N (%)	16 to <18 N (%)	18 to <20 N (%)	20 N (%)	Total N (%)
< -8	0 (0)	0 (0)	2 (2)	4 (5)	1 (4)	1 (9)	8 (2)
-8 to < -6	0 (0)	3 (3)	10 (8)	4 (5)	2 (7)	1 (9)	20 (5)
-6 to < -4	0 (0)	8 (9)	15 (13)	5 (6)	5 (19)	2 (18)	35 (9)
-4 to < -2	8 (19)	20 (23)	27 (23)	22 (26)	4 (15)	3 (27)	84 (23)
-2 to +2	22 (51)	45 (51)	50 (42)	37 (44)	12 (44)	4 (36)	170 (46)
> +2 to +4	8 (19)	10 (11)	12 (10)	8 (9)	2 (7)	0 (0)	40 (11)
> +4 to +6	2 (5)	1 (1)	1 (1)	4 (5)	0 (0)	0 (0)	8 (2)
> +6 to +8	2 (5)	1 (1)	1 (1)	1 (1)	1 (4)	0 (0)	6 (2)
> +8	1 (2)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	1 (<1)
Total	43 (12)	88 (24)	118 (32)	85 (23)	27 (7)	11 (3)	372 (100)
Mean (SD)	1.0 (3.0)	-0.9 (2.7)	-1.8 (3.3)	-1.4 (3.6)	-2.2 (3.7)	-3.8 (2.9)	-1.3 (3.4)
General anesthesia (Handheld GAT/Tonopen average)							
< -8	1 (6)	0 (0)	0 (0)	1 (14)	0 (0)	0 (-)	2 (4)
-8 to < -6	2 (12)	0 (0)	0 (0)	1 (14)	0 (0)	0 (-)	3 (7)
-6 to < -4	3 (19)	3 (43)	2 (14)	1 (14)	1 (50)	0 (-)	10 (22)
-4 to < -2	1 (6)	1 (14)	1 (7)	0 (0)	0 (0)	0 (-)	3 (7)
-2 to +2	7 (44)	2 (29)	8 (57)	4 (57)	1 (50)	0 (-)	22 (48)
> +2 to +4	1 (6)	1 (14)	3 (21)	0 (0)	0 (0)	0 (-)	5 (11)
> +4 to +6	1 (6)	0 (0)	0 (0)	0 (0)	0 (0)	0 (-)	1 (2)
> +6 to +8	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (-)	0 (0)
> +8	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (-)	0 (0)
Total	16 (35)	7 (15)	14 (30)	7 (15)	2 (4)	0 (-)	46 (100)
Mean (SD)	-2.1 (3.7)	-2.3 (3.1)	-0.1 (2.9)	-2.8 (4.4)	-2.0 (3.8)	0 (-)	-1.6 (3.5)

Table 2

Mean difference between Tono-Pen and Goldmann applanation tonometer by age

Instrument comparison	Age group	N	Adjusted mean difference (mm Hg) ^a	Standard error	P value for age ^b
Slit-lamp-mounted GAT minus Tono-Pen office setting	0–5 months	3	–1.2	1.9	<0.001
	6–11 months	0	--	--	
	12–23 months	3	–4.5	1.9	
	2 years	8	–3.1	1.1	
	3 years	9	–1.6	1.1	
	4–5 years	50	–2.1	0.5	
	6–7 years	64	–1.7	0.4	
	8–9 years	74	–1.2	0.4	
	10–12 years	83	–1.0	0.4	
	13–17 years	78	–0.3	0.4	
	6–11 months	10	–1.9	1.1	
Handheld GAT minus Tono-Pen under anesthesia	12–23 months	11	–3.5	1.1	0.03
	2 years	5	–2.7	1.6	
	3 years	6	0.6	1.4	
	4–5 years	7	–1.0	1.4	
	6–7 years	2	–0.3	2.6	
	8–9 years	3	–1.5	2.0	
	10–12 years	2	2.8	2.5	
	13–17 years	0	--	--	

GAT, Goldmann applanation tonometer.

^aDifference adjusted for underlying IOP (average of GAT and Tono-Pen).

^bFrom regression analysis of age versus GAT minus Tono-Pen difference, with age as a continuous factor, adjusting for average of GAT and Tono-Pen.

Table 3

Precision of Tonopen by setting

	Office setting	Under general anesthesia
Distribution of absolute test–retest differences, N (%) ^a	N = 1593	N = 396
2	1338 (84)	301 (76)
4	1522 (96)	367 (93)
6	1577 (99)	386 (97)
8	1588 (100)	391 (99)
Standard error of measurement, overall	1.44	1.82
IOP <12 mm Hg	1.25	1.56
12 IOP <16 mm Hg	1.24	1.82
16 IOP <20 mm Hg	1.61	1.94
IOP 20 mm Hg	1.99	1.93
Coefficient of repeatability	3.99	5.05

^aBased on first 2 measurements.