Comparison of the use of new handheld tonometers and established applanation tonometers in dogs

Christiane Görig, DVM, Dr med vet; Roel T. I. Coenen, DVM; Frans C. Stades, DVM, PhD; Sylvia C. Djajadiningrat-Laanen, DVM; Michael H. Boevé, DVM, PhD

Objective—To examine the practical aspects, accuracy, and reproducibility of 2 new automatic handheld tonometers in dogs and compare them with results for 2 established applanation tonometers.

Animals—15 freshly enucleated canine eyes for manometric evaluation and 20 conscious research dogs, 20 client-owned dogs, and 12 dogs with acute glaucoma for clinical tonometry.

Procedure—Calibration curves were determined for all 4 tonometers on 15 enucleated canine eyes. Intraocular pressure (IOP) was measured with each tonometer consecutively in conscious dogs, with the MacKay-Marg applanation tonometer as the reference device. Measurements were repeated in 20 sedated dogs. An induction-impact tonometer was evaluated clinically on dogs with acute glaucoma. Additionally, measurements obtained by an experienced and an inexperienced examiner and with or without use of topical anesthesia were compared.

Results—The portable pneumatonometer was cumbersome and time-consuming. Compared with results for the reference applanation tonometer, and confirmed by manometry, the portable pneumatonometer increasingly underestimated actual IOP values with increasing IOP. The induction-impact tonometer provided accurate and reproducible measurement values. There was a significant strong correlation between the IOP values obtained by the 2 examiners (r^2, 0.82) and also with or without topical anesthesia (r^2, 0.86). In dogs with glaucoma, the fitted line comparing values for the reference applanation tonometer and induction-impact tonometer closely resembled an ideal 1:1 relationship.

Conclusions and Clinical Relevance—Use of the portable pneumatonometer in dogs appears to have disadvantages. The induction-impact tonometer appears to provide a promising alternative to the use of applanation tonometers in dogs. (*Am J Vet Res* 2006;67:134–144)

Tonometry is the indirect measurement of IOP. It is an essential diagnostic procedure for evaluation of intraocular hypertension or hypotension and for monitoring glaucomatous eyes during treatment.

Traditionally, 2 measurement principles have been used in veterinary ophthalmology (indentation and applanation tonometry). For indentation tonometry (eg, a Schiotz tonometer), the cornea is indented by a weighted plunger within a footplate with a curvature corresponding to the human cornea. The amount of corneal indentation is measured after applying a known weight to the corneal surface. Calibration tables are used to convert tonometer scale measurements to an estimation of IOP.[1] The calibration table for humans was the clinically most useful table for converting Schiotz tonometer measurements to IOP values in eyes of cats and dogs that did not have ocular disease.[2,3]

Applanation tonometers indirectly assess IOP by measuring the force required to flatten (ie, applanate) a constant area of the central corneal surface.[4] This mechanism is based on the Imbert-Fick law, which states that the pressure in a sphere filled with liquid and surrounded by a thin membrane can be measured by the counterpressure necessary to flatten this membrane to a plane.[5] The MacKay-Marg applanation tonometer has been considered the most reliable device for measurement of IOP in clinically normal dogs,[6,7,a] dogs with glaucoma,[8,9] horses,[10,11,a] and cats[12]; however, this tonometer is no longer manufactured. Another commercially available applanation tonometer[b] has become a popular instrument among veterinary ophthalmologists because of its availability, portability, ease of operation, and relatively low cost.[6,7,11–17,a] In human subjects, this commercially available applanation tonometer reportedly[18] has reproducibility and accuracy similar to those of the MacKay-Marg applanation tonometer, but it consistently overestimates IOP in dogs with values < 20 mm Hg and underestimates IOP for values > 40 mm Hg.[7] Because of species variations in ocular anatomy (corneal diameter, thickness, curvature, and rigidity), differing calibration curves are necessary for the various species.[14–16,19,20]

A similar principle of measurement is used in noncontact tonometers; however, a puff of air (rather than a solid material) is used to flatten the cornea.[21,22] Advantages of noncontact tonometers include the avoidance of contaminating eyes and the possibility of measuring IOP without the need for topical anesthetics that could affect IOP.[23] Most noncontact tonometers are desktop instruments and hence not easily applied in animals. The portable, handheld, noncontact tonome-

IOP Intraocular pressure
I-I Induction-impact

Received March 29, 2005.
Accepted May 25, 2005.
From the Department of Clinical Sciences of Companion Animals, Faculty of Veterinary Medicine, University of Utrecht, Yalelaan 8, 3508 TD Utrecht, The Netherlands (Görig, Stades, Djajadiningrat-Laanen, Boevé); and Animal Clinic Groenlo-Lichtenvoorde, Zieuwentseweg 4a, 7131 LB Lichtenvoorde, the Netherlands (Coenen).
Supported by Reichert Ophthalmic Instruments and Tiolat.
Presented in part at the Annual Meeting of the European College of Veterinary Ophthalmologists, München, Germany, June 2004.
The authors thank X. Lescure and H. de Groot for assistance with the study.
Address correspondence to Dr. Görig.

ter used in the study reported here has an automatically activated alignment system inside the eyepiece to guide the operator to the correct alignment position. Then, a puff of air is automatically released, and a measurement value is displayed on the screen. To the authors' knowledge, this tonometer has not yet been tested clinically in dogs. Another similar noncontact tonometer has been used experimentally in rabbits and cats.[24]

A portable tonometer based on a novel measurement method has been commercially released and has gained attention among veterinarians.[c–f] It is a patented induction-based rebound tonometer that allows IOP to be measured rapidly without the need for topical anesthesia. A magnetized probe is brought into contact with an eye, and its return-bounce motion is detected by a sensing coil. The motion for the probe varies on the basis of the IOP and thus can be used to determine IOP. It has been established[25–27] that the inverse of the deceleration time is most closely correlated with IOP. The disposable probe consists of a steel-wire shaft with a round plastic tip (1 mm in diameter) at its front end. This round tip prevents corneal damage that could result from probe impact. This I-I tonometer has been calibrated against manometric measurements of IOP obtained by use of the eyes of Wistar rats.[27]

The purpose of the study reported here was to determine the usefulness, accuracy, and reproducibility for the 2 aforementioned new automatic handheld tonometers in dogs. Additionally, we compared results for the 2 new automatic handheld tonometers with those for 2 established applanation tonometers (a commercially available applanation tonometer and the MacKay-Marg tonometer).

Materials and Methods

Sample population—Fifteen freshly enucleated eyes were obtained for use in the study. In addition, measurements were obtained for 20 conscious research dogs, 20 client-owned dogs while sedated, and 12 dogs with glaucoma. All tonometers were maintained and applied to each eye in accordance with the manufacturer's recommendations. All experiments were performed in accordance with the Association for Research in Vision and Ophthalmology Statement on the Use of Animals in Ophthalmic and Vision Research and were approved by a local animal experimentation committee.

Experimental design—First, 2 applanation tonometers (a commercially available applanation tonometer[b] and the MacKay-Marg[g] applanation tonometer), an I-I tonometer,[h] and a portable pneumatonometer[i] were calibrated manometrically on 15 freshly enucleated canine eyes. Eyes were obtained from dogs without ocular disease that were euthanatized during unrelated research projects. Eyes were removed immediately after the dogs were euthanatized; eyes were then immersed in saline (0.9% NaCl) solution at 4°C. All measurements were performed within 4 hours after enucleation.

Second, all 4 tonometers were compared clinically on 20 conscious research dogs without apparent ocular disease. The tonometers were compared by repeating the setting on 20 client-owned dogs after they were sedated by administration of medetomidine hydrochloride[j] (10 to 40 µg/kg, IV).

Finally, the I-I tonometer was further evaluated. Variables evaluated included precision in measuring IOP in glaucomatous eyes, interobserver reliability, and the need for topical anesthesia to obtain accurate measurements.

Three consecutive measurements were obtained with each tonometer on each eye, and the mean value for each tonometer was determined. The displayed measurement values of the commercially available applanation tonometer and I-I tonometer were values automatically calculated by the tonometers as the mean of 4 or 6 consecutive measurements, respectively. The values were only accepted when the variance was < 5%. When these criteria were not met, the measurements were discarded and another set of measurements was performed. Measurement values of the portable pneumatonometer were used only when they were not low-confidence measurements, as automatically indicated by the tonometer.

Manometric examination—For the manometric calibration (ie, ex vivo examination), the enucleated eyes were positioned on a foam bed by the use of needles to affix them against a vertical silicon ring. A 26-gauge needle was inserted as a cannula through the limbus into the anterior chamber. To prevent leakage of aqueous humor around the needle, it was sealed with cyanoacrylate glue.[k]

After the anterior chamber was entered, the IOP was reduced to 10 cm H_2O; then, it was increased in increments of 10 cm H_2O by the addition of saline solution to achieve a maximum IOP of 100 cm H_2O. Because 1.36 cm H_2O is equivalent to 1 mm Hg, this resulted in measured IOP that ranged from 7.4 to 73.5 mm Hg. A closed system was used.[8,11,16] The system was calibrated to the column of saline solution immediately after the needle entered each eye. When the continuous monitoring revealed a slight decrease in IOP after the measurement was obtained, the pressure in the eye was adjusted again before obtaining a subsequent measurement with another tonometer. The I-I tonometer was always used first, followed by the MacKay-Marg applanation tonometer, the commercially available applanation tonometer, and the portable pneumatonometer. This order was determined by random allocation. Saline solution was periodically applied to the enucleated eyes to keep the cornea moist throughout the testing period.

Clinical tonometry of dogs without ocular disease—For the clinical in vivo examination, IOP was measured by use of all 4 tonometers consecutively in both eyes of 20 conscious research dogs. Dogs were handled such that they would remain as calm as possible and require as little restraint as possible. The MacKay-Marg tonometer was used as the reference tonometer; thus, it was used first, again after one of the new handheld automatic tonometers, and again after the commercially available applanation tonometer. The first MacKay-Marg measurement (ie, MM-0) was conducted to acclimate the dogs to the measurement procedure and was used as the baseline value. The second MacKay-Marg measurement (ie, MM-1) was compared with the measurement obtained by use of either of the new automatic handheld tonometers, and the third MacKay-Marg measurement (ie, MM-2) was compared with the measurement obtained by use of the commercially available applanation tonometer.

To exclude the influence of stress on IOP measurements as much as possible, comparisons were made for tonometer measurements of the eyes of the 20 client-owned dogs that were sedated. In this case, the order of use of the tonometers was randomized.

Clinical tonometry of eyes of dogs with glaucoma—On the basis of analysis of data obtained for healthy dogs, the I-I tonometer appeared to have promising results and was further evaluated on patients with clinical signs of acute glaucoma. Values for the I-I tonometer for the glaucomatous dogs were compared with results obtained by use of the

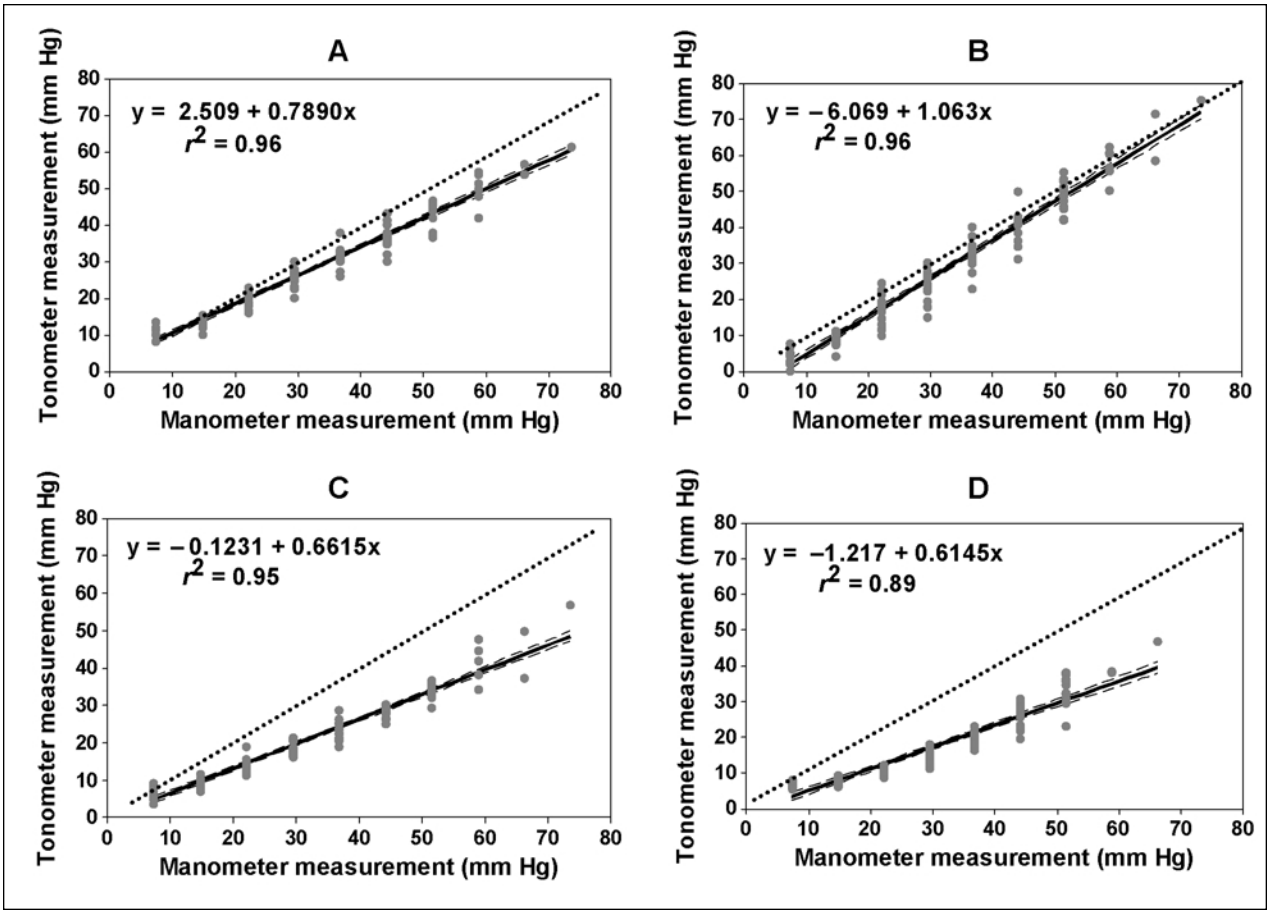

Figure 1—Relationship between manometric measurements of IOP and IOP measurements obtained by use of the MacKay-Marg tonometer[g] (A), an I-I tonometer[h] (B), a commercially available applanation tonometer[b] (C), and a portable pneumatonometer[i] (D) in freshly enucleated canine eyes. Each symbol represents a tonometric measurement (mean value calculated from 3 repeated measurements). The calculated regression line (solid line) and 95% confidence interval (dashed lines) for each tonometer and the ideal linear model (1:1 relationship; dotted line) are indicated.

MacKay-Marg and commercially available applanation tonometers. In this case, the order of use for the tonometers was randomized.

Reliability of the I-I tonometer—Interobserver reliability of the I-I tonometer was also evaluated by comparing measurements of the IOP of 40 eyes of 20 conscious healthy dogs conducted consecutively by 2 examiners (CG and RTIC). Measurements were performed in a randomized order. Furthermore, the manufacturer's manual states that the I-I tonometer can be used without the need for topical ophthalmic anesthesia; therefore, 40 eyes of 20 healthy dogs were measured consecutively without and with topical administration of 4% lidocaine[l] to evaluate any difference in IOP.

Statistical analysis—Data from the enucleated eyes were used to derive an equation that would best represent the relationship between the manometric (independent variable x) and tonometric (dependent variable y) measurements; manometric and tonometric values were plotted against each other on a graph. The equation for best fit was chosen on the criterion of minimization of residual sums of squares. The r^2 values were calculated. Accuracy of each tonometer (ie, absolute difference between the mean IOP measured by the tonometer and that recorded by the manometer) was assessed and compared with the accuracy of each of the other tonometers by use of a paired *t* test. Significance for all comparisons was set at $P < 0.05$.

Reproducibility of the tonometers was evaluated by calculating the mean values of the differences between the highest and lowest (maximum minus minimum) values of the 3 repeated measurements. Because the accuracy of a tonometer for IOP between 25 and 35 mm Hg is of most concern to clinicians and researchers studying glaucoma, IOP values between 7.4 and 36.8 mm Hg were analyzed separately to identify the tonometer that was the most accurate and least variable.

For clinical tonometry, data were used to derive an equation that would best represent the relationship between the MacKay-Marg tonometer (independent variable x) and any of the other tonometers (dependent variable y). The mean values were calculated. In addition, the absolute values of the differences between the tonometer measurements were also calculated and analyzed because equally inaccurate high and low measurements would tend to yield a mean difference close to zero. Because measurements originated from the same eye, a paired Student *t* test was used to assess differences between measurements obtained with each tonometer. In addition, the reproducibility of the tonometers was evaluated and statistically analyzed as described previously. Statistical analysis for data obtained for the sedated dogs was the same as for data obtained in the conscious dogs. Furthermore, data for the glaucomatous dogs were used to derive equations that would best represent the relationship between the I-I tonometer (dependent variable y) and either of the 2 applanation tonometers (independent variable x).

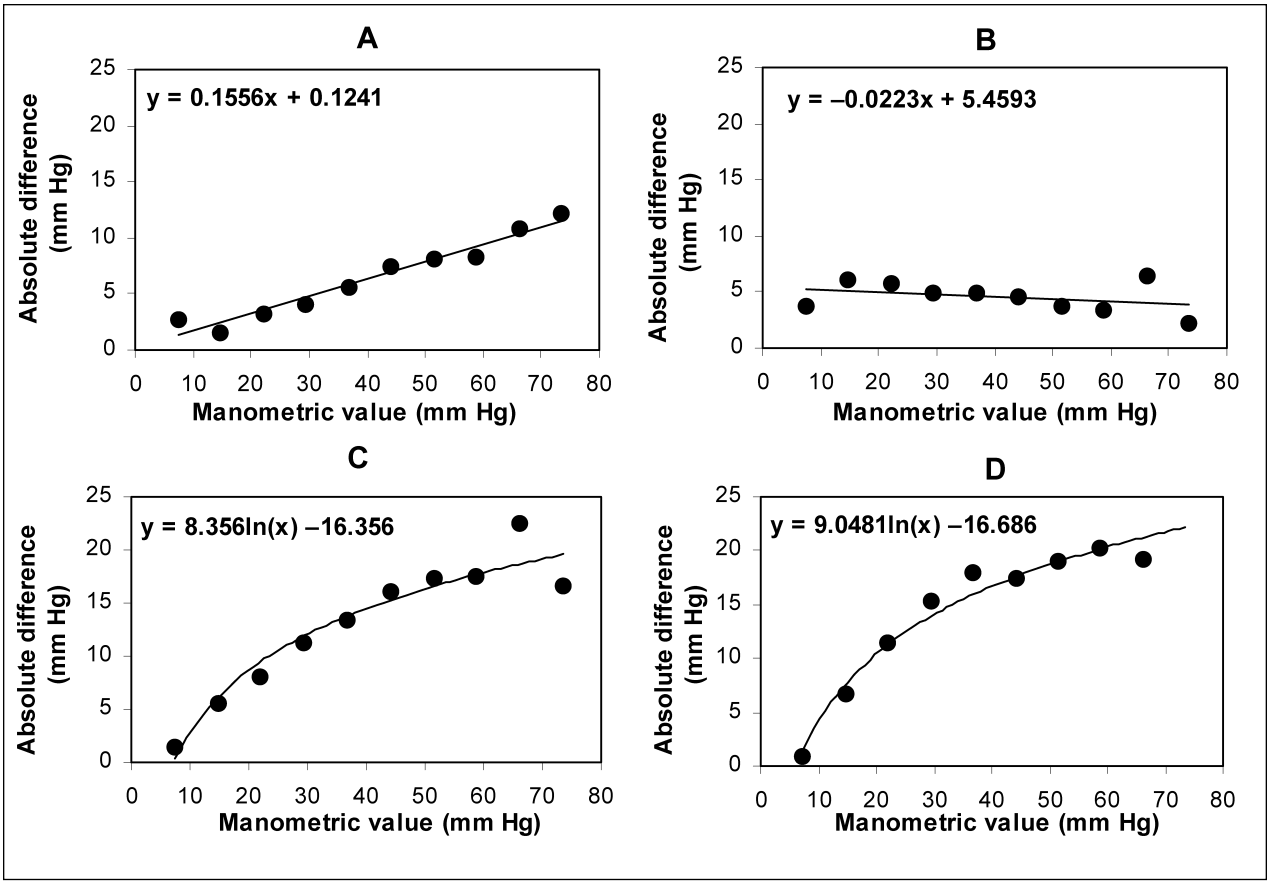

Figure 2—Relationship of the accuracy of IOP measurements obtained by use of the MacKay-Marg tonometer (A), an I-I tonometer (B), a commercially available applanation tonometer (C), and a portable pneumatonometer (D). Fitted regression lines were calculated (solid lines). Accuracy was defined as the mean difference between the IOP measured by use of a tonometer and the IOP measured by use of a manometer on 15 freshly enucleated canine eyes.

Comparisons of measurements between the examiners and between measurements obtained with and without 4% lidocaine were performed by use of paired *t* tests and regression analysis. Absolute differences between the measurements were also calculated and analyzed as described previously.

Results

Manometric evaluation—Mean ± SD and absolute differences between the manometric and tonometric values were determined. The regression curves for all 4 tonometers were essentially linear over the pressure range examined, and the goodness of fit (ie, r^2 value) was between 0.89 for the portable pneumatonometer and 0.96 for the MacKay-Marg and I-I tonometers (**Figure 1**).

Both applanation tonometers and the portable pneumatonometer increasingly underestimated IOP as IOP increased. The regression equation of the I-I tonometer was y = –6.069 + 1.063x. The slope was not significantly different from 1, which indicated that use of this tonometer resulted in a consistent error.

The applanation tonometers and portable pneumatonometer were increasingly less accurate (greater underestimation of true IOP) as IOP increased, particularly at IOP values > 36 mm Hg (**Figure 2**). Accuracy of the I-I tonometer remained almost the same for the entire IOP range evaluated (7.4 to 73.5 mm Hg). Accuracy of the MacKay-Marg tonometer was best in the most clinically relevant range from 7.4 to 36.8 mm Hg, but accuracy for the McKay-Marg tonometer decreased as IOP increased. There was no significant difference between the accuracy of the 4 tonometers for the IOP range from 7.4 to 36.8 mm Hg, but for the entire IOP range (7.4 to 73.5 mm Hg), accuracy of the MacKay-Marg and I-I tonometers was comparable and significantly better than the accuracy of the other 2 tonometers (**Table 1**).

Reproducibility for the MacKay-Marg tonometer remained the same for the entire pressure range (**Figure 3**). However, reproducibility for the I-I tonometer, commercially available applanation tonometer, and portable pneumatonometer decreased linearly as IOP increased.

Clinical tonometry of dogs without ocular disease—Automatic alignment of the portable pneumatonometer was time-consuming, and the measurement procedure required up to 15 min/dog. It was especially difficult to obtain measurements with the portable pneumatonometer in dolichocephalic dogs because of the width (12.7 cm), depth (20.5 cm), and weight (1.3 kg) of the tonometer. Additionally, nervous dogs reacted to the air puff generated by the portable pneumatonometer. The portable pneumatonometer was equipped with a rechargeable 3.5-V battery and charging base; however, loss of battery power was not

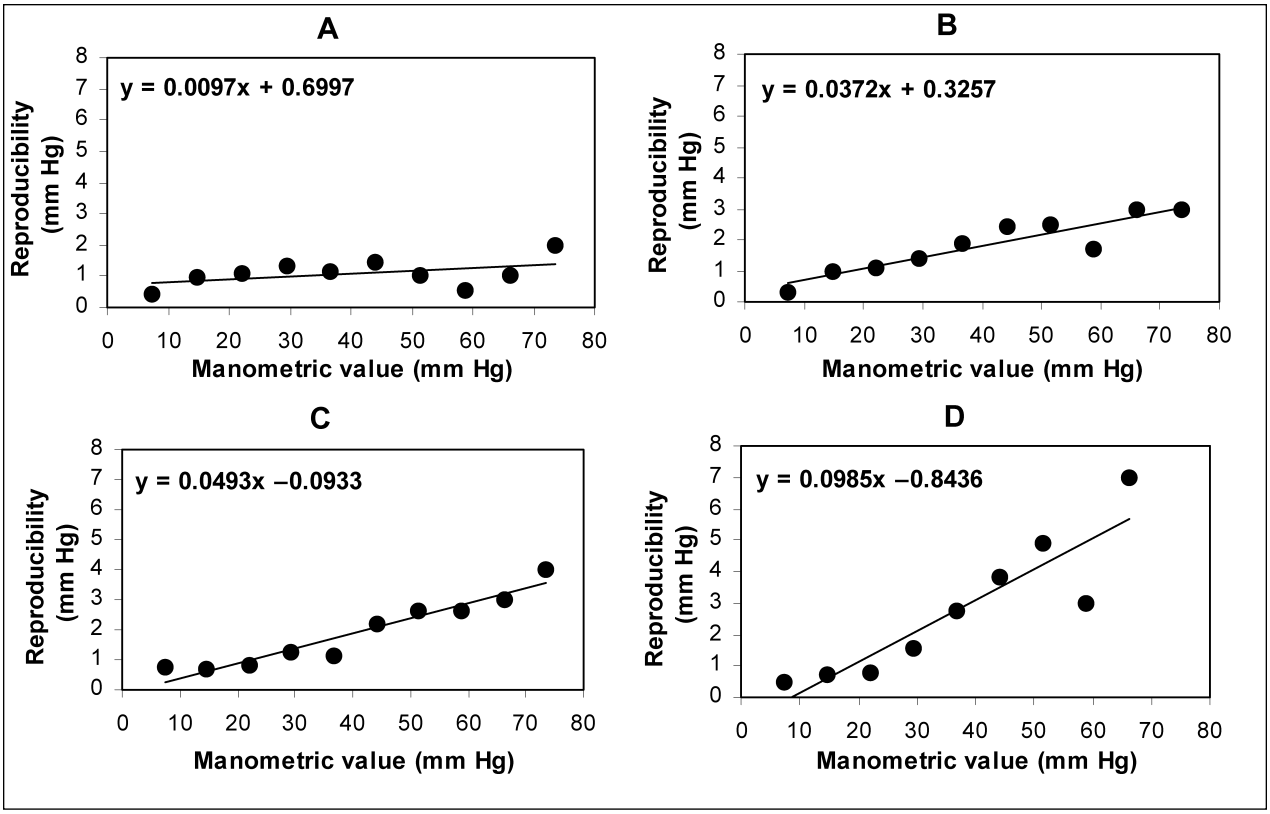

Figure 3—Relationship of the reproducibility of IOP measurements obtained by use of the MacKay-Marg tonometer (A), an I-I tonometer (B), a commercially available applanation tonometer (C), and a portable pneumatonometer (D) in freshly enucleated canine eyes. Fitted regression lines were calculated (solid lines). Reproducibility was defined as the mean value of the differences between the highest and lowest (maximum minus minimum) values of 3 repeated IOP measurements.

a problem, even when measurements were repeatedly obtained on numerous dogs.

The I-I tonometer was tolerated well by all dogs. It provided rapid and minimally stressful tonometric measurements. However, the I-I tonometer had to be held in a horizontal plane at the time of the measurement to prevent the disposable magnetized probe from dropping from the base of the tonometer. These single-use disposable probes were easy to install. Also, instructions in the user's manual for replacement of batteries were easy to follow, although loss of battery power was not a problem and it was not necessary to change the batteries during the entire study.

In conscious dogs, the MacKay-Marg tonometer was used as the reference. Box plots were drawn to enable comparison of results for the 2 new handheld automatic tonometers and the 2 established applanation tonometers (**Figure 4**). Comparison of the second (MM-1) and third (MM-2) MacKay-Marg tonometric examinations in conscious dogs yielded values of $P = 0.773$ for the portable pneumatonometer group and $P = 0.802$ for the I-I tonometer group; thusthere was no significant difference of IOP between the second and the third time the MacKay-Marg tonometer was used. There also was no significant ($P = 0.960$) difference between measurements for the MacKay-Marg tonometer and the I-I tonometer; however, the commercially available applanation tonometer and portable pneumatonometer both had significantly lower values, compared with results for the MacKay-Marg tonometer (**Table 2**).

Table 1—Comparison of the accuracy* for 4 tonometers.

Tonometer	Manometric IOP of 7.4 to 36.8 mm Hg†	Manometric IOP of 7.4 to 73.5 mm Hg†
CAA[b] (mm Hg)	7.92	12.94
MM[g] (mm Hg)	3.46	6.42‡
I-I[h] (mm Hg)	5.08	4.56‡
PP[i] (mm Hg)	10.45	14.24

*Accuracy was defined as the mean difference between the IOP measured by use of a tonometer and the IOP measured by use of a manometer on 15 freshly enucleated canine eyes. †Values listed are absolute values without negative or positive signs. ‡Accuracy of the MM and I-I tonometers was significantly ($P < 0.05$) better than the accuracy of both of the other tested tonometers.

CAA = Commercially available applanation. MM = MacKay-Marg. PP = Portable pneumatonometer.

Analysis of the measurements obtained from sedated dogs yielded results similar to those for conscious dogs (Figure 4; Table 2). In addition, clinical reproducibility of all tonometers was determined. Except for the portable pneumatonometer, reproducibility for the conscious and sedated dogs was less than that for the ex vivo manometric measurements (**Table 3**). However, sedation did improve the reproducibility for all 4 tonometers.

Measurement values obtained by an experienced examiner were not significantly ($P = 0.240$) different from the values obtained by an inexperienced examiner (mean absolute difference, 2.71; range of differences, –9.00 to 6.00), and there was a good correlation

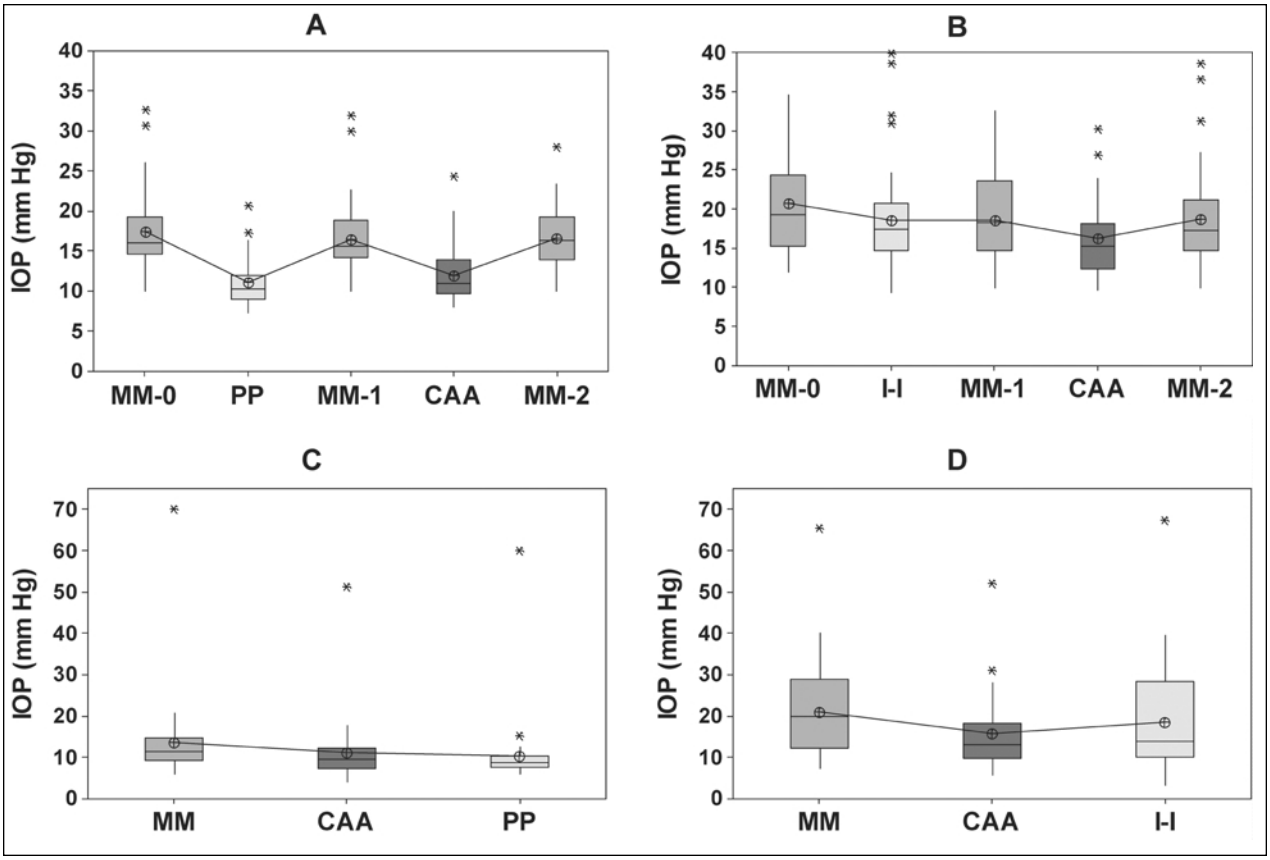

Figure 4—Box-and-whisker plots of serial IOP measurements obtained by the use of the MacKay-Marg tonometer (MM), a portable pneumatonometer (PP), and a commercially available applanation tonometer (CAA; A and C) and the MM, an I-I tonometer (I-I), and the CAA (B and D) in conscious research (A and B) and sedated client-owned (C and D) dogs without ocular disease. In conscious dogs, the MM was used as the reference, and the order of use for the tonometers was as indicated. The first MM measurement (ie, MM-0) was conducted to acclimate the dogs to the measurement procedure and was used as the baseline value but was not used for further statistical evaluation. Values obtained by use of the PP and I-I were compared with the second MM measurement (ie, MM-1), whereas values obtained by use of the CAA were compared with the third MM measurement (ie, MM-2). In sedated dogs, the order of use of the tonometers was randomized. The boxes represent the central 50% of the values (25th to 75th percentiles), the whiskers represent the range of values, the horizontal line in each box represents the median value, the circle containing a cross indicates the mean value, and the asterisks indicate the outliers. The mean values are connected by a line.

Table 2—Mean absolute differences and range of differences in measurement values (mm Hg) derived by the use of 4 tonometers on conscious and sedated dogs.

Comparison	Mean absolute difference*	Range of differences	*P* value†
Conscious			
MM vs PP	5.32	0.33 to 12.67	< 0.001
MM vs CAA	2.96	–4.67 to 9.67	< 0.001
CAA vs PP	3.09	–6.33 to 8.00	0.151
MM vs I-I	3.57	–14.67 to 10.67	0.960
CAA vs I-I	3.53	–17.67 to 7.00	0.001
Sedated			
MM vs PP	3.78	–4.67 to 13.33	< 0.001
MM vs CAA	5.43	–5.02 to 14.67	0.014
CAA vs PP	2.43	–8.67 to 6.00	0.153
MM vs I-I	3.49	–5.00 to 10.67	0.165
CAA vs I-I	4.92	–16.00 to 11.35	0.596

*Both under- and overestimations were assigned a positive value because high and low measurements would be equally inaccurate and would tend to yield a mean difference close to zero. †Values were considered significant at $P < 0.05$.
See Table 1 for remainder of key.

between both values (r^2, 0.82). Also, there was no significant (P = 0.501) difference between the pressure values obtained for the I-I tonometer when used with and without topical ophthalmic anesthetic (mean absolute difference, 1.97; range of differences, –6.67 to 5.33), and the goodness of fit was high (r^2, 0.86; **Figure 5**).

Clinical tonometry of eyes of dogs with glaucoma—The relationship of the 2 applanation tonometers

and the I-I tonometer in dogs with acute glaucoma was determined (**Figure 6**). Regression curves of all 4 tonometers were linear, and the goodness of fit (ie, r^2 value) was high. The fitted line for the plot of the comparison between results for the MacKay-Marg and I-I tonometers resembled an ideal 1:1 relationship. The slope of this graph was not significantly different from a value of 1. In comparison, results for the commercially available applanation tonometer were consistently lower for the entire ranges of IOP, compared with results for the MacKay-Marg tonometer. As the IOP increased, the difference between results for the I-I tonometer and commercially available applanation tonometer increased, with the latter providing results that increasingly underestimated the actual values. Overall reproducibility for the MacKay-Marg tonometer was significantly higher than the reproducibility of all other tonometers (Table 3).

Table 3—Comparison of the reproducibility* for 4 tonometers.

Tonometer	Manometric measurement†	Dogs		Dogs with glaucoma
		Conscious	Sedated	
PP	2.78	2.23	1.46	ND
I-I	1.83	2.75	2.55	3.29
MM	1.09‡	1.55	1.30	1.75‡
CAA	1.90	2.40	1.45	3.73

*Reproducibility was defined as the mean value of the differences between the highest and lowest (maximum minus minimum) values of 3 repeated IOP measurements (mm Hg). †Conducted on 15 freshly enucleated canine eyes. ‡Within a column, reproducibility of the MM was significantly ($P < 0.05$) better than the reproducibility for the other tested tonometers.
ND = Not determined.
See Table 1 for remainder of key.

Discussion

When tonometers designed for use in humans are used in other species, their suitability must be validated by manometric calibration because of differences in anatomic characteristics of the cornea (diameter, thickness, curvature, and rigidity) and surface tension of the tear film.[20] Analysis of results of studies[8,11,16] indicates that there are no significant differences between open and closed manometry systems. Whereas the use of an open system permits IOP to be maintained essentially constant when a tonometer is placed on the cornea, the use of a closed system maintains a constant intraocular volume when the cornea is touched. According to 1 report,[28] pneumatonometers must be calibrated under closed stopcock conditions because they are high-displacement tonometers and cause a substantial increase in IOP during measurement. Therefore, a closed system was used in the manometric setting of the study reported here.

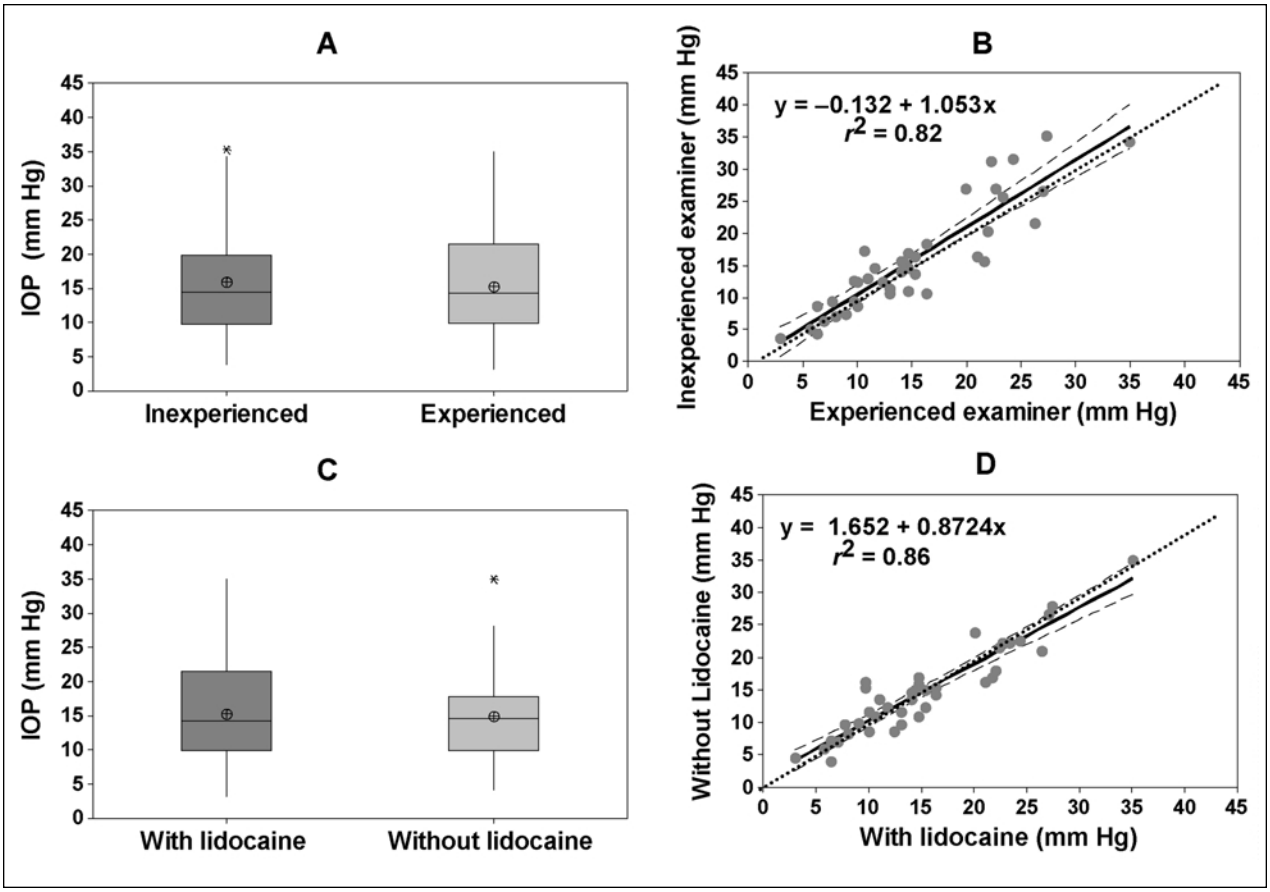

Figure 5—Box-and-whisker plots (A and C) and graphs (B and D) of IOP measurements obtained for 2 examiners (A and B) and for IOP measurements obtained with and without application of a topical ophthalmic anesthetic (C and D). The calculated regression line (solid line) and 95% confidence interval (dashed lines) for data obtained during the study and the ideal linear model (1:1 relationship; dotted line) are indicated. *See* Figure 4 for remainder of key.

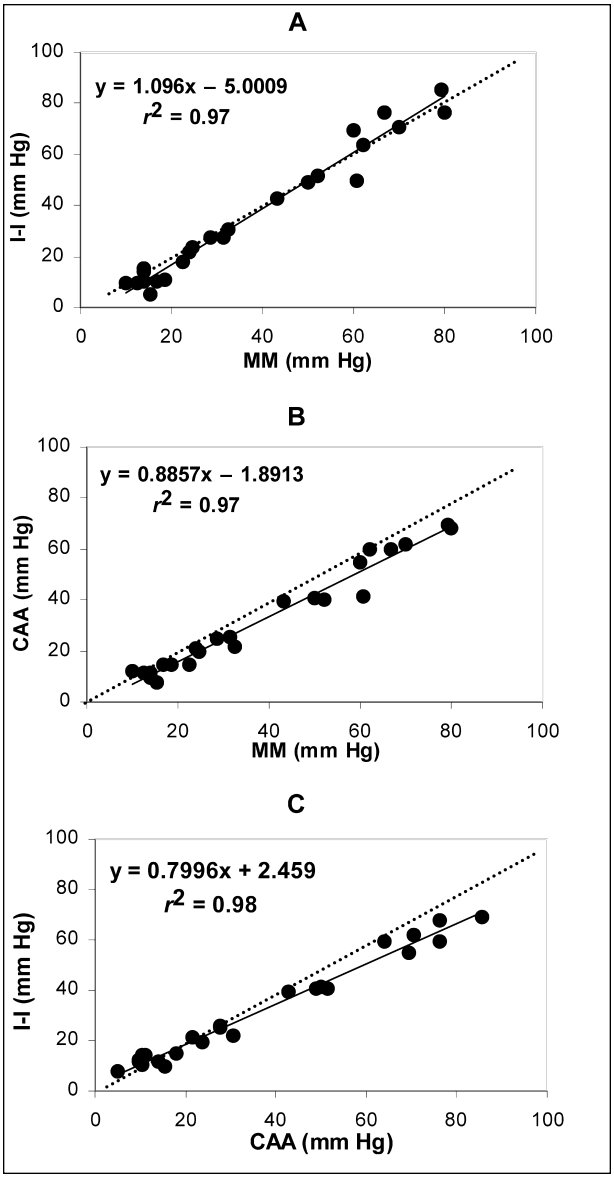

Figure 6—Relationship between IOP measurements obtained by use of the I-I and MM (A), CAA and MM (B), and I-I and CAA (C) tonometers for dogs with glaucoma. The calculated regression line (solid line) for each pair of tonometers and the ideal linear model (1:1 relationship; dotted line) are indicated.

It has been reported[29] that there is an approximately linear decrease of IOP in successive measurements obtained by use of applanation tonometers and that the difference was largest between the first and second measurement. Investigators in 1 study[30] documented that repeated measurements with a commercially available applanation tonometer decreased the IOP. Investigators in another study[6] confirmed that the order of application for applanation tonometers influenced the pressure measurements of a consecutively used tonometer. They obtained a significantly greater underestimation of IOP by use of the commercially available applanation tonometer when its use followed that of the MacKay-Marg tonometer, compared with results when its use preceded that of the MacKay-Marg tonometer. Noncontact tonometers, such as the portable pneumatonometer in the study reported here, have a tonographic effect,[31] whereas such an effect is unlikely for an I-I tonometer because the I-I tonometer only has slight contact with the eye.[32] In the study reported here, we attempted to exclude any tonographic effect within repeated measurements for a tonometer as well as between consecutive tonometers by adjusting the manometric pressure as soon as the continuous printout revealed a slight decrease in IOP. The tonometers were used in a consistent order.

Regression analyses of the 4 tonometers used in the study reported here resulted in a linear fit for the plotted values. Correlation values for the MacKay-Marg tonometer versus manometric measurement (r^2, 0.96) and the commercially available applanation tonometer versus manometric measurement (r^2, 0.95) were similar to those reported elsewhere.[10] Correlation value for the I-I tonometer versus manometric measurement (r^2, 0.96) was comparable to that of the applanation tonometers, but the comparison between the noncontact tonometer (portable pneumatonometer) and manometric measurement revealed a lower correlation (r^2, 0.89). Despite the high r^2 values, it should be realized that considerable variation existed in measurements made at each IOP. Generally, the range of values obtained at a certain IOP increased as IOP increased, and it was highest for the I-I tonometer and lowest for the portable pneumatonometer. For example, use of the MacKay-Marg tonometer yielded minimum and maximum values of 26 and 38 mm Hg at a manometric IOP of 36.8 mm Hg, whereas measurement by use of the I-I tonometer yielded minimum and maximum values of 23 and 40 mm Hg. Minimum and maximum values for the commercially available applanation tonometer were 19 and 28.7 mm Hg, and minimum and maximum values for the portable pneumatonometer were 16.3 and 23 mm Hg. This also indicates that glaucoma (defined simply as an abnormally high IOP) may be missed or may be erroneously diagnosed with all 4 tonometers.

Analysis of the generated line for the comparison between the I-I tonometer versus manometric measurement resulted in the following equation for estimating the actual IOP: $y = 1.063x - 6.069$, where y is the estimate of IOP and x is the value for the I-I tonometer. The slope did not differ significantly from 1, which indicated that a consistent error is made for use of this tonometer. The fitted line for this tonometer best resembled an ideal line (ie, a 1:1 relationship). Slopes for the other tonometers were 0.79, 0.66, and 0.61 for the MacKay-Marg tonometer, commercially available applanation tonometer, and portable pneumatonometer, respectively.

Values recorded for the MacKay-Marg and commercially available applanation tonometer were comparable to those reported elsewhere.[20] According to 1 report,[11] this underestimation of IOP by both applanation tonometers could have been expected because both instruments have been designed for use in human eyes and correction factors are needed for measuring IOP in other species. The same argument is also applicable for the portable pneumatonometer. In contrast, the I-I tonometer has been calibrated by the manufacturer for use in dogs.

The accuracy of both applanation tonometers in the study reported here was consistent with results of another study.[10] Both instruments underestimated the actual IOP, especially at higher IOP values, by an amount that increased linearly as IOP increased (MacKay-Marg tonometer) or increased exponentially as IOP increased (commercially available applanation tonometer). Underestimation of actual IOP has been reported for both tonometers in studies of enucleated horse eyes,[11] eyes of anesthetized rabbits,[13] and glaucomatous eyes of anesthetized dogs.[9] It has been documented in dogs[7] and in cats, cattle, and sheep[20] that the commercially available applanation tonometer overestimates IOP in the subnormal pressure range and underestimates IOP in the physiologic and high pressure range.

In the study reported here, the portable pneumatonometer had the worst accuracy, compared with accuracy for the other 3 tonometers examined. The values decreased exponentially as IOP increased. When the entire pressure range (7.4 to 73.5 mm Hg) was taken into consideration, the I-I tonometer was the most accurate. Interestingly, there was no significant difference among the 4 tonometers within the most clinically relevant pressure range (7.4 to 36.8 mm Hg).

Analysis of results for the manometric evaluation reported here indicates that the reproducibility for the I-I tonometer, commercially available applanation tonometer, and portable pneumatonometer decreased linearly as IOP increased, whereas reproducibility for the MacKay-Marg tonometer remained the same for the entire pressure range and was better than the reproducibility for all other tonometers. The decreased reproducibility as IOP increased may be explained by a thickened cornea secondary to corneal edema. During the in vivo part of this study, a decrease in reproducibility was also registered for glaucomatous eyes when compared with healthy eyes. Again, the reproducibility of the MacKay-Marg tonometer was significantly better than that for the commercially available applanation and I-I tonometers. The annulus that surrounds the plunger on the MacKay-Marg tonometer may account for its greater accuracy and reproducibility in scarred, edematous, or irregular corneas.[33] Deformation of the cornea and surface tension of tears are absorbed by the annulus and therefore do not influence the values as much as in other applanation tonometers. It has been proposed[34] that wrong measurements may be encountered when the cornea is touched in the periphery or when too fast or ungentle hand movements are used with the commercially available applanation tonometer. These factors may play an even more important role for high IOP values when the commercially available applanation tonometer is used on glaucomatous eyes.

Improper positioning of the instrument relative to each eye may account for a decrease in reproducibility of the I-I tonometer, compared with reproducibility for the MacKay-Marg tonometer. In the study reported here, the effect of the starting distance between the probe of the I-I tonometer and cornea was not investigated. Similar measurements performed in eyes of rats appear to be unaffected by the initial distance of the probe, providing the probe is held 3 to 5 mm away from the corneal apex before its launch and the angle of impact of the probe is $< 25°$.[27]

Noncontact tonometry is influenced by biomechanical characteristics of the cornea (especially corneal thickness) and the precorneal tear film to a greater degree than is conventional applanation tonometry.[35] This may be the reason for lower reproducibility of the portable pneumatonometer in the ex vivo part of our study, compared with results for the other tonometers, but also as compared with its clinical performance on healthy eyes. The portable pneumatonometer was not tested on glaucomatous eyes.

Tonometers intended for clinical use should be compared by use of ex vivo and clinical settings because eyes obtained after an animal dies or is euthanatized do not have transient physiologic fluctuations of IOP resulting from pulse, blood pressure, respiration, and anxiety that affect eyes of live animals. These uncontrolled, physiologic variables cause major changes in IOP during short time periods; thus, any tonometer that records a near-instantaneous measurement of IOP is in fact only sampling part of an IOP cycle. These variables could also account for some discrepancies in reproducibility; similarly, the stress of repeated measurements could also cause discrepancies in reproducibility.[15] Even the most accurate tonometer used in humans has an assumed inherent variability of approximately 2 mm Hg when 2 readings are obtained from the same eye by the same examiner.[36] Undoubtedly this variation increases in potentially noncooperative veterinary patients. This may explain the reason that the measurements for all tonometers, except for the portable pneumatonometer, in the study reported here were less reproducible when used in a clinical setting than in a research setting on enucleated eyes. To exclude some of these uncontrolled variables, the clinical comparison was repeated on sedated dogs, which yielded a higher reproducibility for all 4 tonometers, compared with reproducibility for the tonometers when used in conscious dogs.

It was easy to master use of the I-I tonometer. The digital display of IOP on the I-I tonometer offers less chance of misinterpretation and is an improvement on the tracings for the MacKay-Marg tonometer, the interpretation of which may be subject to error. The portable pneumatonometer was more difficult to use in conscious dogs, compared with sedated dogs, because it required a few seconds without ocular movements. In addition, the puff of air distracted some of the dogs.

The MacKay-Marg tonometer was used as the reference in conscious dogs because it is considered to be the most reliable instrument for measuring IOP in clinically normal dogs.[6,7,a] It was used first and last as well as after either use of one of the new automatic tonometers or use of the commercially available applanation tonometer. This was done to exclude or detect any possible tonographic effect. Analysis of the results revealed that there was a significant decrease of IOP between the baseline (MM-0) and MM-1 MacKay-Marg measurements; however, there was no significant difference between the MM-1 and MM-2 measurements. Therefore, the decrease between MM-0 and MM-1 was

not interpreted as having been caused by the repeated measurements with the MacKay-Marg tonometer, but instead it was explained as a psychogenic effect.

We did not detect significant differences between measurements obtained by use of the MacKay-Marg and I-I tonometers; however, the commercially available applanation tonometer and portable pneumatonometer had significantly lower values, compared with values for the MacKay-Marg tonometer. The lack of significant differences between the MacKay-Marg and commercially available applanation tonometers reported here was consistent with the results of another study in cats[12] but differs from results of a study in horses[11] in which no significant difference was detected. This indicates that extrapolating the results of the clinical reliability of a new tonometer among species may be misleading. Analysis of the IOP measurements on sedated dogs yielded similar results and confirmed the result for the comparison in conscious dogs.

The commercially available applanation tonometer has substantial variability in the measurements that is dependent on the examiner.[15] Use of the this applanation tonometer by an inexperienced examiner can increase the measured IOP by up to 12 mm Hg.[30] One of the objectives of the study reported here was to evaluate whether we could detect differences between examiners for the I-I tonometer. Because we also wanted to know whether it was easy for a less experienced examiner to acquire the skills needed to use the I-I tonometer, we compared values obtained by an ophthalmologist and those obtained by a general practitioner not experienced in performing tonometry. We did not detect a significant difference in values obtained by the experienced or inexperienced examiners. Regression analysis revealed a linear model that resembled the ideal line of a 1:1 relationship. Therefore, it was concluded that the skill necessary to operate the I-I tonometer can be rapidly acquired with no obvious learning curve.

The manufacturer's manual states that the I-I tonometer can be used without topical ophthalmic anesthesia. To evaluate this, 40 eyes of 20 dogs were measured consecutively with and without topical application of 4% lidocaine to detect differences in IOP. In contrast to results of another study[23] in which investigators detected a significant decrease in IOP 1 and 5 minutes after instillation of 1 drop of oxybuprocaine and betoxycaine, our study yielded a slightly, but not significantly, higher IOP after application of the local anesthetic. Lidocaine is a potent local anesthetic; however, it induces transient ocular irritation when instilled on the cornea. This pain reaction may have caused an increase in blood pressure and, consequently, the recorded increase in IOP. On the basis of this result, when 4% lidocaine is used as a topical anesthetic agent, IOP should be measured after the induced irritating sensation has disappeared to prevent recording of erroneously high values. Regression analysis of the data yielded a significant linear relationship between the measurement values recorded with topical application of 4% lidocaine versus without use of the local anesthetic. Because measurements with the I-I tonometer can be performed without topical ophthalmic anesthesia, a bias caused by use of topical anesthesia can be prevented.

In eyes with pathologic changes to the cornea, applanation tonometry generally delivers false low measurements, compared with results for intraocular needle tonometry.[37] In 1 study,[9] goodness of fit for results of the MacKay-Marg and pneumatonograph tonometers decreased approximately 10% in glaucomatous eyes of dogs, compared with that of clinically normal canine eyes. In the study reported here, we evaluated clinical reliability of the I-I tonometer in comparison to the 2 applanation tonometers in dogs with glaucoma. The accuracy of the 3 tonometers for measuring IOP of glaucomatous eyes could not be determined because it was impossible to determine IOP manometrically in these dogs. However, regression analysis indicated that a highly significant linear relationship existed between the 2 applanation tonometers (r^2, 0.97), between the MacKay-Marg and I-I tonometers (r^2, 0.97), and between the I-I and commercially available applanation tonometers (r^2, 0.98). The fitted line for the plot of the comparison between values for the MacKay-Marg and I-I tonometers resembled an ideal 1:1 relationship with a slope that did not differ significantly from 1. This means that in the study reported here, clinical reliability of the I-I tonometer for measuring IOP in glaucomatous eyes was as good as that of the MacKay-Marg tonometer. As stated previously, the MacKay-Marg applanation tonometer has been considered the most reliable for measuring IOP in eyes of clinically normal dogs and dogs with glaucoma. Analysis of the results of our study suggests that the I-I tonometer is a valid alternative to the MacKay-Marg tonometer for clinical use.

Results of the study reported here do not support the use of the portable pneumatonometer in dogs. The alignment procedure for the portable pneumatonometer was time-consuming. It required up to 15 minutes to obtain an acceptable measurement, and proper use was especially difficult in dolichocephalic breeds. In addition, the manometrically determined accuracy for the portable pneumatonometer was low.

The I-I tonometer achieved accurate and reproducible measurement values. It was tolerated well and ensured a rapid and minimally stress-inducing method of tonometry in dogs, even without topical ophthalmic anesthesia. Furthermore, it was easy to use, and reliable measurements could be obtained, even by an inexperienced examiner. The I-I tonometer provides a promising alternative to the commercially available applanation tonometer in dogs, and the costs for the 2 devices are similar. Accuracy and practical aspects for use of the I-I tonometer in other species have not yet been documented. Results of the study reported here were based on the performance of 1 selected I-I tonometer instrument, and reproducibility of results among I-I tonometers has not yet been studied.

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j. Domitor, 1 mg/mL, Pfizer Animal Health BV, Capelle a/d Ijssel, The Netherlands.
k. Loctite 401, Loctite UK Ltd, Watchmead, Welwyn Garden City, UK.
l. Lidocaine 4%, AST Farma BV, Oudewater, The Netherlands.

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