Title

Comparison of intraocular pressures estimated by rebound and applanation tonometry in dogs with lens instability: 66 cases (2012-2018).

Journal
Journal of the American Veterinary Medical Association, 259(9)

ISSN
0003-1488

Authors
Schlesener, Brittany N
Leonard, Brian C
Miller, Paul E
et al.

Publication Date
2021-11-01

DOI
10.2460/javma.259.9.1025

Peer reviewed

Comparison of intraocular pressures estimated by rebound and applanation tonometry in dogs with lens instability: 66 cases (2012–2018)

Brittany N. Schlesener DVM

Brian C. Leonard DVM, PhD

Paul E. Miller DVM

Philip H. Kass DVM, MPVM, PhD

Steven R. Hollingsworth DVM

Ann E. Cooper VMD

David J. Maggs BVSc

From the Veterinary Medical Teaching Hospital (Schlesener, Cooper), Department of Surgical and Radiological Sciences (Leonard, Hollingsworth, Maggs), and Department of Population Health and Reproduction (Kass), School of Veterinary Medicine, University of California-Davis, Davis, CA 95616; and Department of Surgical Sciences, School of Veterinary Medicine, University of Wisconsin-Madison, Madison, WI 53706 (Miller).

Address correspondence to Dr. Maggs (djmaggs@ucdavis.edu).

OBJECTIVE

To compare intraocular pressures (IOPs) estimated by rebound and applanation tonometry for dogs with lens instability.

ANIMALS

66 dogs.

PROCEDURES

Medical records of dogs examined between September 2012 and July 2018 were reviewed for diagnoses of anterior (ALL) or posterior (PLL) lens luxation or lens subluxation.

RESULTS

Estimates of IOP obtained with rebound and applanation tonometry significantly differed from each other for all types of lens instability considered collectively (mean ± SE difference between tonometric readings, 8.1 ± 1.3 mm Hg) and specific types of lens instability considered individually (mean ± SE difference between tonometric readings: ALL, 12.8 ± 2.5 mm Hg; PLL, 5.9 ± 1.7 mm Hg; subluxation, 2.8 ± 0.8 mm Hg). Median (range) differences between rebound and applanation tonometer readings for dogs with ALL was 5 mm Hg (–9 to 76 mm Hg), with PLL was 3 mm Hg (–1 to 19 mm Hg), and with lens subluxation was 3 mm Hg (–9 to 18 mm Hg). In eyes with ALL, rebound tonometer readings exceeded applanation tonometer readings on 44 of 60 (73%) occasions.

CONCLUSIONS AND CLINICAL RELEVANCE

Rebound tonometry yielded higher estimates of IOP than did applanation tonometry in eyes with ALL and with all types of lens luxation considered collectively. Estimates of IOP in eyes with lens instability should ideally be obtained with both rebound and applanation tonometers. Veterinarians with only one type of tonometer should interpret results for dogs with lens instability concurrent with physical examination findings.

Assessment of intraocular pressure (IOP) is critical in the diagnosis and management of many ophthalmic conditions, and an accurate and reliable means of tonometry is an essential component of ophthalmic examinations in animals.[1,2] In veterinary medicine, IOP is most commonly assessed indirectly with rebound or applanation tonometry. Applanation tonometry estimates IOP by measuring the force required to flatten, or applanate, a defined surface area of the cornea,[3] whereas rebound tonometry estimates IOP by measuring the deceleration of a magnetized probe directed at the cornea from a fixed distance.[4,5] Because both tonometers use different mechanical principles to estimate IOP, readings with each tonometer are likely to differ among various ocular diseases.[6]

Intraocular pressure readings obtained with different tonometric methods have been compared between healthy[7–21] or diseased[13,14,22–24] eyes of various species. Results of these studies repeatedly indicate that the tonometric-specific algorithm that is inherent to applanation tonometers and is optimized for people tends to underestimate IOP at higher IOPs, compared with results obtained with a manometer.[7,8,14,15,17–21] In contrast, the rebound tonometer's algorithm has been optimized for healthy canine eyes, and IOPs obtained in those eyes more closely approximate manometrically-determined IOPs.[7,9,14,15,21,25] However, rebound tonometry tends to underestimate IOP for hypotensive eyes[7] and when compared with applanation tonometry tends to be more affected by changes in corneal thickness associated with various corneal diseases, such that estimates of IOP generated by rebound tonometry in these instances may be erroneous.[26–32]

Anterior lens luxation is often associated with increased IOP and may cause corneal lesions, including those that affect the mechanical properties of the cornea, especially when the lens and cornea are in contact with each other. Rebound and applanation tonometers are likely affected differently by anterior lens luxation (ALL) itself, associated corneal lesions, and increased IOP, and, therefore, lens instability is a specific instance in which differences between tonometers could have clinically important effects. The objective of the study reported here was to evaluate the differences in IOPs determined with rebound and applanation tonometry in dogs with lens instability. For eyes of dogs with lens instability, IOP estimates obtained with rebound tonometry were hypothesized to significantly differ from those obtained with applanation tonometry.

Materials and Methods

Study population

Medical records of all dogs examined by a house officer or faculty member of the Veterinary Ophthalmology Service at the University of California-Davis between September 2012 and July 2018 were searched for keywords that may indicate that lens instability, zonular disinsertion, lens subluxation, or lens luxation was diagnosed. For the purpose of this study, the presence of vitreous in the anterior chamber was considered evidence of zonular disinsertion. Thus, keywords searched were "lux*," "disl*," "disin*," "instab*," "ALL," "PLL," and "vitre*" (where "*" was a wild card). The starting date for data collection was based on the date of acquisition of the rebound tonometer (TonoVet; Icare Finland Oy). Prior to that date, only applanation tonometers (Tono-Pen Vet and Tono-Pen AVIA Vet; Reichert Inc) were used. Although 2 types of applanation tonometers were used, results of a study[21] indicate that IOPs estimated with these applanation tonometers did not significantly differ, thus supporting inclusion in the present study of the data generated with both applanation tonometers. The medical record search yielded 5,769 occasions, 3,494 visit records, and 1,106 patient records. Visit records then were manually reviewed and data included in the study only if ALL, posterior lens luxation (PLL), or lens subluxation was listed as a diagnosis and both rebound and applanation tonometric readings were recorded from at least 1 affected eye during the same ophthalmic examination. Data retrieved from the medical record included sex; breed; approximate age (provided by the dog owner, with use of the first of the month when the owner provided only birth month and year or January 1 when the owner provided only birth year); eyes affected; rebound and applanation tonometric readings for eyes affected by lens instability and the contralateral eyes unaffected by lens instability; reported duration of lens instability; lens position (ALL, PLL, or subluxation); degree of subluxation; presence of corneal edema and other corneal lesions; vision status determined on the basis of various combinations of menace response, behavioral testing, and observations by the dog's owner; presence of ocular hypertension (IOP > 25 mm Hg recorded with either tonometer[33]), suspected pathogenesis of lens instability (primary, secondary, unknown, or not stated); and, in dogs in which transcorneal lens reduction or intracapsular lens extraction was performed, pre- and postprocedure rebound and applanation tonometric readings. The reported degree of subluxation was retrospectively graded as follows: grade 1 = vitreous within the anterior chamber; grade 2 = phacodonesis or iridodonesis with or without vitreous in the anterior chamber; grade 3 = aphakic crescent or uneven anterior chamber depth with or without vitreous in the anterior chamber, phacodonesis, or iridodonesis; and grade 4 = a portion of the lens protruding through the pupillary aperture with or without vitreous in the anterior chamber, phacodonesis, iridodonesis, or aphakic crescent.

Tonometry

All tonometers were maintained and used according to their manufacturers' recommendations. For each dog, tonometric estimates were obtained by a house officer or faculty member of the Veterinary Ophthalmology Service; minimal physical restraint was used for each dog and physical pressure on the jugular veins was specifically avoided. Intraocular pressure was recorded with all dogs in sternal recumbency, sitting, or standing.[34] Tonometry results were included only if applanation readings had a variance of ≤ 5% and if rebound readings had an acceptable SD displayed on the tonometer (ie, a consistent reading or one for which the displayed line was in the lower position indicating that the SD was ≤ 2.5 mm Hg). In all cases, estimates were first obtained with the rebound tonometer, then after instillation of 1 drop of 0.5% proparacaine HCl with the applanation tonometer. The region of the cornea targeted during tonometry was not recorded in the medical record; however, the standard for the Veterinary Ophthalmology Service was to always aim the tonometer tip or probe as close to the axial portion of the cornea as clinical conditions permitted.

Statistical analysis

On 8 occasions, > 1 reading from the same tonometer was recorded in the medical record. This is typically done in the Veterinary Ophthalmology Service when multiple readings are believed necessary by the clinician to ensure validity of the readings for that dog. On these occasions, median IOP was used for all analyses. In dogs that had multiple visits, lens position sometimes differed among visits. Therefore, data were analyzed on the basis of all occasions in which both rebound and applanation tonometric estimates were obtained, irrespective of eye, dog, or visit. To determine whether observed differences in tonometric estimates were solely attributable to the algorithm specific to tonometer type, some analyses were repeated after tonometric estimates were adjusted to manometric IOP by use of published equations.[7]

Statistical analyses were performed with Excel 2016 (Microsoft Corp) and Stata 15.0/IC (StataCorp). Mixed-effects ANOVA models were used to compare tonometric estimates that considered eye, dog, and visit as nested random effects. Residuals were assessed for approximate normality by use of standardized normal probability plots. Eye was not included as a random effect in analyses of unaffected eyes. In affected eyes, mean IOP estimates from each tonometer were assessed as a function of lens position, subluxation grade, presence of corneal edema or other corneal lesions, presence of ocular hypertension, and suspected pathogenesis of lens instability. A Bonferroni correction was used when post hoc statistical analyses were simultaneously performed. To assess the effect of multiple corneal lesions including corneal edema, the effect of corneal edema alone, and the effect of ocular hypertension on tonometric readings, readings were compared with the predicted mean IOP of the 2 tonometric readings. Predicted mean IOP was the predicted mean for each possible combination of the levels of the variables in the mixed-effect models. A Bland-Altman analysis was performed with commercial software (GraphPad Prism version 8; GraphPad Software) to assess the level of agreement between IOP estimates obtained with rebound tonometry and those obtained with applanation tonometry in dogs with or without lens instability. The difference between the 2 IOP readings was calculated by subtracting the applanation tonometric reading from the rebound tonometric reading. A minimum of 6 occasions/lens instability type was required for statistical analysis to be considered valid. For all analyses, values of $P < 0.05$ were considered significant.

Results

Study population

Sixty-six dogs (91 visits) met the inclusion criteria. The number of male dogs was 32 (neutered, n = 30; sexually intact, 2) and the number of female dogs was 34 (neutered, 33; sexually intact, 1). Dogs were of 35 breeds or mixed breed (n = 16); the most common breeds were Boston Terrier (9), Chihuahua (5), Australian Cattle Dog (4), Cocker Spaniel (4), Rat Terrier (4), and Shih Tzu (4). Twenty-five (38%) dogs were a terrier breed. At the first visit in which IOP was estimated with both rebound and applanation tonometers, mean ± SD dog age was 10.3 ± 3.3 years (range, 0.5 to 16.1 years) and mean ± SD time from the diagnosis of lens instability was 178 ± 472 days (0 to 2,716 days). Lens instability was considered primary for 32 dogs and secondary to chronic uveitis for 10 dogs, chronic glaucoma with buphthalmos for 4 dogs, age-related zonular degeneration for 2 dogs, trauma for 1 dog, or an unknown or unstated cause for 17 dogs. At the first visit, lens instability of some form was diagnosed in the left eye (n = 27), right eye (17), or both eyes (22). Specifically, ALL was diagnosed in 47 eyes, PLL in 6 eyes, and subluxation in 35 eyes (grade 1 subluxation, n = 18; grade 2, 0; grade 3, 13; grade 4, 4).

Tonometry

To assess the effect of lens instability on IOP estimates from the 2 tonometers, data were analyzed by treating each time at which tonometry was performed as an occasion. Thus, each dog could contribute data from multiple examinations, and for 3 dogs, data from before and after medical or other interventions. Intraocular pressure was measured with both tonometers on 120 occasions for 89 eyes with lens instability (right eye, n = 40; left eye, 49) and on 40 occasions for 30 eyes unaffected by lens instability (right eye, 19; left eye, 11). However, only 88 eyes with lens stability were included in the analyses for the first visit because 1 dog developed lens instability in the contralateral eye during the study period. Considering all 89 eyes with lens instability, ALL was noted on 60 occasions, PLL on 12 occasions, and subluxation on 48 occasions. The degree of subluxation was classified as grade 1 on 26 occasions, grade 2 on 0 occasions, grade 3 on 18 occasions, and grade 4 on 4 occasions. Because of the small number of occasions in which grade 4 subluxations were observed and the low statistical power associated with this sample size (< 6 occasions), statistical analysis was not performed for this group.

Rebound tonometric readings were significantly higher than applanation tonometric readings for all types of lens instability when considered collectively and also individually **(Table 1)**. This difference persisted for eyes with ALL and all forms of lens instability collectively even after correction for the inherent

Table 1—Mean ± SE (range) IOP estimates determined with rebound and applanation tonometry and differences between their values for canine eyes with (n = 89 eyes and 120 occasions) and without (30 eyes and 40 occasions) various forms of lens instability. (Occasion defined as each time tonometry was performed, such that each dog could contribute data from multiple examinations.)

	IOP (mm Hg)			
Lens instability (No. of occasions)	**Rebound tonometry**	**Applanation tonometry**	**Difference (rebound minus applanation)**	***P* value**
None (0)	18.0 ± 2.4 (3–80)	15.9 ± 2.4 (3–60)	2.1 ± 0.8	0.005
Subluxation (48)	25.1 ± 2.2 (9–63)	22.3 ± 2.2 (9–54)	2.8 ± 0.8	< 0.001
Grade 1 (26)	26.1 ± 2.8 (12–63)	23.4 ± 2.8 (10–54)	2.8 ± 1.1	0.010
Grade 2 (0)	—	—	—	—
Grade 3 (18)	22.5 ± 3.7 (9–55)	19.8 ± 3.7 (9–50)	2.7 ± 1.0	0.008
Grade 4 (4)	31.3 ± 5.5 (14–41)	28.5 ± 5.5 (13–45)	2.8 ± 3.8	ND
PLL (12)	36.1 ± 6.9 (12–67)	30.2 ± 6.9 (11–60)	5.9 ± 1.7	< 0.001
ALL (60)	37.0 ± 3.0 (3–98)	24.2 ± 3.0 (4–78)	12.8 ± 2.5	< 0.001
All lens instability	31.7 ± 1.8 (3–98)	23.6 ± 1.8 (4–78)	8.1 ± 1.3	< 0.001

Values of $P < 0.05$ indicate that the difference in IOP estimates between tonometric methods is significant. Subluxation grades: 1, vitreous within the anterior chamber; 2, phacodonesis or iridodonesis with or without vitreous in the anterior chamber; 3, aphakic crescent or uneven anterior chamber depth with or without vitreous in the anterior chamber, phacodonesis, or iridodonesis; and 4, a portion of the lens protruding through the pupillary aperture with or without vitreous in the anterior chamber, phacodonesis, iridodonesis, or aphakic crescent.

— = No data. No canine eyes had grade 2 subluxations throughout the study period. ND = Not determined. The number of canine eyes with grade 4 subluxation was small and therefore these data were not compared.

differences in the tonometer-defined algorithm used by the 2 forms of tonometry[7] (data not shown). A Bland-Altman analysis revealed that the mean difference in IOP readings between rebound and applanation tonometry was most pronounced in eyes with ALL (bias, 12.8; **Figure 1**), was markedly less in eyes with PLL (5.9), and was least in eyes with lens subluxation (2.8) or eyes without evidence of lens instability (2.1). The median (range) difference between rebound and applanation tonometric estimates in individual dogs on each occasion was 5 mm Hg (–9 to 76 mm Hg) in eyes with ALL, 3 mm Hg (–1 to 19 mm Hg) in eyes with PLL, 3 mm Hg (–9 to 18 mm Hg) in eyes with lens subluxation, and 1 mm Hg (–5 to 20 mm Hg) in eyes without evidence of lens instability. In eyes with ALL, rebound tonometric readings exceeded applanation tonometric readings on 44 of 60 (73%) occasions, were identical on 4 (7%) occasions, and were less on 12 (20%) occasions. In eyes with PLL, rebound tonometric readings exceeded applanation tonometric readings on 11 of 12 (92%) occasions, were identical on 0 occasions, and were less on 1 (8%) occasion. In eyes with lens subluxation, rebound tonometric readings exceeded applanation tonometric readings on 35 of 48 (73%) occasions, were identical on 0 occasions, and were less on 13 (27%) occasions. In unaffected eyes, rebound tonometric readings exceeded applanation tonometric readings on 23 of 40 (58%) occasions, were identical on 8 (20%) occasions, and were less on 9 (22%) occasions. In eyes with lens instability, predicted mean IOPs for rebound and applanation tonometry were significantly ($P < 0.001$) different in eyes with ocular hypertension (IOP > 25 mm Hg; mean ± SE difference, 11.2 ± 1.8 mm Hg) than in eyes without ocular hypertension (ie, normotensive eyes; 1.4 ± 1.5 mm Hg; $P > 0.99$).

Corneal lesions

Considering only eyes with lens instability, corneal edema (with or without other corneal lesions) was noted on 64 occasions. Predicted mean IOPs for rebound and applanation tonometry were significantly ($P < 0.001$) different when corneal edema was present (mean ± SE difference, 12.6 ± 1.7 mm Hg) but not when corneal edema was absent (3.0 ± 1.9 mm Hg; $P = 0.656$). Rebound tonometric readings exceeded applanation tonometric readings for eyes with corneal edema on 55 (86%) occasions, were identical on 2 (3%) occasions, and were less on 7 (11%) occasions. Rebound tonometric readings exceeded applanation tonometric readings for eyes without corneal edema on 37 of 56 (66%) occasions, were identical on 2 (4%) occasions, and were less on 17 (30%) occasions.

Corneal lesions other than edema (eg, fibrosis, vascularization, pigmentation or melanosis, lipid or mineral deposition, ulceration or facet, keratic precipitates, stromal infiltration of WBCs, anterior synechia, Haab striae, or presence of a conjunctival flap or graft) were documented in eyes that had lens instability on 53 occasions. Corneal edema was concurrent with other corneal lesions on 29 of these 53 (55%) occasions. In eyes with lens instability and any type of corneal lesion including corneal edema, predicted mean IOPs for rebound and applanation tonometry were significantly ($P < 0.001$) different (mean ± SE difference, 10.3 ± 1.6 mm Hg). By contrast, in eyes with lens instability but without corneal lesions, predicted mean IOPs for rebound and applanation tonometry (mean ± SE difference, 2.4 ± 2.6 mm Hg) were not significantly ($P > 0.99$) different.

A procedure to address ALL was performed on 29 eyes on 32 occasions; transcorneal lens reduction (couching) was performed for 16 eyes on 19 occasions, and intracapsular lens extraction was performed for 13 eyes. Rebound and applanation tonometry was performed prior to and after a procedure on 3 occasions for 3 dogs (transcorneal lens reduction in which tonometry was performed before and immediately after lens reduction, n = 2; intracapsular lens extraction in which tonometry was performed before and 3 hours after lens extraction, 1). Readings obtained with the tonometers were more comparable following lens reduction or removal than they

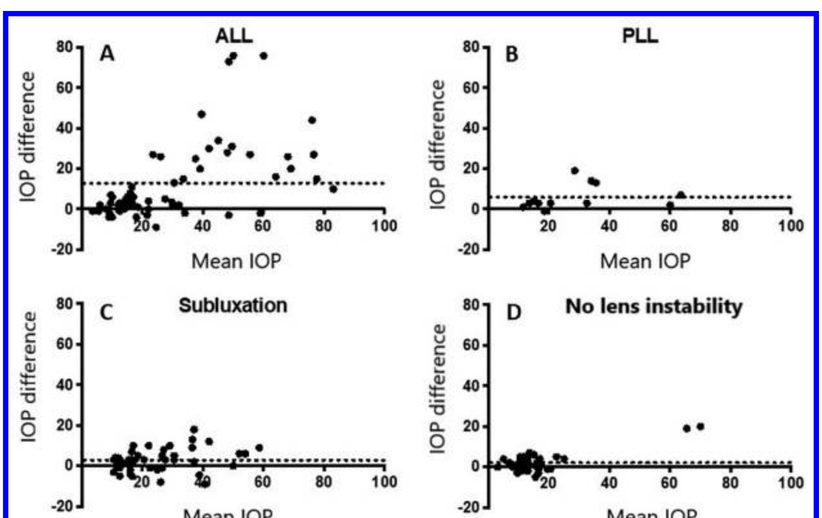

Figure 1—Bland-Altman plots for analysis of agreement between IOP estimates (mm Hg) obtained with rebound and applanation tonometry on 160 occasions for 119 eyes from 66 dogs (120 occasions for 89 eyes with lens instability and 40 occasions for 30 eyes without lens instability). The difference in IOP readings was calculated by subtracting the applanation tonometric estimate from the rebound tonometric estimate. Each point represents a single occasion in which estimates were obtained with both tonometers. The solid line indicates 0 bias. The dotted line indicates the bias (overall mean difference in IOP estimates). Anterior lens luxation was noted on 60 occasions (A), PLL on 12 occasions (B), subluxation on 48 occasions (C), and no lens instability on 40 occasions (D).

were before intervention (before the procedure, differences were 10, 25, and 28 mm Hg; after the procedure, differences were 5, –1, and 3 mm Hg; **Supplementary Table S1**).

Discussion

The purpose of the study presented here was to compare IOP readings obtained with commercially available rebound and applanation tonometers in dogs with lens instability. The data revealed that rebound tonometric readings were significantly higher than applanation tonometric readings for all types of lens instability when considered collectively and that this difference was most pronounced in eyes with ALL, was markedly less in eyes with PLL, and was least in eyes with lens subluxation or eyes without evidence of lens instability. After manometric correction by use of published[7] manometrically derived equations that were designed to account for differences in the tonometric-specific algorithms, this difference remained significant for ALL. This suggested that ALL was at least partially responsible for the differences between the IOP estimates generated by the 2 tonometers. The magnitude of the difference in eyes with ALL was as much as 76 mm Hg, which was of striking clinical relevance. The data clearly indicated that veterinarians need to be aware that these 2 widely used tonometers may yield greatly different estimates of IOP in dogs with lens instability, especially those with ALL, and if possible that they obtain readings using both tonometers for affected dogs. Minimally, if an IOP obtained with a rebound tonometry is high and that reading is inconsistent with clinical signs (such as relatively minor vascular engorgement or corneal edema, or maintenance of neuro-ophthalmic responses and reflexes), then confirmation of that estimate with an applanation tonometer is recommended prior to determining treatment and likely prognosis.

Although the retrospective nature of this study did not permit isolation of a cause of the difference, considering factors that may explain the difference in IOPs between the tonometers remains important. One important factor is the difference in the algorithm inherent to each tonometer. Compared with rebound tonometers, applanation tonometers underestimate IOPs for IOPs within normal ranges,[9,14,21,25,35,36] whereas in glaucomatous eyes, rebound tonometers consistently yield higher IOPs than do applanation tonometers.[7,14,21,23,35,37] In a study[7] of dogs with normal eyes, estimation of IOP by the rebound tonometer was approximately 95% of the actual IOP as determined with manometry (rebound tonometric IOP estimate = [0.95 X manometric IOP] – 0.93 mm Hg), whereas estimation of IOP by the applanation tonometer was approximately 71% of the actual IOP as determined with manometry (applanation tonometric IOP estimate = [0.71 X manometric IOP] + 1.88 mm Hg).[7] However, when these equations were applied to the data in the present study, IOP obtained with the rebound tonometer remained significantly greater than that obtained with the applanation tonometer in eyes with all forms of lens instability considered collectively and in eyes with ALL. This suggested that other biomechanical factors may have also played a role in the differing tonometric readings for canine eyes with lens instability.

Tonometric readings obtained in the present study for eyes with or without corneal lesions and those collected before and shortly after lens reduction or extraction suggested that biomechanical factors may be important cofactors to explain the differences between tonometers, as has been previously demonstrated.[38,39] Similar to the findings from another study,[31] results of the present study showed that rebound and applanation tonometric readings differed significantly in dogs with various corneal lesions, including those with only corneal edema. Possibly this was because of a change in corneal thickness, considering that for the eyes of normal subjects and those with IOPs within normal range, applanation tonometers are relatively insensitive to changes in corneal thickness,[40–42] whereas rebound tonometers are believed to be relatively sensitive to changes in corneal thickness.[28–31] This supposition was supported by the results of the present study in which IOP estimates were not significantly different between the 2 tonometers for eyes with lens instability and normal corneal appearance. On the basis of these observations, future studies should include pachymetry (ie, method of measuring corneal thickness) and advanced imaging with optical coherence tomography in an attempt to identify the cause of the differences between rebound and applanation tonometry in eyes with lens instability. Corneal resistance factors and hysteresis associated with lens instability were also likely to influence tonometric estimates of IOP in the present study[13,24,27,39,43–49]; however, veterinary research on these factors is lacking.[50] Although exclusion of eyes with corneal lesions in the present study may have permitted formulation of a better supposition of the likely cause of the difference between tonometric readings, corneal lesions are common in dogs with lens instability, especially those with ALL, and their exclusion would have decreased the power and the clinical applicability of the study results.

Pressure applied by the lens or prolapsed vitreous on the corneal endothelium may increase tension of the cornea in a focal area or across the entire corneal surface, resulting in discrepancies in tonometric readings. Although the retrospective nature of this study did not permit confirmation of this speculation, it was supported by the findings that the differences between tonometers were greater in eyes with ALL, compared with those with PLL or other types of lens instability, and that the differences between rebound and applanation tonometric readings lessened after lens reduction or removal (vs before intervention). After lens extraction from the anterior chamber, readings were comparable between tonometers for all 3 dogs in which this was recorded, and the mean difference between tonometric readings decreased from 21.0 to 2.3 mm Hg. However, these findings must be interpreted with caution. First, estimates obtained before and after lens reduction or removal were reported for only 3 dogs. Second, because of the retrospective nature of this study, no record was kept of the area of the cornea at which the tonometer probe (tip) was directed. In 1 study,[50] estimation of the IOP in the peripheral cornea of normal dogs was associated with a small but significant (1.0 to 2.9 mm Hg) underestimation of IOP. If corneal location is an important factor, accounting for this may be complex to resolve because it will require simultaneous consideration of the tonometer application site relative to the corneoscleral limbus, the position of the anteriorly luxated lens, and any areas with corneal lesions.

The lack of manometric measurements in the present study made determination of tonometer accuracy impossible. However, data from the present study indicated that applanation and rebound tonometry provided estimates of IOP in eyes with ALL that were sometimes highly disparate and that these differences were often of clinical importance. Although the mechanism responsible for this difference was likely multifactorial, known differences between the tonometers (especially in eyes with increased IOP) undoubtedly played an important role. In addition, mechanical changes and lesions of the cornea and a direct mechanical effect of the lens on corneal rigidity may have also contributed to the differences. Therefore, veterinarians need to be aware that these 2 widely-used tonometers differ in their vulnerability to error in eyes with lens instability, especially eyes with ALL, and that, when possible, IOPs for eyes with lens instability should be estimated using both rebound and applanation tonometers. When only 1 tonometer type is available, clinically important errors in estimated IOPs for dogs with lens instability must be considered and IOP readings should be critically interpreted concurrent with clinical signs and neuro-ophthalmic responses and reflexes.

Acknowledgments

No external funding was used in this study. The authors declare that there were no conflicts of interest.

The authors thank Drs. Michelle Martin de Bustamante, Sydney Edwards, Kathryn Good, Kelly Knickelbein, Mary Lassaline, Bret Moore, Lionel Sebbag, Ann Strøm, Sara Thomasy, and Tomo Wiggans for collecting clinical data used in this study.

References

1. Renwick PW, Petersen-Jones SM. Orbital and ocular pain. In: Peiffer RL Jr, Petersen-Jones SM, eds. *Small Animal Ophthalmology: A Problem-Oriented Approach.* 4th ed. Saunders Elsevier; 2009:227–241.
2. Plummer CE, Regnier A, Gelatt KN. The canine glaucomas. In: Gelatt KN, Gilger BC, Kern TJ, eds. *Veterinary Ophthalmology.* 5th ed. Wiley Blackwell; 2013:1050–1145.
3. Schmidt TF. On applanation tonometry. *Trans Am Acad Ophthalmol Otolaryngol.* 1961;65:171–177.
4. Kontiola AI, Goldblum D, Mittag T, Danias J. The induction/impact tonometer: a new instrument to measure intraocular pressure in the rat. *Exp Eye Res.* 2001;73(6):781–785.
5. Kontiola A. A new electromechanical method for measuring intraocular pressure. *Doc Ophthalmol.* 1996–1997;93(3):265–276.
6. Featherstone HJ, Heinrich CL. Ophthalmic examination and diagnostics. In: Gelatt KN Gilger BC, Kern TJ, eds *Veterinary Ophthalmology*. 5th ed. Wiley Blackwell; 2013:533–613.
7. Nagata N, Yuki M, Hasegawa T. In vitro and in vivo comparison of applanation tonometry and rebound tonometry in dogs. *J Vet Med Sci.* 2011;73(12):1585–1589.
8. Priehs DR, Gum GG, Whitley RD, Moore LE. Evaluation of three applanation tonometers in dogs. *Am J Vet Res.* 1990;51(10):1547–1550.
9. Knollinger AM, La Croix NC, Barrett PM, Miller PE. Evaluation of a rebound tonometer for measuring intraocular pressure in dogs and horses. *J Am Vet Med Assoc.* 2005;227(2):244–248.
10. Gelatt KN, Peiffer RL Jr, Gum GG, Gwin RM, Erickson JL. Evaluation of applanation tonometers for the dog eye. *Invest Ophthalmol Vis Sci.* 1977;16(10):963–968.
11. Gelatt KN, MacKay EO. Distribution of intraocular pressure in dogs. *Vet Ophthalmol.* 1998;1(2-3):109–114.
12. Leiva M, Naranjo C, Pena MT. Comparison of the rebound tonometer (ICare) to the applanation tonometer (Tonopen XL) in normotensive dogs. *Vet Ophthalmol.* 2006;9(1):17–21.
13. McMillan F, Forster RK. Comparison of MacKay-Marg, Goldmann, and Perkins tonometers in abnormal corneas. *Arch Ophthalmol.* 1975;93(6):420–424.
14. Görig C, Coenen RTI, Stades FC, Djajadiningrat-Laanen SC, Boevé MH. Comparison of the use of new handheld tonometers and established applanation tonometers in dogs. *Am J Vet Res.* 2006;67(1):134–144.
15. Tofflemire KL, Wang C, Jens JK, Ellinwood NM, Whitley RD, Ben-Shlomo G. Evaluation of three hand-held tonometers in normal canine eyes. *Vet J.* 2017;224:7–10.
16. Miller PE, Pickett JP, Majors LJ, Kurzman ID. Clinical comparison of the MacKay-Marg and Tono-Pen applanation tonometers in the dog. *Prog Vet Comp Ophthalmol.* 1991;1:171–176.
17. Miller PE, Pickett JP, Majors LJ, Kurzman ID. Evaluation of two applanation tonometers in cats. *Am J Vet Res.* 1991;52(11):1917–1921.
18. Rusanen E, Florin M, Hässig M, Spiess BM. Evaluation of a rebound tonometer (Tonovet) in clinically normal cat eyes. *Vet Ophthalmol.* 2010;13(1):31–36.
19. Dziezyc J, Millichamp NJ, Smith WB. Comparison of applanation tonometers in dogs and horses. *J Am Vet Med Assoc.* 1992;201(3):430–433.
20. Moore CG, Milne ST, Morrison JC. Noninvasive measurement of rat intraocular pressure with the Tono-Pen. *Invest Ophthalmol Vis Sci.* 1993;34(2):363–369.
21. Minella AL, Kiland JA, McLellan GJ. Validation of the TonoVet Plus and Tono-Pen AVIA tonometers in normal canine eyes. *Vet Ophthalmol.* 2019;22(3):E50. 49th Annual Scientific Meeting of the American College of Veterinary Ophthalmologists abstract.
22. Thompson-Hom AL, Gerding PA Jr. Evaluation of intraocular pressure measurements obtained by use of a rebound tonometer and applanation tonometer in dogs before and after elective phacoemulsification. *Am J Vet Res.* 2012;73(5):709–713.
23. von Spiessen L, Karck J, Rohn K, Meyer-Lindenberg A. Clinical comparison of the TonoVet rebound tonometer and the Tono-Pen Vet applanation tonometer in dogs and cats with ocular disease: glaucoma or corneal pathology. *Vet Ophthalmol.* 2015;18(1):20–27.
24. Browning AC, Bhan A, Rotchford AP, Shah S, Dua HS. The effect of corneal thickness on intraocular pressure measurement in patients with corneal pathology. *Br J Ophthalmol.* 2004;88(11):1395–1399.
25. Goldblum D, Kontiola AI, Mittag T, Chen B, Danias J. Non-invasive determination of intraocular pressure in the rat eye. Comparison of an electronic tonometer (TonoPen), and a rebound (impact probe) tonometer. *Graefes Arch Clin Exp Ophthalmol.* 2002;240(11):942–946.
26. Martinez-de-la-Casa JM, Garcia-Feijoo J, Castillo A, Garcia-Sanchez J. Reproducibility and clinical evaluation of rebound tonometry. *Invest Ophthalmol Vis Sci.* 2005;46(12):4578–4580.
27. Chui WS, Lam A, Chen D, Chiu R. The influence of cor-

neal properties on rebound tonometry. *Ophthalmology*. 2008;115(1):80–84.
28. Sahin A, Basmak H, Yildirim N. The influence of central corneal thickness and corneal curvature on intraocular pressure measured by tono-pen and rebound tonometer in children. *J Glaucoma*. 2008;17(1):57–61.
29. Poostchi A, Mitchell R, Nicholas S, Purdie G, Wells A. The iCare rebound tonometer: comparisons with Goldmann tonometry, and influence of central corneal thickness. *Clin Exp Ophthalmol*. 2009;37(7):687–691.
30. Rao A, Kumar M, Prakash B, Varshney G. Relationship of central corneal thickness and intraocular pressure by iCare rebound tonometer. *J Glaucoma*. 2014;23(6):380–384.
31. Park YW, Jeong MB, Kim TH, et al. Effect of central corneal thickness on intraocular pressure with the rebound tonometer and the applanation tonometer in normal dogs. *Vet Ophthalmol*. 2011;14(3):169–173.
32. Ahn JT, Jeong MB, Park YW, et al. Accuracy of intraocular pressure measurements in dogs using two different tonometers and plano therapeutic soft contact lenses. *Vet Ophthalmol*. 2012;15(suppl 1):83–88.
33. Moeller E, Blocker T, Esson D, Madsen R. Postoperative glaucoma in the Labrador Retriever: incidence, risk factors, and visual outcome following routine phacoemulsification. *Vet Ophthalmol*. 2011;14(6):385–394.
34. Broadwater JJ, Schorling JJ, Herring IP, Elvinger F. Effect of body position on intraocular pressure in dogs without glaucoma. *Am J Vet Res*. 2008;69(4):527–530.
35. McLellan GJ, Kemmerling JP, Kiland JA. Validation of the TonoVet rebound tonometer in normal and glaucomatous cats. *Vet Ophthalmol*. 2013;16(2):111–118.
36. Jeong MB, Kim YJ, Yi NY, et al. Comparison of the rebound tonometer (TonoVet) with the applanation tonometer (TonoPen XL) in normal Eurasian Eagle owls (*Bubo bubo*). *Vet Ophthalmol*. 2007;10(6):376–379.
37. Slack JM, Stiles J, Moore GE. Comparison of a rebound tonometer with an applanation tonometer in dogs with glaucoma. *Vet Rec*. 2012;171(15):373.
38. Shah S. Accurate intraocular pressure measurement—the myth of modern ophthalmology? *Ophthalmology*. 2000;107(10):1805–1807.
39. Jorge JM, González-Méijome JM, Queirós A, Fernandes P, Parafita MA. Correlations between corneal biomechanical properties measured with the ocular response analyzer and ICare rebound tonometry. *J Glaucoma*. 2008;17(6):442–448.
40. Bhan A, Browning AC, Shah S, Hamilton R, Dave D, Dua HS. Effect of corneal thickness on intraocular pressure measurements with the pneumotonometer, Goldmann applanation tonometer, and Tono-Pen. *Invest Ophthalmol Vis Sci*. 2002;43(5):1389–1392.
41. Kato K. Comparison of two handheld applanation tonometers and the association of central corneal thickness, age, and intraocular pressure in normal and diseased canine eyes. *Vet Ophthalmol*. 2014;17(6):417–425.
42. Harada Y, Hirose N, Kubota T, Tawara A. The influence of central corneal thickness and corneal curvature radius on the intraocular pressure as measured by different tonometers: noncontact and Goldmann applanation tonometers. *J Glaucoma*. 2008;17(8):619–625.
43. Ogbuehi KC, Osuagwu UL. Corneal biomechanical properties: precision and influence on tonometry. *Cont Lens Anterior Eye*. 2014;37(3):124–131.
44. Liu J, Roberts CJ. Influence of corneal biomechanical properties on intraocular pressure measurement: quantitative analysis. *J Cataract Refract Surg*. 2005;31(1):146–155.
45. Deol M, Taylor DA, Radcliffe NM. Corneal hysteresis and its relevance to glaucoma. *Curr Opin Ophthalmol*. 2015;26(2):96–102.
46. Kotecha A. What biomechanical properties of the cornea are relevant for the clinician? *Surv Ophthalmol*. 2007;52(suppl 2):S109–S114.
47. Rootman DS, Insler MS, Thompson HW, Parelman J, Poland D, Unterman SR. Accuracy and precision of the Tono-Pen in measuring intraocular pressure after keratoplasty and epikeratophakia and in scarred corneas. *Arch Ophthalmol*. 1988;106(12):1697–1700.
48. Madjlessi F, Marx W, Reinhard T, Althaus C, Sundmacher R. Impression and applanation tonometry in irregular corneas. Comparison with intraocular needle tonometry. Article in German. *Ophthalmologe*. 2000;97(7):478–481.
49. Chihara E. Assessment of true intraocular pressure: the gap between theory and practical data. *Surv Ophthalmol*. 2008;53(3):203–218.
50. de Oliveira JK, Montiani-Ferreira F, Williams DL. The influence of the tonometer position on canine intraocular pressure measurements using the Tonovet rebound tonometer. *Open Vet J*. 2018;8(1):68–76.

Supplementary Materials

Supplementary materials are posted online at the journal website: avmajournals.avma.org.