Review of non–invasive blood pressure measurement in animals: Part 2 — Evaluation of the performance of non-invasive devices

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Abstract — Arterial blood pressure is a common parameter evaluated in conscious and anesthetized veterinary patients for a variety of reasons. Non-invasive blood pressure measurement techniques, such as Doppler ultrasound and oscillometry, are attractive in certain veterinary patients due to their availability and ease of use. The greatest limitation to non-invasive blood pressure monitoring can be its inaccuracy, particularly in hypotensive or hypertensive patients and in certain species. Part 1 of this 2-part review summarized the current techniques available to non-invasively measure arterial blood pressure in veterinary species and discussed validation of non-invasive devices. Part 2 summarizes the veterinary literature that evaluates the use of non-invasive blood pressure measurement techniques in conscious and anesthetized species and develops general conclusions for proper use and interpretation of non-invasive blood pressure devices.

Résumé — Mesure de la pression sanguine de manière non-invasive chez les animaux. Partie 2 – Évaluation de la performance des équipements non-invasifs. La pression sanguine artérielle est un paramètre fréquemment évalué chez les patients vétérinaires conscients et anesthésiés pour une variété de raisons. Les techniques non-invasives de mesure de la pression sanguine, telles que les ultrasons Doppler et l'oscillométrie, sont intéressantes chez certains patients vétérinaires étant donné leur disponibilité et leur facilité d'utilisation. La principale limitation du suivi de la pression sanguine par des méthodes non-invasives peut être son imprécision, particulièrement chez des patients hypotensifs ou hypertensifs, et chez certaines espèces. La première partie de cette revue en deux parties résumait les techniques présentement disponibles pour mesurer de manière non-invasive la pression sanguine artérielle chez des espèces animales et discutait de la validation des équipements non-invasifs. La deuxième partie résume la littérature vétérinaire qui évalue l'utilisation de techniques non-invasives de mesure de la pression sanguine chez des espèces conscientes et anesthésiées et développe des conclusions générales pour l'utilisation et l'interprétation appropriées des équipements non-invasifs de mesure de la pression sanguine.

(Traduit par Dr Serge Messier)

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Introduction

In the first part of this 2-part review, the physiology of arterial blood pressure (BP), techniques for its evaluation in veterinary species, and validation of non-invasive monitors were discussed. The second part of this review considers the veterinary literature that evaluates the use of non-invasive blood pressure (NIBP) measurement techniques in conscious and anesthetized animals. The findings are compared to the validation criteria of the American College of Veterinary Internal Medicine (ACVIM) Hypertension Consensus Panel and the Veterinary Blood Pressure Society Recommendations in an attempt to develop general conclusions for proper use and interpretation of NIBP devices. Evaluation of arterial BP plays an important role in veterinary care and disease management. Non-invasive blood pressure can be evaluated using a number of techniques including auscultatory, Doppler ultrasonic flow detector, oscillometry, high definition oscillometry, and plethysmography methods. Doppler and oscillometry techniques are used most often (1,2).

The gold standard for arterial BP measurement in animals is *via* direct arterial catheter placement; however, this technique is not without risk, requires specific technical skill and equipment, is invasive, and is not always justified for most non-critical cases. Therefore, NIBP measurement techniques are attractive alternatives due to their ease of use, availability, and

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non-invasiveness. In order for an NIBP measurement device to be considered a "validated device," it must meet specific criteria to demonstrate that it is an acceptable alternative to the gold standard measurement technique. In veterinary medicine, validation standards have not been established, except for recommendations from the ACVIM Hypertension Consensus Panel and Veterinary Blood Pressure Society Recommendations (AHCP-VBPS Validation) (3). These validation standards were discussed in detail in the first part of this review (4).

Doppler ultrasonic flow detector

Doppler in canine species

In conscious, normotensive dogs, Doppler consistently underestimates direct systolic arterial BP taken from the femoral (5,6) or dorsal pedal artery (7,8). In anesthetized dogs, Doppler has been evaluated against direct systolic arterial BP measured from the dorsal pedal, femoral, radial, or coccygeal artery with conflicting results. In some studies, Doppler tended to underestimate direct systolic arterial BP (8,9), while overestimation was reported in others (10,11). Doppler has also been unreliable in detecting hypotension in anesthetized dogs, correctly identifying hypotension (defined as direct mean arterial BP < 60 mmHg or Doppler pressures of < 90 mmHg) only 66.7% to 69.2% of the time (11). Despite an acceptable mean bias of 2.8 mmHg, the 95% limits of agreement were −46.4 to 51.9 mmHg, demonstrating poor precision (11) (Table 1).

Recently, 2 studies evaluated the level of agreement between Doppler and direct arterial BP in dogs weighing < 5 kg (12,13). In 1 study, conditions of an acceptable direct systolic arterial BP (90 to < 160 mmHg) and low systolic arterial BP (< 90 mmHg) were used for comparisons between Doppler and direct BP measurements (12). In the other study, acceptable direct arterial BP was defined as a mean arterial BP of 60 to 120 mmHg, and low arterial BP as < 60 mmHg (13). It has been hypothesized that when measuring arterial BP using Doppler in dogs of this body weight, the measured value may be more reflective of mean arterial BP rather than systolic arterial BP, which has been previously identified in cats, in which Doppler values tend to underestimate direct systolic arterial BP (14–17). In both canine studies (12,13), Doppler overestimated both direct systolic and mean arterial BP measured from the dorsal pedal artery. The smallest bias was found when Doppler was used as an estimate of direct systolic arterial BP rather than mean arterial BP, during conditions of acceptable and low arterial blood pressures (12,13) (Table 1). In the second study, both values for bias in normotensive and hypotensive conditions were acceptable, but the standard deviation (SD) was exceeded for both situations and the number of measurements within 10 to 20 mmHg of the reference method was always below the desired percentages (13) (Table 1). In both studies, there were large differences between Doppler systolic arterial BP and direct mean arterial BP and Doppler did not meet any of the AHCP-VBPS validation criteria (12,13). The conclusion from these studies is that Doppler BP measurements provide values that are not accurate as an estimate of direct mean arterial BP values in dogs weighing < 5 kg. In at least 1 of these studies the Doppler values were reliable for estimation of direct systolic arterial BP, but only when mean arterial blood pressures were < 60 mmHg (12) (Table 1).

Doppler in feline species

Initial evaluation of NIBP measurement techniques in cats began at similar times as studies in dogs, but there are fewer published studies. An early evaluation of Doppler in anesthetized cats identified that the measurement underestimates direct systolic arterial BP and better predicts direct mean arterial BP, obtained from the femoral artery (15). As a result, the authors proposed a calibration factor such that:

femoral systolic arterial BP = Doppler systolic BP + 14 mmHg (15).

In another study, similar findings were obtained: Doppler underestimated direct systolic arterial BP measured from the femoral artery but was a good predictor of direct mean arterial BP with a bias ± precision of −0.8 ± 6 mmHg (14) (Table 2). This interpretation of Doppler measurement reflecting mean arterial BP rather than systolic arterial BP seems to be unique to cats and continues to be published in the veterinary literature. Studies in cats have invariably demonstrated that Doppler measurements as an estimation of systolic arterial BP values do not comply with the AHCP-VBPS. In anesthetized cats, Doppler measurements in comparison to direct systolic and mean arterial blood pressures measured from the femoral and dorsal pedal arteries were found to be a poor predictor of both direct systolic and mean arterial BP (18) (Table 2).

All of the previous studies in cats that have evaluated Doppler for arterial BP measurement in comparison to direct arterial BP readings have placed the BP cuff on the antebrachium over the median artery and have utilized a cuff width which is 35% to 45% of the circumference of the antebrachium (14–19) (Table 2). A discrepancy in systolic arterial BP values has been identified depending on cuff placement when utilizing Doppler in conscious cats such that cuff placement over the coccygeal artery resulted in consistently higher systolic arterial BP values in comparison to values obtained when the cuff was placed on the antebrachium over the radial artery (20). However, this study made no comparison to direct arterial BP values and therefore conclusions on which location was more accurate cannot be made. It has been shown that Doppler measurements had the highest overall accuracy and lowest failure rate in anesthetized cats (17), probably because it is easier to measure arterial BP with this technique in the anesthetized *versus* the conscious animal and therefore there is less source of error.

Doppler in equine species

In the last 30 y only a single study was published that evaluated the use of Doppler for NIBP measurement in horses (21). This study compared systolic arterial BP measured invasively *via* the facial artery to those measured by Doppler using the coccygeal artery in dorsally recumbent, anesthetized horses. The authors concluded that Doppler could not be recommended as the sole technique for BP monitoring in anesthetized horses due to the inaccuracy of the technique, reporting an error range of ± 20 mmHg in 5% of horses (21).

Table 1. Published studies evaluating Doppler ultrasound and oscillometric non-invasive blood pressure measurement in dogs in comparison with the American College of Veterinary Internal Medicine (ACVIM) criteria for technique validation.

Parameter	Number of animals	Bias (mmHg)	Standard deviation (mmHg)	Correlation	< 10 mmHg (% of measurements)	< 20 mmHg (% of measurements)
ACVIM criteria	8	≤ 10	≤ 15	≥ 0.9	≥ 50	≥ 80
Doppler Ultrasound						
Conscious dogs (5) Direct BP source: Femoral artery NIBP cuff location: Median artery SAP	28	NR	NR	NR	48	70
Conscious dogs (6) Direct BP source: Femoral artery NIBP cuff location: Metatarsal artery SAP	12	11.6	19.7	0.827	43	NR
Conscious dogs (7) Direct BP source: Metatarsal artery NIBP cuff location: Metatarsal artery MAP < 80 mmHg MAP 80–100 mmHg MAP > 100 mmHg	11	−16.6 16.1 8.2	18.9 41.2 37.9	0.63 −0.16 −0.12	NR	NR
Anesthetized dogs (9) Direct BP source: Dorsal pedal artery NIBP cuff location: Cranial tibial artery SAP < 90 mmHg SAP 90–140 mmHg SAP > 140 mmHg	9	0.2 −6 −18	NR	0.05	73 63.6 23.7	100 86.4 45.8
Anesthetized dogs (9) Direct BP source: Dorsal pedal artery NIBP cuff location: Metatarsal artery SAP < 90 mmHg SAP 90–140 mmHg SAP > 140 mmHg	9	−6 −13 −25	NR	0.08	60 42.6 21.7	94.3 72.3 48.3
Anesthetized dogs (9) Direct BP source: Dorsal pedal artery NIBP cuff location: Median artery SAP < 90 mmHg SAP 90–140 mmHg SAP > 140 mmHg	9	10 −3 −26	NR	0.39	41.9 66.7 17.6	100 88.1 39.2
Anesthetized dogs (8) Direct BP source: Dorsal pedal artery NIBP cuff location: Median artery SAP	10	−4.1	24.7	NR	60	70
Conscious dogs (8) Direct BP source: Dorsal pedal artery NIBP cuff location: Median artery SAP	10	−15.1	21.6	NR	20	40
Anesthetized dogs (12) Direct BP source: Dorsal pedal artery NIBP cuff location: Median or cranial tibial artery SAP < 90 mmHg SAP 90–160 mmHg	10	−5.7 −17.3	12.3 14.9	NR	61 23	90 60
Anesthetized dogs (13) Direct BP source: Dorsal pedal artery NIBP cuff location: Metatarsal artery MAP < 60 mmHg MAP 60–120 mmHg	41	10 8.2	27.9 20.9	0.8 0.9	47.8 31.6	51.1 65.8
Anesthetized dogs (11) Direct BP source: 76.7% dorsal pedal artery, 17.8% coccygeal artery, 2.7% femoral artery, 2.7% radial artery NIBP cuff location: Median or cranial tibial artery MAP < 60 mmHg	85	2.8	NR	NR	NR	NR

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Table 1. Published studies evaluating Doppler ultrasound and oscillometric non-invasive blood pressure measurement in dogs in comparison with the American College of Veterinary Internal Medicine (ACVIM) criteria for technique validation *(continued)*.

Parameter	Number of animals	Bias (mmHg)	Standard deviation (mmHg)	Correlation	< 10 mmHg (% of measurements)	< 20 mmHg (% of measurements)
ACVIM criteria	8	≤ 10	≤ 15	≥ 0.9	≥ 50	≥ 80
Oscillometry						
Conscious dogs (5)						
Direct BP source: Femoral artery						
NIBP cuff location: Median artery						
Oscillometric technology: NR						
SAP					37	59
MAP	28	NR	NR	NR	59	89
DAP					41	70
Anesthetized dogs (25)						
Direct BP source: Cranial tibial artery						
NIBP cuff location: Metacarpal artery						
Oscillometric technology: Cardell Veterinary BP Monitor 9301V, CAS Medical						
SAP 50–80 mmHg						
SAP		−6	4			
MAP		6	5			
DAP		11	8			
SAP 90–120 mmHg						
SAP		15	7			
MAP	6	10	8	NR	NR	NR
DAP		10	8			
SAP 120–150 mmHg						
SAP		23	7			
MAP		13	10			
DAP		12	14			
Anesthetized dogs (25)						
Direct BP source: Cranial tibial artery						
NIBP cuff location: Metatarsal artery						
Oscillometric technology: Cardell Veterinary BP Monitor 9301V, CAS Medical						
SAP 50–80 mmHg						
SAP		−4	3			
MAP		6	3			
DAP		12	6			
SAP 90–120 mmHg						
SAP		16	5			
MAP	6	15	4	NR	NR	NR
DAP		13	5			
SAP 120–150 mmHg						
SAP		20	0			
MAP		16	0			
DAP		19	0			
Anesthetized dogs (25)						
Direct BP source: Cranial tibial artery						
NIBP cuff location: Cranial tibial artery						
Oscillometric technology: Cardell Veterinary BP Monitor 9301V, CAS Medical						
SAP 50–80 mmHg						
SAP		−3	3			
MAP		9	3			
DAP		13	6			
SAP 90–120 mmHg						
SAP		21	5			
MAP	6	16	4	NR	NR	NR
DAP		15	4			
SAP 120–150 mmHg						
SAP		25	5			
MAP		23	5			
DAP		24	4			

Table 1. Published studies evaluating Doppler ultrasound and oscillometric non-invasive blood pressure measurement in dogs in comparison with the American College of Veterinary Internal Medicine (ACVIM) criteria for technique validation *(continued)*.

Parameter	Number of animals	Bias (mmHg)	Standard deviation (mmHg)	Correlation	< 10 mmHg (% of measurements)	< 20 mmHg (% of measurements)
ACVIM criteria	8	≤ 10	≤ 15	≥ 0.9	≥ 50	≥ 80
Anesthetized dogs (28)						
Direct BP source: Lingual artery						
NIBP cuff location: Median artery						
Oscillometric technology: Cardell Veterinary Monitor 9402, CAS Medical						
SAP		0.88	1.92			
MAP	8	9.95	1.28	NR	NR	NR
DAP		20.11	1.83			
Anesthetized dogs (28)						
Direct BP source: Lingual artery						
NIBP cuff location: Cranial tibial artery						
Oscillometric technology: Cardell Veterinary Monitor 9402, CAS Medical						
SAP		2.79	1.93			
MAP	8	12.25	1.28	NR	NR	NR
DAP		23.95	1.83			
Anesthetized dogs (28)						
Direct BP source: Dorsal pedal artery						
NIBP cuff location: Median artery						
Oscillometric technology: Cardell Veterinary Monitor 9402, CAS Medical						
SAP		7.75	2.00			
MAP	8	6.36	1.59	NR	NR	NR
DAP		13.67	2.17			
Anesthetized dogs (28)						
Direct BP source: Dorsal pedal artery						
NIBP cuff location: Cranial tibial artery						
Oscillometric technology: Cardell Veterinary Monitor 9402, CAS Medical						
SAP		5.4	2.00			
MAP	8	8.81	1.59	NR	NR	NR
DAP		17.27	2.17			
Anesthetized dogs (31)						
Direct BP source: Femoral or dorsal pedal artery						
NIBP cuff location: Dorsal pedal artery (metacarpal artery in two dogs)						
Oscillometric technology: Surgivet V60046						
SAP < 90 mmHg						
SAP		1.9	11.06	0.65		
MAP		3.4	7.68	0.65		
DAP		8.2	8.85	0.50		
SAP 91–120 mmHg						
SAP		8.6	11.89	0.39	36	68
MAP	34	2.1	0.79	0.74	68	89
DAP		5.2	12.10	0.66	53	80
SAP > 121 mmHg						
SAP		22.7	17.90	0.49		
MAP		5.5	9.58	0.79		
DAP		9.4	10.78	0.76		
Conscious dogs (7)						
Direct BP source: Metatarsal artery						
NIBP cuff location: Metatarsal artery						
Oscillometric technology: Datascope Passport						
MAP < 80 mmHg						
SAP		−15.3	20.4	0.50		
MAP		−12.1	6.9	0.75		
DAP		−6.4	3.5	0.84		
MAP 80–100 mmHg						
SAP		14.6	6.9	0.17		
MAP	11	−5.2	9.2	0.30	NR	NR
DAP		1.6	7.8	0.21		
MAP > 100 mmHg						
SAP		−3.9	41.5	−0.34		
MAP		−17.2	10.5	0.81		
DAP		−3.5	14.6	−0.28		

Table 1. Published studies evaluating Doppler ultrasound and oscillometric non-invasive blood pressure measurement in dogs in comparison with the American College of Veterinary Internal Medicine (ACVIM) criteria for technique validation *(continued)*.

Parameter	Number of animals	Bias (mmHg)	Standard deviation (mmHg)	Correlation	< 10 mmHg (% of measurements)	< 20 mmHg (% of measurements)
ACVIM criteria	8	≤ 10	≤ 15	≥ 0.9	≥ 50	≥ 80
Conscious dogs (7)						
Direct BP source: Metatarsal artery						
NIBP cuff location: Metatarsal artery						
Oscillometric technology: Cardell Veterinary Monitor 9401, Sharn Veterinary						
MAP < 80 mmHg						
SAP		−22.5	5.2	0.97		
MAP		−12.6	3.3	0.96		
DAP		−15.0	5.7	0.86		
MAP 80–100 mmHg						
SAP		15.9	27.6	0.47		
MAP	11	−1.3	8.5	0.60	NR	NR
DAP		−4.6	9.1	0.57		
MAP > 100 mmHg						
SAP		3.0	29.4	0.22		
MAP		−5.8	11.7	0.73		
DAP		−12.1	13.4	0.40		
Anesthetized dogs (29)						
Direct BP source: Dorsal pedal artery						
NIBP cuff location: Median artery						
Oscillometric technology: PetMap, Ramsey Medical						
Normotension						
SAP		−14.7	15.5			
MAP		−14.1	15.8			
DAP		−16.3	12			
MAP ≤ 40 mmHg	8			NR	NR	NR
SAP		−32.2	22.6			
MAP		−16.8	17.2			
DAP		−24.2	19.8			
Anesthetized dogs (9)						
Direct BP source: Dorsal pedal artery						
NIBP cuff location: Median artery						
Oscillometric technology: PC Scout Monitor						
SAP < 90 mmHg						
SAP		6			66.7	100
MAP		NR			85.4	100
DAP		NR			96.5	100
SAP 90–140 mmHg						
SAP		−15			31.8	63.6
MAP	9	NR	NR	NR	86.4	100
DAP		NR			81.0	95.2
SAP > 140 mmHg						
SAP		−42			4.0	16
MAP		NR			63.6	90.9
DAP		NR			66.7	95.8
Anesthetized dogs (30)						
Direct BP source: Dorsal pedal artery						
NIBP cuff location: Median artery						
Oscillometric technology: PetMap graphic, Ramsey Medical						
SAP		9.9				
MAP	21	−6.3	NR	NR	NR	NR
DAP		−8.9				

Table 1. Published studies evaluating Doppler ultrasound and oscillometric non-invasive blood pressure measurement in dogs in comparison with the American College of Veterinary Internal Medicine (ACVIM) criteria for technique validation *(continued)*.

Parameter	Number of animals	Bias (mmHg)	Standard deviation (mmHg)	Correlation	< 10 mmHg (% of measurements)	< 20 mmHg (% of measurements)
ACVIM criteria	8	≤ 10	≤ 15	≥ 0.9	≥ 50	≥ 80
Anesthetized dogs (31)						
Direct BP source: Metatarsal artery						
NIBP cuff location: Metatarsal artery						
Oscillometric technology: Surgivet V9203						
MAP < 60 mmHg						
SAP		7.89	10.2			
MAP		1.30	5.89			
DAP		8.33	7.53			
MAP 60–80 mmHg						
SAP		15.4	15.4			
MAP	29	6.67	6.67	NR	NR	NR
DAP		7.63	7.63			
MAP > 80 mmHg						
SAP		55.11	26.77			
MAP		5.71	8.73			
DAP		5.82	9.90			
Anesthetized dogs (8)						
Direct BP source: Dorsal pedal artery						
NIBP cuff location: Median artery						
Oscillometric technology: PetMap, Ramsey Medical						
SAP		−6.1	−6.1		60	90
MAP	10	−2.9	−2.9	NR	NR	NR
DAP		−6.9	−6.9		60	100
Conscious dogs (8)						
Direct BP source: Dorsal pedal artery						
NIBP cuff location: Median artery						
Oscillometric technology: PetMap, Ramsey Medical						
SAP		−5.8	16.5		50	70
MAP	10	3.8	8.9	NR	NR	NR
DAP		4.6	7.9		70	100
Anesthetized dogs (34)						
Direct BP source: Median caudal artery						
NIBP cuff location: Median artery						
Oscillometric technology: CAS (SunTech) Medical System						
SAP		0.2	6.2	0.9	100	100
MAP	20	−2.5	5.0	1.0	100	100
DAP		−2.6	6.0	0.9	100	100
Anesthetized dogs (34)						
Direct BP source: Median caudal artery						
NIBP cuff location: Median artery						
Oscillometric technology: SunTech Medical						
SAP		3.4	6.3	0.9	100	100
MAP	20	1.6	3.8	1.0	100	100
DAP		2.2	4.5	1.0	100	100
Anesthetized dogs (33)						
Direct BP source: Median sacral artery						
NIBP cuff location: Median artery						
Oscillometric technology: SunTech Medical						
SAP		3.96	6.31	0.95	100	100
MAP	17	2.12	5.14	0.98	100	100
DAP		2.65	4.54	0.97	100	100

NR — not reported. Highlighted values meet validation criteria.

Doppler in exotic species

Extensive investigation of NIBP measurement techniques in exotic species is similarly limited. One validation study in anesthetized Hispaniolan Amazon parrots *(Amazona ventralis)* evaluated Doppler and oscillometry with the NIBP cuffs placed over the superficial ulnar artery of the wing and the ischiatic artery of the leg in comparison to direct arterial BP readings from the superficial ulnar artery or the ischiatic artery of the contralateral limbs (22). This study found that the readings obtained *via* Doppler disagreed considerably from direct systolic arterial BP readings (Table 3), leading the authors to conclude that this technique could not be recommended for use in this species (22), and the technique did not meet the passing criteria of AHCP-VBPS validation (3). Another study evaluated the same 2 NIBP measurement techniques in conscious and anesthetized red-tailed hawks *(Buteo jamaicensis)* against direct mean arterial BP over a range of arterial BP values, using 3 cuff sizes: 20% to 30% of circumference, 30% to 40% of circumference, and 40% to 50% of circumference of the superficial ulnar artery or median metatarsal artery. This study demonstrated good agreement for Doppler, according to the combined bias of 2 ± 13 mmHg when a cuff width:limb circumference ratio of 40% to 50% was used (23), complying with the passing criteria of AHCP-VBPS validation (3) (Table 3).

In anesthetized rabbits, Doppler measured from the dorsal carpal branch of the radial artery using an average cuff width:limb circumference ratio of 50% was in good agreement with direct systolic arterial BP readings from the auricular artery, and was found to be a reliable technique in positively predicting systolic arterial BP values below 80 mmHg 91% of the time (24). The bias of 1 ± 8 mmHg and 95% limits of agreement from -14 to 17 mmHg of Doppler with respect to direct arterial BP measurements in this study (24) is within the recommended minimum passing criteria of AHCP-VBPS validation (3) (Table 3).

Oscillometry

Oscillometry in canine species

Many studies in veterinary species have evaluated the performance of oscillometric BP monitors in comparison with direct arterial BP values. Conclusions across studies are difficult because not all technologies of oscillometric monitors are the same; the algorithms are likely to vary between manufacturers and have an impact on the performance of the monitor. The first oscillometric monitor for veterinary use was the Dinamap Veterinary Blood Pressure monitor, developed in 1993 by Critikon (Tampa, Florida, USA) (25). This monitor received a lot of attention in the earlier veterinary studies that evaluated oscillometric BP measurement in dogs (26,27). In studies in conscious dogs, acceptable readings were obtained with the Dinamap monitor when the oscillometric cuff was placed over the coccygeal artery at the base of the tail (6,27).

Critikon discontinued their monitor in 1999 and the following year Sharn Veterinary (Caledonia, Michigan, USA) developed the Cardell Veterinary Blood Pressure monitor (25). As this and newer oscillometric BP monitors have become available, studies evaluating their performance have emerged in the veterinary literature. The most extensively studied oscillometric monitors in canine patients have been the Cardell Veterinary Monitor, the SurgiVet Monitor by Smiths Medical (Minneapolis, Minnesota, USA) and the petMAP Blood Pressure Measurement Device by Ramsay Medical (Ramsay Medical, NSW, Australia).

In anesthetized dogs, the performance of the Cardell Veterinary Blood Pressure monitor has been evaluated over a range of systolic arterial BP values: > 200 mmHg, 120 to 150 mmHg, 90 to 120 mmHg, and 50 to 80 mmHg as well as cuff positions: metacarpal artery, median artery, metatarsal artery, and cranial tibial artery (25,28). Results between studies are sometimes conflicting and make conclusions and generalization difficult in terms of which of the arterial BP readings — systolic, diastolic or mean — is more reliable with this technology. This is due to different methodology used to evaluate the arterial BP ranges. In one study, when arterial BP was increased with administration of phenylephrine, the bias and precision for all pressures were better and there were slight variations among comparisons in the measurements between forelimb and hind limb *versus* direct measurement from the dorsal pedal artery or lingual artery (28). The measurements were usually below the established mean error of 10 ± 15 mmHg (mean $\pm$ SD) by the AHCP-VBPS validation (3). In the latter study (28), diastolic arterial BP tended to have less accurate bias and precision than systolic and mean arterial BP (Table 1). Conversely, in another study (25), arterial BP ranges were manipulated by anesthetic depth, and bias and precision for systolic and mean arterial BP were within the limits of the AHCP-VBPS validation, only when systolic arterial BP values were in the 50 to 80 mmHg range (Table 1).

In conscious dogs, placing the cuff above the tibiotarsal joint over the cranial tibial artery during conditions of low arterial BP (mean arterial BP < 80 mmHg), measured directly from the dorsal pedal artery, demonstrated that the Cardell monitor performed better than another oscillometric device (Datascope Passport; Datascope Corp, Paramus, New Jersey, USA) or Doppler, despite a tendency for overestimating most direct arterial BP values (systolic, diastolic and mean) (7). In conditions of higher arterial BP values (mean arterial BP > 80 mmHg), the Cardell monitor underestimated systolic and overestimated both diastolic and mean arterial BP values. Conditions of AHCP-VBPS validation were only met, or almost met, for mean arterial BP during low arterial BP and for diastolic and mean arterial BP during higher arterial BP values (7) (Table 1).

The petMAP is a portable, oscillometric BP measurement device that claims to provide species and cuff site optimization for enhanced accuracy of NIBP measurement. In a model of hypotension (MAP < 40 mmHg) created *via* significant blood loss in anesthetized dogs, considerable disagreement was identified between NIBP measurements taken from a cuff placed over the median artery and direct arterial BP readings taken from the dorsal pedal artery with this monitor (29). The monitor was found to greatly overestimate hypotension, and the performance of the monitor during normotension (defined as mean arterial BP 66 ± 9 mmHg) was no better, demonstrating consistently large biases and SD (29) (Table 1). These findings led the authors to conclude that the monitor was unreliable in

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Table 2. Published studies evaluating Doppler ultrasound and oscillometric non-invasive blood pressure measurement in cats in comparison with the American College of Veterinary Internal Medicine (ACVIM) criteria for technique validation.

Parameter	Number of animals	Bias (mmHg)	Standard deviation (mmHg)	Correlation	< 10 mmHg (% of measurements)	< 20 mmHg (% of measurements)
ACVIM criteria	8	≤ 10	≤ 15	≥ 0.9	≥ 50	≥ 80
Doppler Ultrasound						
Anesthetized cats (19)						
Direct BP source: Femoral artery						
NIBP cuff location: Dorsal pedal artery						
SAP	11	9.4	14.86	0.96	46	31
MAP		8.6	15.25	0.95	39	37
Anesthetized cats (19)						
Direct BP source: Femoral artery						
NIBP cuff location: Coccygeal artery						
SAP	11	−4.7	22.87	0.91	45	27
MAP		−1.8	19.68	0.91	42	32
Anesthetized cats (14)						
Direct BP source: Femoral artery						
NIBP cuff location: Median artery						
SAP	8	−25	7.4	0.88	NR	NR
MAP		−0.8	6	0.89		
Anesthetized cats (18)						
Direct BP source: Dorsal pedal artery (19 cats), femoral artery (20 cats)						
NIBP cuff location: Median artery						
SAP	39	−8.8	NR	0.65	NR	NR
MAP		14		0.66		
DAP		27.9		0.68		
Oscillometry						
Anesthetized cats (16)						
Direct BP source: Femoral artery						
NIBP cuff location: Median artery						
Oscillometric technology: Cardell Veterinary BP Monitor 9301V, CAS Medical						
MAP < 60 mmHg	6			NR	NR	NR
SAP		−5.2	4.2			
MAP		0.7	4.3			
DAP		−3.9	5.9			
MAP 60–140 mmHg						
SAP		−12.1	6.5			
MAP		0.1	3			
DAP		−0.3	5.6			
MAP > 140 mmHg						
SAP		−17.7	7.8			
MAP		−3.3	4.2			
DAP		3.7	6.2			
Anesthetized cats (35)						
Direct BP source: Dorsal pedal artery						
NIBP cuff location: Median artery						
Oscillometric technology: PetMap, Ramsey Medical						
SAP	21	−14.9	NR	NR	NR	NR
MAP		−1.3				
DAP		4.4				
Anesthetized cats (35)						
Direct BP source: Dorsal pedal artery						
NIBP cuff location: Median artery						
Oscillometric technology: Cardell Max-1 Veterinary Monitor						
SAP	21	−13.4	NR	NR	NR	NR
MAP		−3.6				
DAP		8.0				

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Table 2. Published studies evaluating Doppler ultrasound and oscillometric non-invasive blood pressure measurement in cats in comparison with the American College of Veterinary Internal Medicine (ACVIM) criteria for technique validation *(continued)*.

Parameter	Number of animals	Bias (mmHg)	Standard deviation (mmHg)	Correlation	< 10 mmHg (% of measurements)	< 20 mmHg (% of measurements)
ACVIM criteria	8	≤ 10	≤ 15	≥ 0.9	≥ 50	≥ 80
Anesthetized cats (36)						
Direct BP source: Femoral artery						
NIBP cuff location: Coccygeal artery						
Oscillometric technology: Cardell Veterinary Monitor 9403, Midmark						
SAP		−10.1	16.7	0.896		
MAP	6	10.0	13.3	0.917	NR	NR
DAP		20.2	12.7	0.898		
Anesthetized cats (37)						
Direct BP source: Dorsal pedal artery						
NIBP cuff location: Median artery						
Oscillometric technology: PetMap Classic, Ramsey Medical						
SAP		4.2	28.5			
MAP	8	−1.9	14.6	NR	NR	NR
DAP		−6.1	13.2			
Anesthetized cats (37)						
Direct BP source: Dorsal pedal artery						
NIBP cuff location: Coccygeal artery						
Oscillometric technology: PetMap Classic, Ramsey Medical						
SAP		7.2	31.3			
MAP	8	−1.1	11.7	NR	NR	NR
DAP		−6.1	11.6			
Anesthetized cats (37)						
Direct BP source: Dorsal pedal artery						
NIBP cuff location: Median artery						
Oscillometric technology: PetMap Graphic, Ramsey Medical						
SAP		7.7	27.0			
MAP	8	0.2	13.0	NR	NR	NR
DAP		−4.3	11.5			
Anesthetized cats (37)						
Direct BP source: Dorsal pedal artery						
NIBP cuff location: Coccygeal artery						
Oscillometric technology: PetMap Graphic, Ramsey Medical						
SAP		10.9	29.6			
MAP	8	−0.1	12.1	NR	NR	NR
DAP		−4.4	11.7			

NR — Not reported. Highlighted values meet validation criteria.

identifying hypotension, and of clinical importance, it is likely to overestimate hypotension (29). The monitor has been evaluated in anesthetized dogs with NIBP measurements taken from a cuff placed over the median artery and compared to direct arterial BP readings from the dorsal pedal artery (8,30). These studies identified poor agreement (30) and poor precision (8) between the petMAP and directly measured arterial BP values, leading one group of authors to conclude that the device could not be recommended (30). Both studies reported very wide limits of agreement for systolic, mean, and diastolic arterial BP measurements (Table 1).

The SurgiVet monitor has a unique BP cuff, having the entire cuff inflate during measurement. This monitor has been evaluated in 2 studies in anesthetized dogs; 1 utilized clinical cases (31), while the other induced hypotension *via* blood loss (32). The performance of the monitor was evaluated over a range of arterial BP values: systolic arterial BP > 121 mmHg, between 91 and 120 mmHg, and < 90 mmHg (31); or mean arterial BP values > 80 mmHg, between 60 and 80 mmHg, and < 60 mmHg (32). Both studies compared oscillometric BP measured from a cuff placed on the metatarsal artery to direct arterial BP readings from the dorsal pedal artery. The results showed that the monitor tended to underestimate arterial BP across the range of BP values evaluated, but provided the best agreement with direct mean arterial BP (31,32) (Table 1). These results meet the AHCP-VBPS validation criteria; however, data for correlation and the percentage of BP measurements that fell within 10% and 20% of the direct arterial BP readings were not provided. Furthermore, the criteria for mean error and SD were only met when the heart rate of the study dogs was < 120 bpm (32). Of clinical importance, in both studies the monitor correctly predicted hypotension.

Table 3. Published studies evaluating Doppler ultrasound non-invasive blood pressure measurement technique in exotic species in comparison with the American College of Veterinary Internal Medicine (ACVIM) criteria for technique validation.

Parameter	Number of animals	Bias (mmHg)	Standard deviation (mmHg)	Correlation	< 10 mmHg (% of measurements)	< 20 mmHg (% of measurements)
ACVIM criteria	8	≤ 10	≤ 15	≥ 0.9	≥ 50	≥ 80
Doppler Ultrasound						
Anesthetized Hispaniolan Amazon parrots (22) Direct BP source: Superficial ulnar artery NIBP cuff location: Superficial ulnar artery (wing) SAP	16	24	NR	NR	NR	NR
Anesthetized Hispaniolan Amazon parrots (22) Direct BP source: Superficial ulnar artery NIBP cuff location: Ischiatic artery (leg) SAP	16	14	NR	NR	NR	NR
Conscious red-tailed hawks (23) Direct BP source: Superficial ulnar artery NIBP cuff location: Superficial ulnar artery (cuff width 40–50% of circumference) SAP MAP	6	59 20	33 33	NR	NR	NR
Anesthetized rabbits (24) Direct BP source: Auricular artery NIBP cuff location: Median artery SAP MAP	17	1 −13	8 8	0.82 0.79	85 NR	NR

NR — Not reported. Highlighted values meet validation criteria.

Devices in 2 studies in anesthetized, normotensive dogs have met all the AHCP-VBPS validation criteria of the ACVIM for NIBP measurement devices (33,34) (Table 1). The oscillometric technology used in both of these studies was from Suntech Medical (Morrisville, North Carolina, USA) and is available in the company's own veterinary monitors or the multiparameter monitors manufactured by DRE Veterinary (Louisville, Kentucky, USA), the DRE Waveline Pro and the DRE Waveline Touch. In both studies, the dogs were anesthetized and the oscillometric cuff was placed on the antebrachium over the median artery and direct arterial BP readings were measured from the median caudal artery (34) or the median sacral artery (33) (Table 1).

Oscillometry in feline species

When oscillometric BP monitoring was first investigated in feline patients, the Dinamap Veterinary Blood Pressure monitor (Critikon) was used to evaluate the clinical utility. These studies found that this monitor did not accurately measure arterial BP in comparison to direct arterial BP readings taken from the femoral artery (14,19). This may be the reason for the initial conclusion that oscillometric devices were inaccurate in cats.

Studies evaluating the performance of the Cardell Veterinary Blood Pressure monitor in cats demonstrated similar results. The first study evaluated the monitor in 6 isoflurane-anesthetized cats over 3 BP ranges: mean arterial BP > 140 mmHg, 60 to 140 mmHg, and < 60 mmHg. It was found that the Cardell monitor provided a good estimate of mean and diastolic arterial BP but tended to underestimate systolic arterial BP, which became worse as BP increased: the oscillometric cuff was placed on the antebrachium over the median artery and compared to direct arterial BP readings from the femoral artery (16) (Table 2). The same study also identified no effect of clipping the hair on the limb prior to placement of the oscillometric BP cuff. Evaluation of the Cardell monitor with the cuff also placed on the antebrachium over the median artery and compared to direct arterial BP readings from the dorsal pedal artery also showed poor agreement, but the monitor came closest to correctly estimating mean arterial BP (35). The bias was smallest for mean arterial BP (Table 2); however, the limits of agreement were very wide (−31.6 to 24.5 mmHg), and similar findings for systolic and diastolic arterial BP values were identified (35). Placement of the cuff on the base of the tail and comparison to direct arterial BP readings from the femoral artery in 6 anesthetized cats met the AHCP-VBPS validation criteria for bias, limits of agreement, and correlation coefficient for mean arterial BP evaluation using the Cardell monitor (36) (Table 2).

The petMAP has been evaluated in anesthetized cats in 2 studies (35,37), both of which compared the NIBP measurements to direct arterial BP readings from the dorsal pedal artery. In both studies, the monitor performed poorest with estimation of systolic arterial BP, regardless of the cuff being placed on the antebrachium or the tail (35,37). The monitor did meet some of the AHCP-VBPS validation criteria (Table 2).

Oscillometry in equine species

Oscillometric BP monitoring techniques have only recently been evaluated in the veterinary literature in horses, with 6 papers being published in the last 3 y (38–43). Four oscillometric

Table 4. Published studies evaluating oscillometric non-invasive blood pressure measurement technique in foals and horses in comparison with the American College of Veterinary Internal Medicine (ACVIM) criteria for technique validation.

Parameter	Number of animals	Bias (mmHg)	Standard deviation (mmHg)	Correlation	< 10 mmHg (% of measurements)	< 20 mmHg (% of measurements)
ACVIM criteria	8	≤ 10	≤ 15	≥ 0.9	≥ 50	≥ 80
Oscillometry						
Anesthetized foals (45) Direct BP source: Metatarsal artery NIBP cuff location: Coccygeal artery Oscillometric technology: ProPaq Encore						
SAP		8.0				
MAP	6	−1.1	NR	NR	NR	NR
DAP		−1.3				
Conscious foals (45) Direct BP source: Metatarsal artery NIBP cuff location: Coccygeal artery Oscillometric technology: ProPaq Encore						
SAP		15.0				
MAP	4	−0.5	NR	NR	NR	NR
DAP		−0.4				
Anesthetized foals (44) Direct BP source: Metatarsal artery NIBP cuff location: Coccygeal artery Oscillometric technology: Cardell Veterinary Monitor 9402, CAS Medical						
MAP	10	−0.5	8.8	NR	NR	NR
Anesthetized foals (44) Direct BP source: Metatarsal artery NIBP cuff location: Median artery Oscillometric technology: Cardell Veterinary Monitor 9402, CAS Medical						
MAP	10	−10.8	8.8	NR	NR	NR
Anesthetized foals (44) Direct BP source: Metatarsal artery NIBP cuff location: Metatarsal artery Oscillometric technology: Cardell Veterinary Monitor 9402, CAS Medical						
MAP	10	−4.1	8.8	NR	NR	NR
Anesthetized horses (41) Direct BP source: Transverse facial artery NIBP cuff location: Coccygeal artery Oscillometric technology: Cardell 9401 BP Monitor						
MAP	6	0.39	2.96	NR	NR	NR
Conscious horses (40) Direct BP source: Facial or transverse facial artery NIBP cuff location: Coccygeal artery Oscillometric technology: Datex-Ohmeda B30, GE Healthcare						
SAP		−8	17			
MAP	7	−4	10	NR	NR	NR
DAP		−7	14			
Anesthetized horses (56) Direct BP source: Facial or transverse facial artery NIBP cuff location: Coccygeal artery Oscillometric technology: Cardell Veterinary Monitor 9402, CAS Medical						
SAP		3.3	8.5	0.92	80	95
MAP	8	0.5	12.0	0.81	55	95
DAP		0.6	11.6	0.76	70	90

Table 4. Published studies evaluating oscillometric non-invasive blood pressure measurement technique in foals and horses in comparison with the American College of Veterinary Internal Medicine (ACVIM) criteria for technique validation *(continued)*.

Parameter	Number of animals	Bias (mmHg)	Standard deviation (mmHg)	Correlation	< 10 mmHg (% of measurements)	< 20 mmHg (% of measurements)
ACVIM criteria	8	≤ 10	≤ 15	≥ 0.9	≥ 50	≥ 80
Conscious horses (56)						
Direct BP source: Facial or transverse facial artery						
NIBP cuff location: Coccygeal artery						
Oscillometric technology: Cardell Veterinary Monitor 9402, CAS Medical						
SAP		30.0	24.9	0.84	17	34
MAP	8	16.4	16.6	0.88	31	72
DAP		8.9	17.5	0.84	52	79
Anesthetized horses (43)						
Direct BP source: Facial or metatarsal artery						
NIBP cuff location: Coccygeal artery						
Oscillometric technology: Datex Ohmeda S/5 Compact						
SAP		2.96	12.69			
MAP	40	3.78	8.77	NR	NR	NR
DAP		2.30	8.65			

NR — Not reported. Highlighted values meet validation criteria.

BP monitors have been evaluated in horses. In a clinical study of anesthetized horses, the Sentinel Blood Pressure monitor (Sentinel Healthcare, Seattle, Washington, USA) was found to result in a high degree of variability and was not recommended as an alternative to direct arterial BP monitoring in horses (38) (Table 4). The authors recommended that in laterally recumbent horses the oscillometric cuff should be placed on the tail and in dorsally recumbent horses the oscillometric cuff should be placed on the cannon bone as these cuff placements resulted in the lowest difference between NIBP readings compared to direct arterial BP values; however, the study did not report a Bland-Altman analysis (38). One study that evaluated 17 combinations of cuff size and measurement location *via* oscillometry using the Cardell Veterinary Blood Pressure monitor in anesthetized horses, reported that only when the cuff was placed on the tail and had a cuff width of 25% of the tail circumference did the monitor provide mean arterial BP measurements that were comparable to direct arterial BP readings taken from the transverse facial artery, reporting an acceptable bias of 0.39 mmHg and SD of 2.96 mmHg, which both meet the AHCP-VBPS validation criteria (41) (Table 4). The oscillometric technology within the Datex Ohmeda Multiparameter monitor (GE Healthcare, St. Louis, Missouri, USA) has been evaluated in standing (40) and anesthetized (43) horses, with placement of the oscillometric cuff over the coccygeal artery at the base of the tail (Table 4). The study in conscious, standing horses varied BP pharmacologically and utilized the facial or transverse facial artery to measure direct arterial BP. A correction factor of +0.736 mmHg/cm difference in height was applied (40). The authors identified that the monitor was not reliable during periods of second-degree atrioventricular block, a common arrhythmia in horses, but may be acceptable to measure mean arterial BP in standing horses (40). The authors did not recommend the use of the monitor in anesthetized horses after comparison to direct arterial BP values measured from the facial or metatarsal artery due to the wide limits of agreement (43) (Table 4). In both studies only bias and SD were reported; however, the Datex Ohmeda monitor met the AHCP-VBPS validation criteria for mean and diastolic arterial BP (40,43).

In anesthetized and conscious foals 2 studies found oscillometry to provide an acceptable estimate of mean arterial BP when measured from the tail in comparison to direct mean arterial BP measured from the metatarsal artery regardless of the monitor used (ProPaq Encore, Cardell or Dinamap) (44,45) (Table 4). The lowest bias (−1.07 mmHg) and narrowest limits of agreement (−9.39 to 7.25 mmHg) were identified for the ProPaq Encore monitor (45), although all 3 monitors were clinically acceptable for estimation of mean arterial BP.

Oscillometry in ruminant species

The authors are aware of only 4 studies evaluating NIBP measurement techniques in ruminant species; all of which evaluated oscillometry in anesthetized animals using 3 different monitors (46–49). The Datascope Passport Monitor was evaluated in anesthetized alpacas, llamas (46), and sheep, goats, and cattle (48) comparing NIBP measured *via* a cuff placed on the metacarpal artery to direct arterial BP readings from the auricular artery in most animals, or the medial saphenous artery of some camelids (Table 5). Both studies identified significant variability and wide limits of agreement in NIBP measurements, leading the authors to conclude that oscillometry cannot be recommended as an alternative to invasive BP monitoring in these species (46,48). Two other monitors have been evaluated in sheep anesthetized for concurrent prospective surgical studies (47,49). The petMAP oscillometric BP monitor demonstrated similar findings in anesthetized sheep with narrow limits of agreement when the BP cuff was placed over the metatarsal artery or metacarpal artery and compared to direct arterial BP readings from the auricular artery (49), but did not meet the AHCP-VBPS validation criteria for other parameters. Good agreement was also found for non-invasive oscillometric BP measured in sheep by the Surgivet V9203 monitor using a cuff

Table 5. Published studies evaluating oscillometric non-invasive blood pressure measurement in domestic ruminants in comparison to the American College of Veterinary Internal Medicine (ACVIM) criteria for technique validation.

Parameter	Number of animals	Bias (mmHg)	Standard deviation (mmHg)	Correlation	< 10 mmHg (% of measurements)	< 20 mmHg (% of measurements)
ACVIM criteria	8	≤ 10	≤ 15	≥ 0.9	≥ 50	≥ 80
Oscillometry						
Anesthetized camelids (46)						
Direct BP source: Auricular or medial saphenous artery						
NIBP cuff location: Metacarpal artery						
Oscillometric technology: Datascope Passport						
SAP		−9.9	21.9			
MAP	20	−2.9	17.0	NR	NR	NR
DAP		1.8	15.6			
Anesthetized sheep (47)						
Direct BP source: Auricular artery						
NIBP cuff location: Median or metatarsal artery						
Oscillometric technology: SurgiVet Advisor Vital Signs monitor V9203, Smiths Medical PM						
SAP		3	8	0.87	79	97
MAP	20	−7	6	0.90	69	100
DAP		−10	7	0.86	48	92
Anesthetized sheep and goats (48)						
Direct BP source: Auricular artery						
NIBP cuff location: Metacarpal artery						
Oscillometric technology: Datascope Passport						
SAP		0	16			
MAP	20	8	13	NR	NR	NR
DAP		13	16			
Anesthetized cattle < 150 kg (48)						
Direct BP source: Auricular artery						
NIBP cuff location: Metacarpal artery						
Oscillometric technology: Datascope Passport						
SAP		0	19			
MAP	20	4	16	NR	NR	NR
DAP		6	18			
Anesthetized cattle > 150 kg (48)						
Direct BP source: Auricular artery						
NIBP cuff location: Metacarpal artery						
Oscillometric technology: Datascope Passport						
SAP		−18	32			
MAP	20	−5	28	NR	NR	NR
DAP		7	29			
Anesthetized sheep (49)						
Direct BP source: Auricular artery						
NIBP cuff location: Metacarpal artery						
Oscillometric technology: PetMap, Ramsey Medical						
SAP		0	12		70.2	91.7
MAP	13	−10	11	0.87	44.6	NR
DAP		−16	13		NR	NR
Anesthetized sheep (49)						
Direct BP source: Auricular artery						
NIBP cuff location: Metatarsal artery						
Oscillometric technology: PetMap, Ramsey Medical						
SAP		12	13		NR	NR
MAP	13	−4	12	0.83	61.2	91.7
DAP		−11	14		NR	NR

NR — not reported. Highlighted values meet validation criteria.

placed on the median artery or metatarsal artery in comparison to direct arterial BP readings from the auricular artery (47) (Table 5). In this study, the Surgivet V9203 monitor came very close to meeting all the AHCP-VBPS validation criteria.

Oscillometry in exotic species

In 2 previously mentioned studies in avian species (22,23), the oscillometric Cardell Veterinary Blood Pressure monitor failed to provide any measurements in either of the evaluated locations and was therefore excluded from statistical analysis, leading the authors to conclude that the use of this monitor could not be recommended in avian species (22). In conscious and anesthetized red-tailed hawks *(Buteo jamaicensis)*, the study also demonstrated that the Cardell monitor performed poorly, with 54% of measurements failing to return a reading; thus the authors did not perform a statistical analysis (23).

It has been reported that NIBP measurement obtained *via* the oscillometric Dash 3000 Patient Monitor in anesthetized rabbits demonstrated better correlation with direct arterial BP readings from the abdominal aorta, although it tended to underestimate the BP measurements. Unfortunately, this study does not report numerical values for level of agreement making conclusions regarding the monitor's suitability as a substitute for direct arterial BP monitoring difficult (50).

Oscillometric BP measurement in anesthetized boid snakes using the Cardell Veterinary Monitor with the BP cuff placed just distal to the vent was found to underestimate mean and diastolic arterial BP, and overestimate systolic arterial BP, in comparison with direct arterial BP readings from the aortic arch (51). The significant bias $\pm$ SD (3.71 $\pm$ 15.29 mmHg for systolic arterial BP, −14.75 $\pm$ 10.37 mmHg for mean arterial BP, and −26.46 $\pm$ 7.70 mmHg for diastolic arterial BP) and wide limits of agreement (−26.26 to 33.69 mmHg for systolic arterial BP, −35.08 to 5.59 mmHg for mean arterial BP, and −41.56 to −11.37 mmHg for diastolic arterial BP) led the authors to conclude that this measurement technique could not be used as a substitute for invasive BP monitoring in this species (51). The performance of the monitor in this species did not meet any of the AHCP-VBPS validation criteria.

High definition oscillometry in veterinary species

With claims of increased accuracy of high definition oscillometric monitors (HDO), studies have begun to be published evaluating its use in canine patients (10,52). However, the technology has not been found to perform much better than traditional oscillometric monitors. In anesthetized dogs, and in comparison to direct arterial BP readings from the dorsal pedal artery, HDO demonstrated better agreement with mean arterial BP while performing poorest when measuring systolic arterial BP. While both studies identified an acceptable bias for mean arterial BP [−0.5 mmHg (10) and −1 mmHg (52)], the wide limits of agreement in both [−20 to 20 mmHg (10) and −22 to 19 mmHg (52)] demonstrated poor precision of the monitor. Similar results were identified for systolic and diastolic arterial BP values. The HDO was also found to overestimate hypotension, whether the oscillometric cuff was placed over the coccygeal artery (52) or the median artery (10). The monitor only met AHCP-VBPS validation criteria for the bias from these 2 studies (Table 6).

In awake cats, the monitor reportedly performed well when measuring systolic arterial BP with the oscillometric cuff placed over the coccygeal artery, in comparison with direct arterial BP readings measured from the femoral artery (53). The authors concluded that their study findings validate this monitor for measurement of systolic arterial BP in cats; however, the monitor cannot in fact be validated based on the results of this study because it failed to meet the criteria for the minimum number of animals (3) (Table 6). Furthermore, the authors do not report bias or limits of agreement for mean arterial BP measured *via* HDO in comparison with direct arterial BP values. In anesthetized cats, HDO overestimated the degree of hypotension, which has important clinical implications, when the cuff was placed on the antebrachium over the median artery and compared to direct arterial BP readings taken from the dorsal pedal artery. Despite an acceptable bias, the limits of agreement were very wide (−52.9 to 32.2 mmHg for systolic arterial BP, −32.9 to 51.2 mmHg for mean arterial BP, and −32.1 to 58.0 mmHg for diastolic arterial BP), similar to the results in dogs, demonstrating poor precision of the monitor in cats as well (35). An additional study evaluating HDO in anesthetized cats also concluded that the device overestimated hypotension (54). This latter study was in comparison to Doppler ultrasonic flow detection rather than direct arterial BP readings and therefore final conclusions are difficult. Based on the current studies, the monitor does not meet the AHCP-VBPS validation criteria for NIBP evaluation in cats (Table 6).

High definition oscillometric monitor (HDO) readings measured from the coccygeal artery have been recently evaluated in anesthetized cheetahs *(Acinonyx jubatus)* in comparison with direct arterial BP readings measured from the femoral or dorsal pedal artery (55). The best agreement was identified with directly measured dorsal pedal arterial BP and HDO provided the best estimate of mean arterial BP; however, the limits of agreement in the study demonstrate that the precision of the monitor is also poor in this species (55). The monitor did meet a number of AHCP-VBPS validation criteria (Table 6).

In horses, HDO has only been evaluated in 2 studies (39,42). One study evaluated the performance of the HDO during hypotension (mean arterial BP $<$ 60 mmHg), normotension (mean arterial BP 60 to 110 mmHg) and hypertension (mean arterial BP $>$ 110 mmHg) *via* pharmacologic manipulation of arterial BP in healthy adult horses (39). This study identified that the monitor demonstrated the best agreement between systolic and mean arterial BP measured non-invasively *via* the coccygeal arterial and directly *via* the facial artery during normotension, but underestimated hypertension and overestimated hypotension. This led the authors to conclude that the monitor is unreliable during hemodynamic instability and direct arterial BP monitoring in horses was recommended (39). Recently, the monitor's performance was evaluated during inhalant *versus* total intravenous anesthesia and it was found that variability of non-invasively measured BP was greater during total intravenous anesthesia, which is of important clinical relevance in horses,

Table 6. Published studies evaluating high definition oscillometric non-invasive blood pressure measurement in comparison with the American College of Veterinary Internal Medicine (ACVIM) criteria for technique validation.

Parameter	Number of animals	Bias (mmHg)	Standard deviation (mmHg)	Correlation	< 10 mmHg (% of measurements)	< 20 mmHg (% of measurements)
ACVIM criteria	8	≤ 10	≤ 15	≥ 0.9	≥ 50	≥ 80
Anesthetized dogs (10)						
Direct BP source: Dorsal pedal artery						
NIBP cuff location: Median or coccygeal artery						
SAP		7			36	70
MAP	20	−0.5	NR	NR	67	95
DAP		−7			52	87
Anesthetized dogs (52)						
Direct BP source: Dorsal pedal artery						
NIBP cuff location: Coccygeal artery						
SAP		5				
MAP	50	−1	NR	NR	NR	NR
DAP		3				
Conscious cats (53)						
Direct BP source: Femoral artery						
NIBP cuff location: Coccygeal artery						
SAP		−2.2	1.1	0.92	88	96
MAP	6	NR	NR	NR	NR	NR
DAP		22.3	1.6	0.81	13	38
Anesthetized cheetahs (55)						
Direct BP source: Dorsal pedal artery						
NIBP cuff location: Coccygeal artery						
SAP		−3.2	18.2	0.88	33.8	73.0
MAP	8	1.1	12.4	0.92	66.9	95.3
DAP		−0.04	14.6	0.88	55.4	89.9
Anesthetized cheetahs (55)						
Direct BP source: Femoral artery						
NIBP cuff location: Coccygeal artery						
SAP		−10.4	13.8	0.93	38.9	77.8
MAP	8	−1.2	11.1	0.95	75.9	96.3
DAP		−1.8	13.4	0.91	60.2	92.6
Anesthetized horses (39)						
Direct BP source: Facial artery						
NIBP cuff location: Coccygeal artery						
MAP < 60 mmHg						
SAP		−20.0	20.9			
MAP		−11.4	19.6			
DAP		−4.7	20.1			
MAP 60–110 mmHg						
SAP		0.1	19.6			
MAP	7	0.5	14.0	NR	NR	NR
DAP		4.7	15.6			
MAP > 110 mmHg						
SAP		26.1	37.3			
MAP		4.2	19.4			
DAP		1.5	16.8			
Inhalant-anesthetized horses (42)						
Direct BP source: Facial artery						
NIBP cuff location: Coccygeal artery						
SAP		3.5	13.6		63.3	
MAP	24	6.3	10.0	NR	75.0	NR
DAP		7.8	13.6		59.5	
Injectable-anesthetized horses (42)						
Direct BP source: Facial artery						
NIBP cuff location: Coccygeal artery						
SAP		3.8	28.3		37.2	
MAP	24	4.0	23.3	NR	33.6	NR
DAP		4.0	21.2		38.7	

NR — Not reported. Highlighted values meet validation criteria.

although the authors did not advise against its use (42). The limits of agreement from both studies demonstrate poor precision of the monitor however; the monitor did meet the AHCP-VBPS validation criteria for use in isoflurane-anesthetized horses for those values that were reported (Table 6).

In canine patients, Doppler provides an estimate of systolic arterial BP but it is likely to poorly predict hypotension in anesthetized dogs (11) and should not be used as a substitute for direct arterial BP measurement in high-risk cases. In dogs weighing < 5 kg, Doppler provides a better estimate of direct systolic arterial BP but it is likely to overestimate it (12,13). In cats, Doppler provides a good estimate of direct mean arterial BP (14,15). Doppler may, or may not, have clinical utility for NIBP measurement in exotic species. In rabbits, Doppler provides a good estimate of direct systolic arterial BP and performs well in identifying hypotension (24). Doppler has not been well-studied in horses or other large animal species.

Oscillometric BP measurement depends significantly on the monitor that is being used. The Cardell Veterinary Blood Pressure monitor provides a good estimate of mean arterial BP especially during normotension in dogs (28) and cats (16,35). The Surgivet monitor also provides a good estimate of mean arterial BP and accurately predicts hypotension in canine patients (31,32) and good agreement with direct arterial BP readings in ruminant species (47). The petMAP monitor has poor precision in studies evaluating its use in dogs (8,29,30), cats (35,37), and ruminant species (49), and cannot be recommended for clinical use. In large animal species, oscillometric BP monitors in general demonstrate a high degree of variability and are not appropriate substitutes for direct arterial BP monitoring (41,43,46,48,49). In adult horses, oscillometric cuff placement over the coccygeal artery at the base of the tail (40) and in foals oscillometric cuff placement over the metatarsal artery (44,45) provide the most appropriate location for estimation of mean arterial BP. In the few studies evaluating oscillometric BP measurement in exotic species, the technology performs poorly (22,23,51) and cannot be recommended as a substitute for direct arterial BP evaluation.

With respect to HDO, the performance of this technology does not differ much from that of traditional oscillometric monitors, demonstrating the best agreement with direct mean arterial BP and the poorest agreement with direct systolic arterial BP (52,57). High definition oscillometric monitors demonstrate (HDO) consistently poor precision across species in which it has been evaluated (10,35,39,42,52,53,55). Of significant clinical importance, in anesthetized dogs (10,52), cats (35,54), and horses (39,42), HDO has been consistently found to overestimate arterial BP during periods of hypotension meaning that significantly low arterial BP may go unidentified if this monitor is utilized as the sole agent for trending arterial BP values. CVJ

References

1. Haskins S. Monitoring anesthetized patients. In: Grimm KA, Lamont LA, Tranquilli WJ, Greene SA, Robertson SA, eds. Lumb and Jones Veterinary Anesthesia and Analgesia. 5th ed. Ames, Iowa: Wiley Blackwell, 2015:86–113.
2. Clarke KW, Trim CM, Hall LW. Patient monitoring and clinical measurement. In: Clarke KW, Trim CM, Hall LW, eds. Veterinary Anaesthesia. 11th ed. St. Louis, Missouri: Elsevier, 2014:30–38.
3. Brown S, Atkins R, Bagley R, et al. Guidelines for the identification, evaluation and management of systemic hypertension in dogs and cats. J Vet Intern Med 2007;21:542–558.
4. Skelding A, Valverde A. Non–invasive blood pressure measurement in animals: Part 1 — Techniques for measurement and validation of non-invasive devices. Can Vet J 2020;61:368–374.
5. Stepien RL, Rapoport GS. Clinical comparison of three methods to measure blood pressure in nonsedated dogs. J Am Vet Med Assoc 1999; 215:1623–1628.
6. Haberman CE, Kang CW, Morgan JD, Brown SA. Evaluation of oscillometric and Doppler ultrasonic methods of indirect blood pressure estimation in conscious dogs. Can J Vet Res 2006;70:211–217.
7. Bosiack AP, Mann FA, Dodam JR, Wagner-Mann CC, Branson KR. Comparison of ultrasonic Doppler flow monitor, oscillometric, and direct arterial blood pressure measurements in ill dogs. J Vet Emerg Crit Care 2010;20:207–215.
8. Vachon C, Belanger MC, Burns PM. Evaluation of oscillometric and Doppler ultrasonic devices for blood pressure measurements in anesthetized and conscious dogs. Res Vet Sci 2014;97:111–117.
9. Garofalo NA, Teixera Neto FJ, Alvaides RK, de Oliveira FA, Pignaton W, Pinheiro RT. Agreement between direct, oscillometric and Doppler ultrasound blood pressures using three different cuff positions in anesthetized dogs. Vet Anaesth Analg 2012;39:324–334.
10. Seliskar A, Zrimsek P, Sredensek J, Petrič AD. Comparison of high definition oscillometric and Doppler ultrasound devices with invasive blood pressure in anaesthetized dogs. Vet Anaesth Analg 2013;40:21–27.
11. Bourazak LA, Hofmeister EH. Bias, sensitivity, and specificity of Doppler ultrasonic flow detector measurement of blood pressure for detecting and monitoring hypotension in anesthetized dogs. J Am Vet Med Assoc 2018;253:1433–1438.
12. Kennedy MJ, Barletta M. Agreement between Doppler and invasive blood pressure monitoring in anesthetized dogs weighing < 5 kg. J Am Anim Hosp Assoc 2015;51:300–305.
13. Moll X, Aguilar A, Garcia F, Ferrer R, Andaluz A. Validity and reliability of Doppler ultrasonography and direct arterial blood pressure measurement in anaesthetized dogs weighing less than 5 kg. Vet Anaesth Analg 2018;45:135–144.
14. Caulkett NA, Cantwell SL, Houston DM. A comparison of indirect blood pressure monitoring techniques in the anesthetized cat. Vet Surg 1998;27:370–377.
15. Grandy JL, Dunlop CI, Hodgson DS, Curtis CR, Chapman PL. Evaluation of the Doppler ultrasonic method of measuring systolic arterial blood pressure in cats. Am J Vet Res 1992;53:1166–1169.
16. Pedersen KM, Butler MA, Ersbøll AK, Pedersen HD. Evaluation of an oscillometric blood pressure monitor for use in anesthetized cats. J Am Vet Med Assoc 2002;221:646–650.
17. Haberman CE, Morgan JD, Kang CW, Brown SA. Evaluation of Doppler ultrasonic and oscillometric methods of indirect blood pressure measurements in cats. Intern J Appl Res Vet Med 2004;2:279–289.
18. da Cunha AF, Saile K, Beaufrère H, Wolfson W, Seaton D, Acierno MJ. Measuring the level of agreement between values obtained by directly measured blood pressure and ultrasonic Doppler flow detector in cats. J Vet Emerg Crit Care 2014;24:272–278.
19. Binns SH, Sisson D, Buoscio DA, Schaeffer DJ. Doppler ultrasonographic, oscillometric, sphygmomanometric and photoplethysmographic techniques for noninvasive blood pressure measurement in anesthetized cats. J Vet Int Med 1995;9:405–414.
20. Zeugswetter FK, Tichy A, Weber K. Radial vs coccygeal artery Doppler blood pressure measurement in conscious cats. J Feline Med Surg 2018; 20:968–972.
21. Bailey JE, Dunlop CI, Chapman PL, et al. Indirect Doppler ultrasonic measurement of arterial blood pressure results in a large measurement error in dorsally recumbent anaesthetized horses. Equine Vet J 1994; 26:70–73.
22. Acierno MJ, da Cunha A, Smith J, et al. Agreement between direct and indirect blood pressure measurements obtained from anesthetized Hispaniolan Amazon parrots. J Am Vet Med Assoc 2008;233: 1587–1590.
23. Zehnder AM, Hawkins MG, Pascoe PJ, Kass PH. Evaluation of indirect blood pressure monitoring in awake and anesthetized red-tailed hawks *(Buteo jamaicensis)*: Effects of cuff size, cuff placement, and monitoring equipment. Vet Anaesth Analg 2009;36:464–479.
24. Harvey L, Knowles T, Murison PJ. Comparison of direct and Doppler arterial blood pressure measurements in rabbits during isoflurane anesthesia. Vet Anaesth Analg 2012;39:174–184.

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25. Sawyer DC, Guikema AH, Siegel EM. Evaluation of a new oscillometric blood pressure monitor in isoflurane anesthetized dogs. Vet Anaesth Analg 2004;31:27–39.
26. Gains MJ, Grodecki KM, Jacobs RM, Dyson D, Foster RA. Comparison of direct and indirect blood pressure measurements in anesthetized dogs. Can J Vet Res 1995;59:238–240.
27. Bodey AR, Michell AR, Bovee KC, Buranakurl C, Garg T. Comparison of direct and indirect (oscillometric) measurement of arterial blood pressure in conscious dogs. Res Vet Sci 1996;61:17–21.
28. McMurphy RM, Stoll MR, McCubrey R. Accuracy of an oscillometric blood pressure monitor during phenylephrine induced hypertension in dogs. Am J Vet Res 2006;67:1541–1545.
29. Shih A, Robertson S, Vigani A, da Cunha A, Pablo L, Bandt C. Evaluation of an indirect oscillometric blood pressure monitor in normotensive and hypotensive anesthetized dogs. J Vet Emerg Crit Care 2010;20:313–318.
30. Acierno MJ, Fauth E, Mitchell MA, da Cunha A. Measuring the level of agreement between directly measured blood pressure and pressure readings obtained with a veterinary-specific oscillometric unit in anesthetized dogs. J Vet Emerg Crit Care 2013;23:37–40.
31. Deflandre CJA, Hellebrekers LJ. Clinical evaluation of the Surgivet V60046, a noninvasive blood pressure monitor in anaesthetized dogs. Vet Anaesth Analg 2008;35:13–21.
32. Drynan EA, Raisis AL. Comparison of invasive versus noninvasive blood pressure measurements before and after hemorrhage in anesthetized greyhounds using the Surgivet 9203. J Vet Emerg Crit Care 2013;23: 523–531.
33. Ramos SJ, da Cunha AF, Domingues M, Shelby AM, Stout RW, Acierno MJ. Comparison of blood pressure measurements of anesthetized dogs obtained noninvasively with a cylindrical blood pressure cuff and an anatomically modified conical blood pressure cuff. Am J Vet Res 2016; 77:59–64.
34. da Cunha AF, Ramos SJ, Domingues, et al. Agreement between two oscillometric blood pressure technologies and invasively measured arterial pressure in the dog. Vet Anaesth Analg 2016;43:199–203.
35. Acierno MJ, Seaton D, Mitchell MA, da Cunha A. Agreement between directly measured blood pressure and pressures obtained with three veterinary-specific oscillometric units in cats. J Am Vet Med Assoc 2010; 237:402–406.
36. Zwijnenberg RJ, del Rio CL, Cobb RM, Ueyama Y, Muir WW. Evaluation of oscillometric and vascular access port arterial blood pressure measurement techniques versus implanted telemetry in anesthetized cats. Am J Vet Res 2011;72:1015–1021.
37. Cerejo SA, Teixeira Neto FJ, Garofalo NA, Rodrigues JC, Celeita-Rodríguez N, Lagos-Carvajal AP. Comparison of two species-specific oscillometric blood pressure monitors with direct blood pressure measurement in anesthetized cats. J Vet Emerg Crit Care 2017;27:409–418.
38. Hatz LA, Hartnack S, Kummerle J, Hässig M, Bettschart-Wolfensberger R. A study of measurement of noninvasive blood pressure with the oscillometric device, Sentinel, in isoflurane-anaesthetized horses. Vet Anaesth Analg 2015;42:369–376.
39. Tunsmeyer J, Hopster K, Feige K, Kästner SB. Agreement of high definition oscillometry with direct arterial blood pressure measurement at different blood pressure ranges in horses under general anaesthesia. Vet Anaesth Analg 2015;42:286–291.
40. Olsen E, Pedersen TLS, Robinson R, Haubro Andersen P. Accuracy and precision of oscillometric blood pressure in standing conscious horses. J Vet Emerg Crit Care 2016;26:85–92.
41. Tearney CC, Guedes AGP, Brosnan RJ. Equivalence between invasive and oscillometric blood pressures at different anatomic locations in healthy normotensive anaesthestized horses. Equine Vet J 2016;48: 357–361.
42. Duke-Novakovski T, Ambros B, Feng C, Carr AP. The effect of anesthetic drug choice on accuracy of high-definition oscillometry in laterally recumbent horses. Vet Anaesth Analg 2017;44:589–593.
43. Yamaoka TT, Flaherty D, Pawson P, Scott M, Auckburally A. Comparison of arterial blood pressure measurements obtained invasively or oscillometrically using a Datex S/5 Compact monitor in anaesthetized adult horses. Vet Anaesth Analg 2017;44:492–501.
44. Giguere S, Knowles HA Jr, Valverde A, Bucki E, Young L. Accuracy of indirect measurement of blood pressure in neonatal foals. J Vet Intern Med 2005;19:571–576.
45. Nout YS, Corley KTT, Donaldson LL, Furr MO. Indirect oscillometric and direct blood pressure measurements in anesthetized and conscious neonatal foals. J Vet Emerg Crit Care 2002;12:75–80.
46. Aarnes TK, Hubbell JAE, Lerche P, Bednarski RM. Comparison of invasive and oscillometric blood pressure measurement techniques in anesthetized camelids. Can Vet J 2012;53:881–885.
47. Trim CM, Hofmeister EH, Peroni JF, Thoresen M. Evaluation of an oscillometric blood pressure monitor for use in anesthetized sheep. Vet Anaesth Analg 2013;40:e31–e39.
48. Aarnes TK, Hubbell JAE, Lerche P, Bednarski RM. Comparison of invasive and oscillometric blood pressure measurement techniques in anesthetized sheep, goats, and cattle. Vet Anaesth Analg 2014;41:174–185.
49. Almeida D, Barletta M, Mathews L, Graham L, Quandt J. Comparison between invasive blood pressure and a non-invasive blood pressure monitor in anesthetized sheep. Res Vet Sci 2014;97:582–586.
50. Ypsilantis P, Didilis VN, Poulitou M, Bougioukas I, Bougioukas G, Simopoulos C. A comparative study of invasive and oscillometric methods of arterial blood pressure measurement in the anesthetized rabbit. Res Vet Sci 2005;78:269–275.
51. Chinnadurai SK, Wrenn A, DeVoe RS. Evaluation of noninvasive oscillometric blood pressure monitoring in anesthetized boid snakes. J Am Vet Med Assoc 2009;234:625–630.
52. Rysnik MK, Cripps P, Iff I. A clinical comparison between non-invasive blood pressure monitor using high definition oscillometry (Memodiagnostic MD 15/90 Pro) and invasive arterial blood pressure measurement in anaesthetized dogs. Vet Anaesth Analg 2013;40: 503–511.
53. Martel E, Egner B, Brown SA, et al. Comparison of high-definition oscillometry — A non-invasive technology for arterial blood pressure measurement — with a direct invasive method using radio-telemetry in awake healthy cats. J Feline Med Surg 2013;15:1104–1113.
54. Petric AD, Petra Z, Jerneja S, Alenka S. Comparison of high definition oscillometric and Doppler ultrasonic devices for measuring blood pressure in anaesthetized cats. J Feline Med Surg 2010;12:731–737.
55. Cassia EVS, Boswood A, Tordiffe ASW. Comparison of high definition oscillometric and direct arterial blood pressure measurement in anesthetized cheetahs *(Acinonyx jubatus)*. J Zoo Wildl Med 2015;46:506–516.
56. Heliczer N, Lorello O, Casoni D, Navas de Solis C. Accuracy and precision of noninvasive blood pressure in normo-, hyper-, and hypotensive standing and anesthetized adult horses. J Vet Int Med 2016;30:866–872.