Non–invasive blood pressure measurement in animals: Part 1 — Techniques for measurement and validation of non-invasive devices

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Abstract — Arterial blood pressure is a common parameter evaluated in conscious and anesthetized veterinary species. Non-invasive blood pressure measurement techniques, such as Doppler ultrasonic flow detector and oscillometry, are attractive in certain animals 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 summarizes the current techniques available to non-invasively measure arterial blood pressure in animals and discusses 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 data from non-invasive blood pressure devices.

Résumé — Mesures de la pression sanguine chez les animaux de manière non-invasive : Partie 1 – Techniques pour mesurer et validation d'appareils non-invasifs. La pression sanguine artérielle est un paramètre fréquemment évalué chez les espèces animales conscientes et anesthésiées. Des techniques non-invasives de mesure de la pression sanguine, telles que le détecteur ultra-sonique de flot Doppler et l'oscillométrie, sont attirantes chez certains animaux étant donné leur disponibilité et facilité d'utilisation. La plus grande limitation au suivi non-invasif de la pression sanguine peut être son imprécision, particulièrement chez les patients hypotensifs ou hypertensifs et chez certaines espèces. La partie 1 de cette revue en deux parties résume les techniques présentement disponibles pour mesurer de manière non-invasive la pression sanguine artérielle chez des animaux et discute la validation d'équipements non-invasifs. La partie 2 résume la littérature vétérinaire qui évalue l'utilisation de techniques de mesure non-invasives de la pression sanguine chez des espèces conscientes et anesthésiées et développe des conclusions générales pour l'utilisation appropriée et l'interprétation des données obtenues d'équipements non-invasifs de mesure de la pression sanguine.

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Introduction

Part 1 of this 2-part review summarizes the non-invasive blood pressure (NIBP) techniques available to measure arterial blood pressure in animals and discusses validation of devices used for this purpose. Part 2 will summarize the veterinary literature that evaluates the use of NIBP measurement techniques in conscious and anesthetized animals and develops general conclusions for proper use of NIBP devices and interpretation of the measurements obtained from them.

Arterial blood pressure (BP) is a common parameter evaluated in conscious and anesthetized animals for various reasons. These reasons include monitoring disorders such as heart disease, renal disease, and endocrinopathies, assessment of an animal's physiological status and, most commonly, as a parameter to monitor the cardiovascular status of an animal under anesthesia.

Arterial BP is the force exerted by blood flow on the arterial wall (1). Systemic arterial BP can be divided into 3 components: systolic arterial BP, mean arterial BP, and diastolic arterial BP. Systolic arterial BP is the maximum intra-arterial pressure of each cardiac cycle; diastolic arterial BP is the minimum intra-arterial pressure preceding the next heart beat; and mean arterial BP is the average area under the pulse pressure waveform, which tends to be closer to the diastolic arterial BP because of the time spent in diastole during each cardiac cycle (2,3). Normal arterial BP values have been reported in a number of conscious and anesthetized veterinary species (Tables 1, 2).

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Table 1. Reported direct arterial blood pressure (mmHg) and cardiac index (mL/kg BW per minute) values in conscious and anesthetized [1.0 to 1.25 and 1.75 to 2.0 minimum alveolar concentration (MAC) of sevoflurane] in dogs and cats. Values reported as mean ± SD.

Species	Systolic	Mean	Diastolic	Cardiac index	Inhalant	Reference
Dogs						
Conscious	134 ± 17	96 ± 17	73 ± 7	95 ± 16	NA	(42)
1.0–1.25 MAC	104 ± 17	75 ± 10	60 ± 10	105 ± 32	Sevoflurane	(42)
1.75–2.0 MAC	79 ± 13	59 ± 10	46 ± 10	80 ± 32	Sevoflurane	(42)
Cats						
Conscious	126 ± 9	106 ± 10	91 ± 11		NA	(43)
	131 ± 8	113 ± 7	94 ± 7		NA	(44)
	136 ± 13	117 ± 12	101 ± 9	188 ± 64	NA	(45)
1.0 to 1.25 MAC	79 ± 7	61 ± 5	51 ± 5	258 ± 49	Sevoflurane	(46)
1.75 to 2.0 MAC	74 ± 7	56 ± 5	47 ± 7	205 ± 27	Sevoflurane	(46)

BW — body weight; NA — not applicable.

Arterial BP values can vary depending on the anatomic site from which they are measured, which has important considerations when evaluating NIBP measurement devices. Systolic arterial BP increases towards the periphery as a result of reflection of pressure waves from smaller arterioles due to a stronger muscular wall and higher resistance, whereas diastolic arterial BP decreases slightly, and mean arterial BP stays fairly constant (4). In anesthetized dogs, the systolic arterial BP from the dorsal pedal artery and femoral artery is higher than from the carotid artery (5), but variations in arterial pressure in smaller peripheral arteries also occur. For example, during normotension, the systolic arterial BP in anesthetized dogs is higher in the dorsal pedal artery than in the lingual artery (6) and in anesthetized horses, the systolic arterial BP tends to be higher in the metatarsal artery than in the facial artery and the transverse facial artery (7). The difference between systolic and diastolic arterial pressures is the pulse pressure. As a result of the increase in systolic arterial BP, the pulse pressure also increases from the aorta to the periphery. In humans this difference is, on average, 15 mmHg (8).

Mean arterial BP (MABP) is the product of cardiac output (CO) and total systemic vascular resistance (SVR); therefore, it is directly affected by these 2 factors.

$$\text{MABP} = \text{CO} \times \text{SVR} \qquad \textit{Equation 1}$$

This equation shows that alterations in vascular resistance could result in similar changes in mean arterial BP; even if cardiac output remains unchanged blood flow to tissues could be compromised. Clinically, mean arterial BP is more readily measured than CO, but when monitoring arterial BP it is important to take into consideration how changes in CO and SVR can impact the measured arterial BP value. Studies in anesthetized animals have shown that poor correlation exists between CO and arterial BP (9–11). This poor correlation is even more apparent with the administration of drugs that increase SVR, but do not result in a concomitant increase in CO. This is well-documented following the administration of α_2 agonists in small animal patients in which SVR increases resulting in an increase in arterial BP but CO decreases significantly (12). Increases in SVR and afterload can have detrimental effects on cardiac work and CO, especially if contractility is impaired or hypovolemia is present. Conversely, arterial BP values can be lower than normal values due to a decrease in SVR, as commonly occurs with the use of inhalational anesthetics or phenothiazines due to their vasodilatory properties. Cardiac output can still be within acceptable values because the decrease in afterload eases cardiac work (12) (Table 1).

Tissue demand for oxygen [oxygen consumption ($\dot{V}O_2$)] normally determines the amount of blood flow (CO) reaching the tissues; therefore, $\dot{V}O_2$ is the independent factor. The relationship between CO and $\dot{V}O_2$ is linear under physiological conditions, such as during periods of exercise in which enhanced tissue blood flow is required to satisfy the increased $\dot{V}O_2$. During general anesthesia with inhalational anesthetics at doses up to 2× the minimum alveolar concentration, there is a decrease in CO but also a decrease in $\dot{V}O_2$, such that tissue demand for oxygen remains fulfilled (13).

An appropriate value for mean arterial BP does not necessarily reflect adequate blood flow to peripheral tissues. Despite this, an association has been established in non-cardiac human patients between mean arterial BP values of < 55 mmHg, recorded during surgery, and the risk of developing acute kidney injury or myocardial injury after surgery (14). In contrast, septic human patients in an intensive care unit receiving titrated norepinephrine did not show any improvement in skin microcirculatory blood flow, urine output, or splanchnic perfusion, when the mean arterial BP was increased from 65 to 85 mmHg (15). These findings emphasize the importance of proper interpretation of arterial BP values, consideration of all factors that influence arterial BP as discussed, the age or health status of the patient, whether the patient is conscious, sedated, or anesthetized, and the pharmacological effects of drugs used prior to BP measurements. It has been shown that arterial BP values differ between conscious and anesthetized states as well as across veterinary species (Table 2), which is another important consideration when interpreting arterial BP values.

Validation of noninvasive blood pressure devices

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 a "gold standard" measurement technique. In human medicine, NIBP devices may

Table 2. Reported direct arterial blood pressure (mmHg) values in normal, awake veterinary species. Values reported as mean ± SD.

Species	Systolic	Mean	Diastolic	Catheter site (artery)	N	Reference
Dogs	154 ± 20	107 ± 11	84 ± 9	Femoral	27	(47)
	134 ± 17	96 ± 17	73 ± 7	Aorta	11	(42)
Cats	126 ± 9	106 ± 10	91 ± 11	Femoral	6	(43)
	130.9 ± 8.2	113.2 ± 7.2	94.4 ± 6.9	Carotid	17	(44)
Horses	169 ± 24.6	131.5 ± 18	110.4 ± 16.3	Coccygeal artery	8	(48)
Cattle	159.7 ± 11.3	127 ± 6.2	96.7 ± 8.6	Auricular	6	(49)
Elephants	178.6 ± 2.94	144.6 ± 2.90	118.7 ± 3.10	Auricular	15	(50)
Rabbits	68	57 ± 8.2	48	Auricular	14	(51)
Canada geese	177 ± 5.5	141 ± 5.2	112 ± 5.6	Dorsal metatarsal	6	(52)
Great horned owls	232 ± 37	203 ± 28	178 ± 25	Brachiocephalic	6	(53)
Red-tailed hawks	220 ± 51	187 ± 42	160 ± 45	Brachiocephalic	6	(53)

N — total number of animals.

be validated for accuracy using 1 of 3 outlined methods: the Association for the Advancement of Medical Instrumentation (AAMI) in the United States, adopted by the International Standards Organization (AAMI-ISO) in 2007, revised in 2013; the British Hypertension Society (BHS), revised in 1993; or the European Society of Hypertension International Protocol (ESH-IP), revised in 2010 (16). The ESH-IP protocol is an updated version of the BHS protocol, with more refined parameters and more stringent criteria to reflect advancements in technology, and it is the most widely used validation protocol for NIBP devices (16). Recently, these organizations came together to develop an internationally recognized and universally accepted standard protocol for the validation of BP measuring devices in human patients. The collaboration statement outlines 9 key aspects to the validation process, such as the minimum sample size for a validation study, BP cuff location and minimum number of patients assessed per cuff size and width variation, recommendations for general population *versus* special population studies, reference method (auscultatory) and required reporting in published studies (17). As a follow-up to this statement, a fully developed standard is set to be published soon (17).

In human studies, the reference method for validation of the NIBP device in question is the auscultatory technique, which utilizes a mercury sphygmomanometer and stethoscope to auscultate the Korotkoff sounds to detect systolic and diastolic arterial BP. In regard to passing criteria for the device to be validated, the ESH-IP requires the following criteria to be fulfilled: i) that 2 of the following are met, 74% (73/99) measurement errors to be within 5 mmHg, at least 88% (87/99) to be within 10 mmHg and at least 97% (96/99) to be within 15 mmHg of the auscultatory method values; and ii) that all of the following are met, 66% (65/99) measurement errors to be within 5 mmHg, at least 82% (81/99) to be within 10 mmHg and at least 96% (95/99) to be within 15 mmHg of the auscultatory method values (16).

In veterinary medicine, consensus validation standards have not been established, but there are recommendations from the American College of Veterinary Internal Medicine (ACVIM) Hypertension Consensus Panel and the Veterinary Blood Pressure Society Recommendations (AHCP-VBPS Validation) (18). In those assessments, it was recognized that none of the devices used in dogs and cats meet the criteria of human protocols. They recommended that the tested indirect device be compared to a direct, intra-arterial BP measurement, or to an indirect device for which validation has been previously published in a refereed journal (18). Interestingly, the BHS protocol for validation of devices in human medicine did not recommend comparison of indirect methods to direct intra-arterial BP since systolic and diastolic arterial BP values obtained by the direct technique are different from measurements obtained by indirect methods. This is due to considerable beat-to-beat variation in BP, which is not reflected in indirect readings. Blood pressure simultaneously measured directly and indirectly from the same artery can have random discrepancies in systolic arterial BP as great as 24 mmHg for systolic and l6 mmHg for diastolic arterial BP (19). An updated consensus statement on the diagnosis and management of systemic hypertension in dogs and cats has been published by the ACVIM; however, no adjustments have been made to the recommended validation criteria for NIBP measurement devices (20).

The AHCP-VBPS Validation also recommends that findings of any validated device should be applied only to the species and conditions in which the study was conducted, and this includes anesthetized *versus* conscious patients. The passing criteria recommended by this panel includes that the mean error must be at most 10 ± 15 mmHg (mean ± SD) for systolic and diastolic arterial BP, with a correlation of ≥ 0.9, that 50% of all BP measurements lie within 10 mmHg of the reference method; that 80% of all measurements lie within 20 mmHg of the reference method; that the results are published in a refereed journal; and that the database contain at least 8 individuals for comparison with an intra-arterial method, or 25 animals for comparison with a previously validated indirect device (18). The criteria do not specifically mention requirements for measurements of mean arterial BP, but it can be assumed that these should meet the same standards for validation of any BP monitor that measures mean arterial BP. While a number of studies in the veterinary literature have utilized these criteria in an attempt to validate NIBP monitors in conscious and anesthetized veterinary species, a recent study suggested limited utility of these validation criteria stating that they are designed for the detection of hypertension in conscious animals (21).

The level of agreement between 2 different assays can be assessed using a Bland-Altman plot, and is the most appropriate statistical method to compare the performance of a NIBP monitor to direct arterial BP values (gold standard method). If an NIBP monitor is to be used interchangeably with direct arterial BP monitoring, the bias (mean of the differences between the 2 methods) should be small and the limits of agreement (standard deviation) should be $< 30\%$. The importance of critical evaluation of the statistical comparison of 2 techniques has been reviewed (22) and it is necessary that the assumptions of the Bland-Altman plot be met when used for statistical analysis; these include, constant bias, constant variability, normality, and independence of the values (22). It has been suggested that since the correlation coefficient does not measure level of agreement but only the linear relationship between the values it is not a useful parameter in BP method comparison studies (22). However, since there are no other standards, the AHCP-VBPS Validation criteria of the ACVIM are the only guidelines available to follow (18).

Techniques for non-invasive blood pressure measurement

Non-invasive blood pressure monitoring techniques are frequently used in veterinary practice. Techniques that have been evaluated in veterinary species include auscultatory, Doppler ultrasonic flow detector, oscillometry, high definition oscillometry, and plethysmography. The most commonly used techniques are Doppler and oscillometry (3,23). The first measurement of arterial BP in any species was taken in 1731 in a horse when Stephen Hales cannulated the femoral artery of a mare and documented the associated height of the blood column in a glass tube and the presence of pulsatile pressure (2,4). The most common method for measuring arterial BP in human patients, the auscultatory method, was developed in 1905. Unfortunately, the technique has minimal utility in veterinary species because of the difficulty in characterizing the Korotkoff sounds due to the vessel size and skin thickness (24).

Appropriate cuff size and position is an important consideration for obtaining accurate results when using NIBP measurement techniques. A cuff that is too narrow or too loose tends to overestimate arterial BP, whereas a cuff that is too wide or too tight tends to underestimate arterial BP values (1,3). In dogs, the recommended cuff width is 30% to 40% of the circumference of the appendage (forelimb, hind limb, or tail) from which arterial BP is being measured (25,26). These recommendations have been adopted for cats (27) and carried across species for which the same guidelines have not been established (28,29). Recently, a new study evaluated the use of a conical shaped cuff compared to the traditional cylindrical cuff, placed on the antebrachium over the median artery, for oscillometric BP measurement in dogs. Data from the conical shaped cuff had poor agreement with direct arterial BP values (30). The inflatable portion of the cuff should be positioned directly over the artery to be compressed and the appendage from which BP is being measured should be positioned at the same level as the heart.

Auscultatory technique

The auscultatory, or Riva-Rocci, technique was first developed in the 19th century and is the gold standard technique used to measure arterial BP in human patients (4). The technique utilizes an inflatable cuff, a sphygmomanometer, and a stethoscope. The principle of the technique is that blood flowing through a peripheral artery creates vibrations of the vessel wall and a low frequency sound that is audible to the human ear (4). The cuff is placed around the peripheral artery of an extremity with the bell of the stethoscope placed over the audible pulse distal to the cuff. When the cuff is inflated to a pressure that exceeds systolic arterial BP, inhibiting blood flow, the audible pulse disappears. Then the cuff pressure is slowly deflated until the first audible sound returns and the pressure at this point is taken to be the systolic arterial BP value. The cuff pressure at which the last audible sound is detected is taken to be the diastolic arterial BP value (4). If systolic and diastolic arterial pressures are known, mean arterial BP can be estimated using the following equation:

$$MAP = \frac{\text{SAP} + 2\ \text{DAP}}{3} \qquad \textit{Equation 2}$$

As previously mentioned, this technique has limited clinical utility in veterinary species. The technique was evaluated in a group of anesthetized dogs with the arterial sounds amplified using a contact microphone to make them audible and the measurements were found to be comparable to those taken *via* a direct arterial catheter (24). Nevertheless, in veterinary patients the arterial (Korotkoff) sounds are of low amplitude and frequency making them non-audible to the human ear, thus making the clinical utilization of this technique challenging (24,31).

Optical plethysmography

Plethysmography is the determination of changes in volume by means of a plethysmograph. In order to use it for the estimation of arterial BP, the plethysmographic display of the pulse oximeter is required (32). In veterinary species this technique requires a pulse oximeter that displays the pulse pressure waveform, an inflatable cuff and a sphygmomanometer. The pulse oximeter probe is placed on a distal extremity or the tongue and the occlusive cuff is placed proximally. The cuff is inflated until the plethysmographic waveform is no longer visualized on the display and then the cuff is slowly deflated until the waveform returns. The cuff pressure that allows visualization of the waveform is taken to be the systolic arterial BP (32).

Studies evaluating this technique in veterinary species are limited; however, it has been assessed in dogs (32) and cats (33). Optical plethysmography was evaluated on the tongue in a group of 20 dogs in which anesthesia was induced with propofol or thiopental and maintained with isoflurane in 100% oxygen. The technique was assessed over a wide range of blood pressures and was found to be within 10 mmHg for 95% of direct systolic arterial BP values ≤ 85 mmHg, for 70% of values between 90 and 120 mmHg, and for 30% of values ≥ 125 mmHg (32). Therefore, the bias (mean value of the difference between the plethysmography value and direct arterial pressure value) and precision (2 standard deviations of the difference) showed the best agreement (-2 ± 6 mmHg; $r = 0.86$) at low systolic arterial BP values and least (-18 ± 13 mmHg; $r = 0.55$) at high systolic arterial BP values. The authors concluded that this is an acceptable method of arterial BP measurement in anesthetized dogs. According to the criteria recommended by the AHCP-VBPS Validation, most criteria were met in this study, with the lower values of systolic arterial BP, except for the correlation value, which was < 0.9 for all ranges of systolic arterial BP.

In 8 isoflurane–anesthetized cats, optical plethysmography was evaluated on the thoracic limb during conditions of 3 systolic arterial BP ranges: 80 to 100 mmHg, 60 to 80 mmHg and < 60 mmHg (33). In comparison with the direct method, plethysmography consistently underestimated systolic arterial BP and was found to have a large bias (-25 ± 7.5 mmHg) (33), and these values are unacceptable for the AHCP-VBPS Validation. However, when the plethysmography value was compared with direct mean arterial BP, the bias was minimal and precision was improved (0.6 ± 5.5 mmHg; $r = 0.9$), leading the authors to conclude that optical plethysmography in cats may be a better predictor of mean arterial BP than of systolic arterial BP (33). These values comply with the AHCP-VBPS Validation, but it is clear that these values do not represent the intended systolic arterial BP comparison.

Doppler ultrasonic flow detector

The principle of determining arterial BP using Doppler is similar to the auscultatory method except that a distally placed flow detector is utilized instead of a stethoscope to amplify the arterial sounds. The Austrian physicist and mathematician Christian Doppler first described the principle of the Doppler effect in 1842 (34). Ultrasonic Doppler flow detectors have a Doppler probe, which contains 2 piezoelectric ultrasound crystals. The first of the 2 crystals is the transmitting crystal, which transmits ultrasound energy through the skin, deep tissues, and arterial wall and the second is the receiving crystal, which receives the echo that is reflected from the tissues (3,23,35). A stationary structure will reflect an echo of the same frequency back to the receiving crystal; however, a structure in motion, such as red blood cells, will reflect an echo of different, or "shifted" frequency. The Doppler-shift is the difference in frequency between the transmitted ultrasound signal and the echo that is received back. The phase-shifted ultrasound waves are then transformed into an audible signal, with frequencies proportional to the velocity of the reflecting surface (3,34,35).

To utilize this principle to measure arterial BP, ultrasonic gel, which serves as a conductive medium, is placed on the surface of the Doppler probe and the probe is then placed over a peripheral artery, from which the hair has been clipped. An occlusive cuff is placed proximally and a sphygmomanometer is used to inflate the cuff until blood flow, and therefore systolic arterial BP, is impeded, causing the audible signal to disappear (3,23). The cuff is slowly deflated and the cuff pressure at which the first audible sound returns should correspond to the highest pressure in the vessel; a systolic arterial BP value. However, in veterinary species there is discrepancy between systolic arterial BP measured with Doppler technology and direct systolic arterial BP measured *via* catheterization of various peripheral arteries, and in some instances can be more reflective of the measured direct mean arterial BP; this is thoroughly described in part 2 of this review.

In addition to being minimally invasive, the Doppler technique is advantageous in that it is inexpensive, easy to use, has utility in a variety of patient sizes, and provides a consistently audible pulse signal. However, the accuracy and effectiveness of the Doppler are affected by motion of the patient and it is often difficult to obtain an audible signal in patients experiencing peripheral vasoconstriction.

Oscillometry

Oscillometric BP monitors are automated devices that provide estimates of systolic, mean, and diastolic arterial BP, in addition to heart rate (1,23). Oscillometric devices automatically inflate the occlusive cuff until arterial blood flow is impeded (no arterial wall vibrations or oscillations are detected). As the pressure in the cuff is slowly deflated, the oscillometer measures the mean arterial BP as the value at which the pressure oscillations in the cuff have maximum amplitude and an algorithm is used to compute systolic and diastolic arterial BP values from the measured mean arterial BP (1,4,23). The algorithm varies between monitors and thus so can the displayed estimate of arterial BP values (23). The mean arterial BP is considered to be the most accurate BP value from oscillometric monitors because it is the measured parameter, whereas the systolic and diastolic arterial BP values are estimated.

Oscillometric monitors are simple and easy to use and some monitors have the advantage of being automated such that BP readings can be taken at set time intervals and stress to the patient from repeated handling can be minimized. However, they may be less accurate in very small patients, patients with very rapid heart rates, arrhythmias, or systemic vasoconstriction, hypotensive animals with low pulse pressure or during patient movement (restlessness, shivering, seizure activity).

High definition oscillometry

High definition oscillometric BP monitors introduce a new technology for non-invasive measurement of arterial BP and have been evaluated in a few veterinary species (36–39). The technology allows pulse detection of up to 600 beats/min and detects a wider range of pressures (0 to 450 mmHg) compared to standard oscillometry (40). The monitor also displays real time pulse wave analysis such that arrhythmias or artifact can be visualized (40). During BP measurement, high definition oscillometry (HDO) initially evaluates the pulse rate of the animal and adjusts the rate of cuff deflation accordingly for subsequent readings (40). High definition oscillometry also differs from standard oscillometry in that the technology directly measures systolic, mean, and diastolic arterial BP values making the monitor, in theory, more accurate than traditional oscillometric monitors that utilize algorithms to compute systolic and diastolic arterial BP.

Clinical use and interpretation of BP values obtained *via* NIBP measurement

The gold standard for arterial BP measurement in veterinary species is *via* direct arterial catheter placement. Clinically, direct arterial BP monitoring is indicated for animals that are in shock, hemodynamically unstable, high anesthetic risk, severely hypertensive, requiring sympathomimetic support, or receiving mechanical ventilation (41). Due to the wide variation of arterial BP across veterinary species (Table 2), direct arterial BP monitoring may also be indicated during anesthesia in those species in which normal values are unknown and in large animal species in which adequate muscle perfusion is crucial to the animal's recovery. Direct arterial BP monitoring is technically demanding, invasive, and costly, and it is therefore not indicated for every animal. Additionally, the placement of an arterial catheter in animals at high risk of bleeding (coagulopathic) or infection may make direct arterial BP monitoring more detrimental than beneficial. The above-mentioned NIBP monitoring techniques provide good alternatives to direct arterial BP evaluation in certain populations. The greatest limitation to NIBP monitoring is its inaccuracy, particularly in hypotensive or hypertensive animals and in certain species. However, the ease of use, availability, non-invasiveness, and lower cost make NIBP monitoring advantageous in healthy, stable, and low risk or elective anesthetic cases (41).

Perhaps the biggest challenge veterinarians face when using NIBP monitors is recognizing the accuracy, or inaccuracy, of the results and how they should be interpreted. Critical evaluation of the reference literature is important. As discussed, consideration of the non-invasive monitor used, animal population studied, how measurements of BP were taken and methods of statistical analysis are all important. Non-invasive monitors can vary in performance based on manufacturer algorithm and study results do not necessarily translate across devices. Blood pressure values differ across veterinary species (Table 2) and if an animal is conscious or anesthetized (Table 1); therefore, findings of monitor performance in one study cannot be extrapolated to another species nor can findings in conscious animals be translated to anesthetized animals. Any simultaneous administration of drugs that alter cardiovascular performance needs to also be considered as these can affect BP values and monitor performance (6,12). Finally, the method of statistical comparisons of direct arterial BP readings to non-invasive arterial BP measurements and the arterial location from which both were measured can impact the results (5,7). All of these factors must be contemplated when making final decisions on the performance of an NIBP monitor.

Reviewing the literature shows that, although much work has been done and continues to be done to evaluate NIBP measurement across a variety of veterinary species, a general conclusion with respect to NIBP monitors cannot be made for all veterinary species. However, although definitive conclusions within species are difficult, some trends have been identified that are discussed in Part 2 of this review.

In conclusion, evaluation of arterial BP has great utility in veterinary species and the NIBP measurement devices available vary greatly between techniques and how they determine estimations of arterial BP. The biggest challenge when using NIBP monitors is the proper interpretation of the BP values provided when using them to guide veterinary patient management and treatment. In the second part of this 2-part review the veterinary literature evaluating the use of NIBP measurement techniques in conscious and anesthetized species will be critically evaluated such that general conclusions for proper use and interpretation of these devices can be formed. CVJ

REVIEW ARTICLE

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