Comparison of directly measured arterial blood pressure at various anatomic locations in anesthetized dogs

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OBJECTIVE
To determine whether directly measured arterial blood pressure differs among anatomic locations and whether arterial blood pressure is influenced by body position.

ANIMALS
33 client-owned dogs undergoing anesthesia.

PROCEDURES
Dogs undergoing anesthetic procedures had 20-gauge catheters placed in both the superficial palmar arch and the contralateral dorsal pedal artery (group 1 [n = 20]) or the superficial palmar arch and median sacral artery (group 2 [13]). Dogs were positioned in dorsal recumbency, and mean arterial blood pressure (MAP), systolic arterial blood pressure (SAP), and diastolic arterial blood pressure (DAP) were recorded for both arteries 4 times (2-minute interval between successive measurements). Dogs were positioned in right lateral recumbency, and blood pressure measurements were repeated.

RESULTS
Differences were detected between pressures measured at the 2 arterial sites in both groups. This was especially true for SAP measurements in group 1, in which hind limb measurements were a mean of 16.12 mm Hg higher than carpus measurements when dogs were in dorsal recumbency and 14.70 mm Hg higher than carpus measurements when dogs were in lateral recumbency. Also, there was significant dispersion about the mean for all SAP, DAP, and MAP measurements.

CONCLUSIONS AND CLINICAL RELEVANCE
Results suggested that arterial blood pressures may be dependent on anatomic location and body position. Because this may affect outcomes of studies conducted to validate indirect blood pressure measurement systems, care must be used when developing future studies or interpreting previous results. (Am J Vet Res 2015;76:266–271)

Measurement of systemic arterial blood pressure has long been recognized as an important part of monitoring anesthetized patients as well as evaluating critically ill animals and their response to treatment.1,2 Because of its importance, blood pressure is quickly becoming the fourth vital sign, accompanying temperature, pulse, and respiration.3 Anesthetized cats and dogs are especially at risk for hypotension, given that many anesthetic drugs have the potential to depress cardiac output as well as decrease peripheral vascular resistance.4 Additionally, certain disease conditions5–8 and medications9 are associated with secondary hypertension in dogs. This has important clinical implications because hypertension can damage target organs such as the eyes, kidneys, heart, and brain.7 Placement of a catheter in a suitable artery and use of a transducer to measure arterial blood pressure waves represents the criterion-referenced standard for blood pressure measurement.10,11 This is technically challenging and causes discomfort for patients; therefore, it is unsuitable for many clinical situations.12 Clinically, veterinarians primarily rely on indirect blood pressure measurements, such as those obtained with Doppler ultrasonography and oscillometric devices, to estimate actual arterial blood pressure.13 Nevertheless, studies14–22 designed to validate values obtained with Doppler ultrasonography and oscillometric units have yielded disappointing and sometimes conflicting results.

Since 2004, several peer-reviewed studies3,14–22 have been conducted to examine the relationship between results of direct and indirect blood pressure measurements in dogs. In most of those studies,14–20...
investigators examined the relationship between results for oscillometric devices and direct blood pressure measurements, and investigators in the other 3 studies compared results for both oscillometric devices and Doppler ultrasonography against directly measured blood pressure. Most studies failed to confirm good agreement between the direct and indirect blood pressure measurements. The central tenet of all these validation studies has been that arterial blood pressure is a constant and the same regardless of the location where it is measured. Thus, arterial blood pressure measured on a forelimb is expected to be equivalent to arterial blood pressure measured on a hind limb.

It seems plausible that the failure of these studies to confirm agreement is because of variations in blood pressure throughout the body. The purpose of the study reported here was to determine whether there would be good agreement between directly measured blood pressures obtained at 2 anatomic locations and whether body position would influence this agreement. Our hypothesis was that agreement would be poor between directly measured blood pressures obtained at 2 anatomic locations and that body position would affect this agreement.

Materials and Methods

Animals

A convenience sample of 33 dogs undergoing anesthetic procedures at the veterinary teaching hospital at Louisiana State University were enrolled in the study. Enrollment of dogs was not restricted on the basis of the type or degree of illness. The only exclusion criterion was the inability of investigators to place a 20-gauge catheter into each of 2 selected arteries. Owner consent was obtained for all dogs. The School of Veterinary Medicine Clinical Protocol Review Committee and the university institutional animal care and use committee approved the protocol for the study.

Procedures

A prospective, randomized, single-center study was conducted. Dogs were anesthetized in accordance with teaching hospital protocols and monitored by one of the investigators (AMS). A multifunction monitor was used to continuously monitor heart rate and rhythm, pulse oximetry, expired end-tidal \( P_{CO_2} \), and body temperature. Dogs were manually ventilated as needed to maintain end-tidal \( P_{CO_2} \) between 35 and 45 mm Hg. A convective warmer was used to maintain body temperature, if needed. All blood pressure measurements for the study were obtained prior to the procedure. No dog received vasopressors or bolus administration of fluids before or during the study.

Dogs were allocated into 2 groups on the basis of a random number table. Catheter sites on each anesthetized dog were aseptically prepared. For dogs of group 1, a 20-gauge catheter was placed in both the superficial palmar arch (carpus) and contralateral dorsal pedal artery (hind limb). For dogs of group 2, a 20-gauge catheter was placed in both the superficial palmar arch (carpus) and median sacral artery (tail). Catheters were connected to a pressure transducer via noncompliant tubing filled with saline (0.9% NaCl) solution; the saline solution–filled tubing was replaced between successive dogs. Transducers were connected to a data acquisition system. The system was connected to a pressurized (300 mm Hg) bag of saline solution. Transducers were placed at the level of the heart base (sternum for dogs in lateral recumbency or point of the shoulder for dogs in dorsal recumbency) and calibrated (zero) to atmospheric pressure. Prior to use, each system was assessed for accuracy against a mercury manometer by use of a 4-point validation technique. Briefly, the manometer, transducer, and pressurized bag of saline solution were connected via a 4-way stopcock that allowed simultaneous pressurization of both devices. The system was pressurized, and agreement between the manometer and transducer was evaluated at 0, 50, 100, and 150 mm Hg. The dynamic response of the direct blood pressure monitoring system was tested with the fast flush test. In accordance with previously described techniques, the allowable damping coefficient for this system was determined to be adequate for the dogs being evaluated. The direct blood pressure monitoring system was visually inspected and periodically flushed to prevent clots and to remove air bubbles, both of which could change the damping coefficient of the system. Direct blood pressure measurements were assessed for stability and consistency, and the waveform was analyzed before study recordings commenced. Specifically, the anacrotic limb, flow wave, anacrotic shoulder, dicrotic notch, and dicrotic limb of the recordings were analyzed for consistency.

Each dog was placed in dorsal recumbency. Direct arterial blood pressure measurements (SAP, DAP, and MAP) were recorded for both arteries of each dog 4 times, with 2 minutes between successive measurements. Dogs then were placed in right lateral recumbency, and after an equilibration period of 2 minutes, blood pressure measurements were repeated.

Statistical Analysis

Distribution of body weight and age was examined by means of the Shapiro-Wilk test of normality. Differences between the 2 groups were examined by use of the Mann-Whitney \( U \) test. Agreement between the direct blood pressure measurements was determined by use of Bland-Altman analysis in which carpal blood pressure was used as the reference. Because the sampling strategy involved a repeated-measures approach, measurements from each dog could not be considered independent. Therefore, mean SAP, DAP, and MAP measurements for each artery were calculated and used for analysis. Bias was defined as the mean difference between the 2 arteries, and 95% LOA were calculated as the bias \( \pm (1.96 \times SD) \). Because of the potential for underestimating the SD of differences when
repeated measures are used, calculated SDs were corrected as described elsewhere. All statistical analyses were performed with commercially available software. Values of $P < 0.05$ were considered significant.

**Results**

**ANIMALS**

Thirty-three dogs were included in the study. Twenty dogs (9 males and 11 females) were assigned to group 1 and 13 (7 males and 6 females) were assigned to group 2. Dogs in group 1 required anesthesia for procedures including MRI (n = 3), ovariohysterectomy (3), removal of cutaneous masses (3), exploratory abdominal surgery (2), castration (2), rhinoscopy (2), arthroscopy (2), mandibulectomy (1), endoscopy (1), and laser ablation of an ectopic ureter (1). Procedures performed in group 2 included castration (n = 6), ovariohysterectomy (3), limb amputation (1), arthroscopy (1), removal of cutaneous masses (1), and endoscopy (1).

![Figure 1](image1.png)

**Figure 1**—Bland-Altman plots for analysis of agreement between directly measured SAP (A), DAP (B), and MAP (C) obtained at the superficial palmar arch (carpus) and dorsal pedal artery (hind limb) of 20 dogs (group 1) positioned in dorsal recumbency. The solid horizontal line represents the bias, and the dotted lines represent the 95% LOA. Blood pressure measured at the carpus was used as the reference.

![Figure 2](image2.png)

**Figure 2**—Bland-Altman plots for analysis of agreement between directly measured SAP (A), DAP (B), and MAP (C) obtained at the superficial palmar arch (carpus) and dorsal pedal artery (hind limb) of 20 dogs (group 1) positioned in lateral recumbency. See Figure 1 for key.
Body weight and age were not normally distributed. Median body weight for group 1 was 30 kg (range, 8.1 to 56.0 kg), whereas median body weight for group 2 was 21 kg (range, 13.5 to 55.5 kg). Actual age was known for only 14 dogs of group 1 (median, 6.5 years; range, 0.25 to 13 years) and 5 dogs of group 2 (median, 7.0 years; range, 0.7 to 13 years). Body weight and age did not differ significantly between the 2 groups.

Group 1

For dogs of group 1 in dorsal recumbency, SAP agreement analysis revealed bias of −16.12 mm Hg (LOA, −43.17 to 11.16 mm Hg; Figure 1), DAP agreement analysis revealed bias of 1.71 mm Hg (LOA, −5.93 to 9.35 mm Hg), and MAP agreement analysis revealed bias of −0.40 mm Hg (LOA, −7.49 to 6.69 mm Hg). For dogs of group 1 in lateral recumbency, SAP agreement analysis revealed bias of −14.70 mm Hg (LOA, −43.17 to 13.77 mm Hg; Figure 2), DAP agreement analysis revealed bias of 1.71 mm Hg (LOA, −5.93 to 9.35 mm Hg), and MAP agreement analysis revealed bias of −0.40 mm Hg (LOA, −7.49 to 6.69 mm Hg).
revealed bias of 2.41 mm Hg (LOA, –4.91 to 9.73 mm Hg), and MAP agreement analysis revealed bias of –0.31 mm Hg (LOA, –7.82 to 7.21 mm Hg).

**GROUP 2**

For dogs of group 2 in dorsal recumbency, SAP measurement analysis revealed bias of –3.08 mm Hg (LOA, –23.68 to 17.48 mm Hg; Figure 3), DAP agreement analysis revealed bias of 0.42 mm Hg (LOA, –7.66 to 8.50 mm Hg), and MAP agreement analysis revealed bias of –2.02 mm Hg (LOA, –9.96 to 5.92 mm Hg). For dogs of group 2 in lateral recumbency, SAP agreement analysis revealed bias of –4.67 mm Hg (LOA, –24.32 to 15.00 mm Hg; Figure 4). DAP agreement analysis revealed bias of –0.73 mm Hg (LOA, –7.71 to 6.33 mm Hg), and MAP agreement analysis revealed bias of –2.11 mm Hg (LOA, –9.07 to 4.85 mm Hg).

**Discussion**

In the present study, direct blood pressure measurements obtained at 2 anatomic locations in 2 groups of dogs were compared. For group 1, arterial blood pressure was measured at the superficial palmar arch (carpus) and dorsal pedal arch (hind limb); arterial blood pressure in group 2 was measured at the superficial palmar arch (carpus) and median sacral artery (tail). In all cases, there were pressure differences that could affect comparison studies. This was especially true for all SAP measurements but was most pronounced for SAP measurements of group 1 especially true for all SAP measurements but was relatively minor. In the present study, SAP and DAP biases were on opposite sides of zero; thus, one bias would be positive and the other negative, depending on the reference artery. In the present study, SAP and DAP biases were on opposite sides of zero; MAP had relatively little bias. However, the large negative biases for SAP measurements in dogs of group 1 suggested that the dorsal pedal arch was much more centrally located than the superficial palmar arch. This is difficult to justify anatomically. More problematic was the relatively wide LOA resulting from the extensive dispersion of pressure measurements around the bias. This implied that much of the variation was nonsystematic in nature. Therefore, results of the present study cannot be completely explained on the basis of distal pulse wave amplification.

Another possible explanation for results of the study reported here was the manner in which direct blood pressure was measured. In this study, each artery was catheterized with a 20-gauge arterial catheter connected to a transducer via noncompliant saline-filled tubing. This generally is considered the criterion-referenced standard for blood pressure measurement and has been validated. Although electrical and fiber-optic transducers that can be inserted directly into an artery are available, they are less commonly used. Most importantly, to explain the lack of agreement in previous studies, we used the same techniques for direct blood pressure measurement that had been used in those studies. It seems plausible that relying on arterial blood pressure to move a column of water to affect a transducer may not be accurate for use in dogs; however, the present study was not designed to evaluate this.

One shortcoming of the present study was the relatively few blood pressure measurements in the hypertensive range. Nevertheless, a wide range of blood pressures was examined. Because these were client-owned animals, no attempt was made to pharmacologically manipulate blood pressure. Considering that we were unable to obtain good SAP agreement for measurements in the normotensive and hypotensive range, there seemed to be little benefit to further explore agreement for measurements in the hypertensive range; nevertheless, it is possible that agreement for DAP and MAP could be worse for dogs with hypertensive conditions.

It has long been known that arterial waveforms change as a pulse travels from the aorta to the peripheral vasculature. Specifically, the anacrotic limb becomes steeper, the peak becomes higher, the dicrotic notch becomes delayed, and the dicrotic limb dips lower. Therefore, it seems plausible that if an artery were more central than another artery, Bland-Altman analysis would yield SAP and DAP with biases on opposite sides of zero. Thus, one bias would be positive and the other negative, depending on the reference artery. In the present study, SAP and DAP biases were on opposite sides of zero; MAP had relatively little bias. However, the large negative biases for SAP measurements in dogs of group 1 suggested that the dorsal pedal arch was much more centrally located than the superficial palmar arch. This is difficult to justify anatomically. More problematic was the relatively wide LOA resulting from the extensive dispersion of pressure measurements around the bias. This implied that much of the variation was nonsystematic in nature. Therefore, results of the present study cannot be completely explained on the basis of distal pulse wave amplification.

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In the present study, we attempted to investigate whether the failure to validate indirect blood pressure measurement devices could have been attributable to variations in arterial blood pressure at different anatomic locations. We found small differences in DAP and MAP, but there were significant differences in SAP. This was especially pronounced when comparing SAP obtained at the carpus and hind limb. Although some of the observed differences may have been caused by distal pulse wave amplification, that phenomenon cannot explain the wide dispersion of observations around the bias. Some of the observed scattering may have been attributable to the commonly used method of catheterizing an artery and connecting it to a transducer via noncompliant saline solution-filled tubing. This study was not designed to evaluate that concern; however, results of previous studies have suggested that this is a valid method for measurement of blood pressure. Until it can be determined whether the differences detected in this study were attributable to the methods used or to actual anatomically related differences in arterial blood pressure, care must be taken when designing or interpreting studies that compare directly and indirectly measured blood pressure.

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Footnotes
a. Prism, version 6.0 for Macintosh, GraphPad Software Inc, San Diego, Calif.
b. Abbocati, Hospira, Lake Forest, Ill.
c. SP 841 physiological sensor, MEMSCAP Sensor Solutions, Skoppum, Norway.

References