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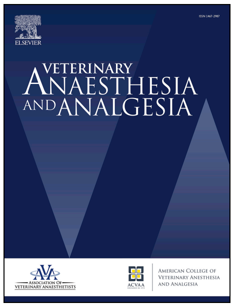

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Assessment of agreement between invasive blood pressure measured centrally and peripherally and the influence of different haemodynamic states in anaesthetised horses.

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Authors' contributions

KW: Instrumentation, data recording, collection and interpretation, management of anaesthesia, experimental methodology, statistical analysis and manuscript preparation.

AR: Instrumentation, data collection, experimental methodology and design, revision of manuscript.

ED: Experimental methodology, management of anaesthesia, instrumentation, data recording, revision of manuscript

MM: Instrumentation, data collection, experimental methodology and design, revision of manuscript

GL: Experimental methodology and revision of manuscript.

JH: Management of anaesthesia, data collection and cross checking.

GH: Instrumentation, experimental design, statistical analysis and revision of manuscript.

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Agreement between invasive blood pressure measured centrally and peripherally in anaesthetized horses.

Abstract

Objective To determine the agreement of invasive blood pressure measured in the facial artery, the metatarsal artery and the carotid. Additionally, to evaluate the effects of two haemodynamic conditions on agreement.

Study design Prospective, randomized study.

Animals Eight horses aged 7 (4 -23) years with a body weight of 493 ± 33 kg.

Methods Horses were anaesthetized and positioned in dorsal recumbency. Invasive blood pressure was measured simultaneously via catheters placed in the facial, metatarsal and carotid artery. Cardiovascular function and agreement between arteries was assessed before and during administration of phenylephrine and sodium nitroprusside. These were administered until carotid mean pressure (MAPc) increased or decreased from baseline (65 ± 5 mmHg) to > 90 mmHg or < 50 mmHg, respectively. Data recorded at each sample time included systolic (SAP), mean (MAP) and diastolic (DAP) for carotid (c), facial (f) and metatarsal (m) artery as well as cardiac output ($\dot{Q}t$) and systemic vascular resistance (SVR). Bland-Altman analysis was used to assess agreement between peripheral and central sites and regression analysis was used to determine influence of $\dot{Q}t$ and SVR.

Results The largest difference was observed in SAPc and SAPm with a bias and limits of agreement (LOA) of 2 (-15 to 19) mmHg. The bias (LOA) for MAPc and MAPf was 2 (-4 to 9) mmHg and for MAPc and MAPm was 5 (-4 to 14) mmHg. The best agreement for DAP was seen between DAPc and DAPf with bias (LOA) of 1 (-3 to 5) mmHg. Regression analysis indicated marginal influence on agreement by $\dot{Q}t$ on MAPc and MAPf.

Conclusion and clinical relevance The MAP and DAP of the carotid was generally higher compared to the peripheral arteries, which may lead to overzealous treatment of hypotension, albeit maintaining central pressures. Cardiac output and systemic vascular resistance did not largely influence the difference between sites.

Keywords equine, blood pressure, cardiovascular monitoring, metatarsal, facial carotid.

Introduction

It is well reported that recognition and management of hypotension will reduce the incidence and severity of post anaesthetic myopathy (Grandy et al. 1987; Johnston et al. 2002). As a result of these studies, it is now commonplace to monitor invasive blood pressure (IBP) in anaesthetized horses directly via a catheter placed in the easily accessible peripheral arteries.

Recent studies in anaesthetized ponies and dogs have demonstrated poor agreement between pressure measured in peripheral arteries compared to the larger conducting artery, the carotid (Monteiro et al. 2013; Gent et al. 2015). In both these studies, other measures of cardiovascular function like systemic vascular resistance (SVR) and cardiac output ($\dot{Q}t$) were not assessed. A recent clinical study in anaesthetized horses reported haphazard patterns of agreement between the three peripheral sites commonly used to measure blood pressure; the facial, transverse facial and metatarsal arteries (Wilson et al. 2017). This raises the question as to whether pressure measured in peripheral arteries can provide a meaningful indication of perfusion of the vital organs, especially over a range of hemodynamic states.

In a study using an electrical model of circulation, it was illustrated that a partial obstruction (such as that created by an arterial catheter), or change in vessel shape from decreased SVR, lead to turbulent flow in the peripheral arteries. This could lead to attenuation of the waveform, affecting agreement between central and peripheral sites (Ercole 2006). There are no known published studies in anaesthetized horses investigating agreement of IBP measured in the peripheral arteries compared to the carotid during different haemodynamic states induced by changes to $\dot{Q}$t and SVR.

The aims of this study were to determine the agreement of IBP between the facial and the metatarsal artery with the carotid and with each other and to evaluate the effects of two haemodynamic conditions (hypotension and hypertension) on agreement. It was hypothesized that agreement would be poor between central and peripheral sites and changes to systemic vascular resistance would influence agreement.

Materials and methods

Animals

Eight adult horses with ASA (American Society of Anesthesiologists) physical status I and II were included in the study. A sample size of 8 horses was determined to give a 95% confidence interval for the estimation of the limits of agreement (LOA) within ± 1.2 (SD) (www.users.york.ac.uk/~mb55/meas/sizemeth). Donated horses, that were unable to be rehomed and that the owner had agreed to use in teaching or research prior to humane euthanasia were used for this study. The horses were deemed healthy with no cardiac disease, according to physical, echocardiographic and haematological examinations. The use of these horses in this study was approved by an Institutional

Animal Ethics committee (Permit number R2861/16) and was performed in accordance with the Animal Welfare act of Western Australia.

Study design

Each horse was anaesthetized once. Blood pressure was measured throughout anaesthesia and hemodynamic states were altered by administration of phenylephrine (hypertension) or sodium nitroprusside (hypotension). Phenylephrine and sodium nitroprusside were administered until carotid mean pressure (MAPc) increased and decreased from baseline (65 ± 5 mmHg) to > 90 mmHg and < 50 mmHg, respectively. The order for administration of phenylephrine and sodium nitroprusside was balanced (4 nitroprusside/phenylephrine; 4 phenylephrine/nitroprusside) and allocated randomly by selecting the protocol from sealed envelopes on the day of the study.

Anaesthesia

The horses were fasted for at least 12 hours before induction of anaesthesia, but water was available *ad libitum* until premedication. A 14 gauge catheter was placed in the left jugular vein. Each horse was sedated with romifidine (0.08 mg kg^{-1}; Sedivet; Boehringer Ingleheim, MO, USA) intravenously (IV) and five minutes later, anaesthesia was induced with ketamine (2.2 mg kg^{-1}; Ilium, NSW, Australia) and diazepam (0.1 mg kg $^{-1}$; Ilium, NSW, Australia) IV in the same syringe. Following orotracheal intubation, the horses were hoisted onto a padded surgery table and positioned in dorsal recumbency. The horses were then connected to a large animal anaesthetic machine using a circle breathing system (Tafonius junior; Vetronics, UK). Anaesthesia was maintained with isoflurane (VCA, NSW, Australia) delivered in 95-

98% oxygen. Mechanical ventilation was performed in all horses to maintain an end-tidal carbon dioxide tension of 5.33-6.66 kPa (40-50 mmHg). Tidal volume was adjusted between 10-15 mL kg^{-1} and respiratory rate between 8-9 breaths minute^{-1} to achieve this value, which was then confirmed by arterial blood gas analysis [arterial partial pressure of carbon dioxide ($PaCO_2$) 45 – 55 mmHg]. Once a value within this range was achieved, no adjustment to ventilation parameters were made. Anaesthesia monitoring included pulse oximetry, electrocardiography (ECG) and IBP which were obtained using the Surgivet V9203 multiparameter monitor (Sound Medical, Australia). Sidestream capnography and inspiratory and end-expiratory agent analyses were performed using the Vamos plus (Dräger; DRE Medical, KY, USA). Supportive care included administration of Hartmanns's solution (Baxter Healthcare, NSW, Australia) at 5 mL kg^{-1} hour^{-1} by infusion pumps. Dobutamine (Hospira, Australia) at 0.5-1.5 µg kg^{-1} minute^{-1} was used to maintain MAP > 60 mmHg prior to baseline measurements when required and was stopped at least 10 minutes prior to measurements.

Instrumentation

Arterial catheters were placed in the left facial artery (f) at the most ventral part as it traversed the mandible, the right metatarsal artery (m) distal to the head of the lateral splint bone and the right carotid (c) retrograde to the heart. At each site, a 20 gauge 1.88-inch catheter (BD Instyle; Becton, Dickenson and Company, USA) was placed after clipping and disinfection of the site. The carotid catheter was placed after surgical exposure of the proximal third of the artery. This involved an incision over the ventral midline followed by blunt dissection. Following catheterization, the artery was left in the natural position to prevent interference with blood flow. The catheters were connected to electronic pressure transducers (DTX Plus; Argon, Singapore) via identical non-compliant fluid-filled extension lines (150 cm). The transducers were connected to multiparameter monitors (Surgivet V9203; Sound Medical, Australia). Prior to anaesthesia, the accuracy of each transducer was checked using a water manometer (Drynan et al. 2016) and for linearity at 200 mmHg, 100 mmHg, 50 mmHg and 20 mmHg. After placement of the catheters, all pressure transducers were positioned at the level of the scapulohumeral joint which was confirmed using a laser and spirit level. Each transducer was then zeroed to atmospheric pressure and the difference in height between the transducer and each arterial catheter was recorded. Prior to the first data collection and whenever the waveform changed, a rapid flush test was performed and the amount of damping of the waveform assessed subjectively to ensure that the damping was similar between arteries. Using a screen capture of the waveforms recorded during the rapid flush test, the damping coefficient was calculated subsequently to confirm that differences in damping were not responsible for differences between pressures measured in different arteries.

Central venous pressure was measured from the right atrium via a 90 cm 19 gauge polyurethane equine central venous catheter (Mila International Inc, KY, USA). After clipping and disinfection of the right jugular, the catheter was advanced into the ventricle and then retracted into the right atrium and the location was confirmed by pressure waveform analysis. The catheter was attached to an electronic transducer which was zeroed to atmospheric pressure and positioned at the level of the scapulohumeral joint.

Data collection

Cardiovascular measurements included systolic (SAP), mean and diastolic arterial pressure (DAP), heart rate (HR), $\dot{Q}t$ and central venous pressure (CVP). All variables were recorded on a separate record sheet. Cardiac index (CI), SVR, systemic vascular resistance index (SVRI) and body surface area (BSA) were subsequently calculated using the following formulae:

SVR (dynes second cm^{-5}) = 80(MAP – CVP)/$\dot{Q}t$

CI (L $minute^{-1}$ m^{-2}) = $\dot{Q}t$/BSA

SVRI (dynes second cm^{-5} m^{-2}) = 80(MAP- CVP)/CI

BSA (m^2) = 10.5 x (body mass in $g)^{2/3}$ x 10^{-4}

Concurrent measurements of blood pressure from all arteries were recorded at baseline [when carotid mean pressure (MAPc) was 65 ± 5 mmHg], and during administration of phenylephrine or sodium nitroprusside when MAPc had been increased and decreased to maintain a stable pressure of > 90 mmHg or < 50 mmHg, respectively, for at least 5 minutes. At each measurement point, three recordings were taken within 60 seconds and the average calculated for data analysis. In order to prevent variability due to ventilation, data were recorded during transient periods of apnoea where the first IBP recording was started 20 seconds after switching off the ventilator.

Cardiac output was determined following administration of 0.003 mmol of lithium chloride kg^{-1} (0.15 mmol mL^{-1}) into the jugular catheter. Duplicate $\dot{Q}t$ determinations were obtained within a 3-minute period, and the mean $\dot{Q}t$ was calculated for each sample time. Prior to each duplicate, [sodium (Na^+)] and [haemoglobin (Hb)] were measured via arterial blood gas analysis. The sensor was connected to an arterial catheter placed in the right facial artery (opposite side to IBP measurement). The first cardiac output was performed simultaneously with the IBP recording during apnoea, whilst the second was performed three minutes later during another period of apnoea.

All horses were euthanized after completion of further approved investigations using pentobarbitone 0.1 mL kg^{-1} (Lethabarb; Virbac, Australia)

Statistical analysis

Based on normal distribution being verified, body weight, age, HR, $\dot{Q}t$, CVP, SVR and damping coefficients were examined by means of the Shapiro-Wilk test of normality and reported as mean ± standard deviation (SD). Other results are given as median (range). Repeatability of the three consecutive IBP measurements were defined by the coefficient of variation and the mean coefficient was reported for each artery. A Wilcoxon ranked sign test was used to compare damping coefficients between the between arterial sites and paired t-tests were used to compare baseline values prior to administration of each drug. A $p<0.05$ was considered significant for these analyses.

Agreement of the SAP, MAP and DAP between the carotid and the peripheral sites as well as between the peripheral sites were described using the Bland-Altman method for single paired measurements, plotting the difference in paired measurements against the mean of the two measurements (Bland & Altman 2007). The bias was calculated as the mean difference between arteries, the precision as the standard deviation of the bias and the limits of agreement (LOA) calculated as the bias ± 1.96 SD (Bland & Altman 2007). The pattern of agreement was visually assessed. We considered acceptable LOA as ± 5 mmHg. This allowed a difference in magnitude of up to 10 mmHg between sites. A leniency of this magnitude was considered acceptable in light of using this information to dictate treatment in clinical cases. Bland Altman and descriptive statistical analyses were performed using GraphPad Prism Version 6.00 for Mac OS X (GraphPad Software, Inc., CA, USA).

For the purpose of exploring whether cardiac output or systemic vascular resistance could explain the disagreement between carotid and facial or metatarsal pressure, regression analysis was performed for SAP, MAP and DAP. The disagreement in measurement was regressed (R^2) on $\dot{Q}t$ and SVR. The R^2 was recorded for addition of first $\dot{Q}t$, and then SVR, and used as a description of how much variation in the disagreement the variables could explain. Regression analysis was performed using SAS v 9.4 (SAS Institute, NC, USA).

Results

Eight horses (two mares and six geldings) were included, with an age of 7 (4 -23) years and a body weight of 493 ± 33 kg. Duration of anaesthesia from induction to last measurement was 168 ± 35 minutes. Time to first measurement after induction was 70.5 (60-116) minutes.

Damping coefficients from the IBP(c), IBP(f) and IBP(m) were calculated as 0.2 (0.15-0.35) and were not significantly different ($p > 0.99$) between all three sites. One set of data from the metatarsal artery was removed from analysis due to significant overdamping being present immediately after measurements. The mean coefficient of variation of the three consecutive IBP measurements was 2% for each individual artery.

Phenylephrine was administered at a range of 0.5 - 2 µg kg^{-1} $minute^{-1}$ to increase MAPc and sodium nitroprusside at 0.1-1.5 µg kg^{-1} $minute^{-1}$ to decrease MAPc. Dobutamine was administered prior to 7/32 baseline data collection periods. There was no significant difference detected between baseline measurements prior to phenylephrine or sodium nitroprusside administration: SAPc (*p* = 0.16), MAPc (*p*= 0.19), DAPc (*p* = 0.22), HR (*p* = 0.13) or $\dot{Q}t$ (*p* = 0.74). Cardiovascular parameters during baseline, phenylephrine and sodium nitroprusside administration as well as arterial blood gas results (PaO_2 and $PaCO_2$) are described in Table 1.

Bland-Altman scatter plots for all measurements between the IBP(c) and the peripheral sites as well as between IBP(f) and the IBP(m) showed poor agreement with wide LOAs above ± 5 mmHg (Figs. 1-3, Table 2).

[Figs 1-3 here]

The worst agreement with the widest LOA was for SAP between the carotid and metatarsal and the facial and metatarsal, with limits spanning a magnitude of 36 mmHg and a bias (LOA) of 2 (-15 to 19) mmHg and 1 (-16 to 18) mmHg, respectively (Figs. 2a and 3a, Table 2). Visual assessment of the Bland-Altman SAP plots showed a haphazard (non-systematic) pattern of agreement with a marginal bias and data points in both the positive and negative direction of the plot across the spectrum of pressures evaluated (Figs. 1a, 2a and 3a).

There was a general tendency for the MAPc and DAPc to be underestimated by the peripheral arteries as indicated by a positive bias and as illustrated in the plots. However, overestimation did also occur with some points in the negative regions of the plots (Figs. 1b, 1c, 2b and 2c). This underestimation of MAP and DAP by the more peripheral vessel (further from the heart) was also present when the facial and the metatarsal were compared (Figs. 3b and 3c). The bias (LOA) for MAPc and MAPf was 2 (-4 to 9) mmHg and MAPc and MAPm was 5 (-4 to 14) mmHg. Visual inspection of the Bland-Altman Plots showed changing bias for MAPm across the spectrum of measurements compared to a consistent bias for MAPf compared to MAPc (Figs. 1b and 2b).

The best agreement for DAP and overall was seen between DAPc and DAPf with bias (LOA) of 1 (-3 to 5) mmHg.

Regression analysis on the difference between the carotid and facial artery measurements for SAPf, MAPf and DAPf, Q̇t explained 20%, 37% and 17% of the variance respectively, with SVR having negligible association as indicated by the influence of the combined Q̇t and SVR as 20%, 38% and 19% respectively. The difference between the metatarsal artery and the carotid for SAPm, MAPm and DAPm showed no association with Q̇t and SVR.

Discussion

To the authors’ knowledge, this is the first study comparing direct blood pressure measurements between central and peripheral arteries at different haemodynamic states in horses. The results revealed poor agreement between the carotid, facial and metatarsal arteries as well as between the two peripheral arteries across the pressures evaluated. No influence of systemic vascular resistance was observed on agreement between sites whilst cardiac output marginally influenced agreement between the carotid and the facial arteries. This suggests other factors have greater influence on the disparity observed.

The poor agreement observed between central and peripheral sites, supported our first hypothesis. However, there was a general trend for the facial and metatarsal artery to underestimate the MAP and DAP of the carotid. This underestimation has also been observed in studies in dogs and ponies (Monteiro et al. 2013; Gent et al. 2015). Although, in human studies there are conflicting findings (O'Rourke et al. 1968; Dorman et al. 1998; Mignini et al. 2006). There are no studies in horses investigating the effects of changes to central pressure, even though perfusion of vital organs such as the brain, heart, kidneys, gastrointestinal tract as well as the skeletal muscles and the gravid uterus is determined by blood flow in these conducting arteries. The underestimation of MAP by the peripheral arteries may result in the overzealous treatment of hypotension in clinical cases, albeit maintaining central pressures well above the driving pressure necessary to perfuse these organs.

The agreement between MAP measured at the carotid and peripheral arteries was poor overall, as indicated by wide LOA, with the worse agreement observed between the carotid and the metatarsal artery. The length of the vascular tree in horses could result in a greater degree of dispersion of reflecting sites minimizing the effects of wave reflection and could explain the worsening agreement seen at more peripheral sites (O’Rourke et al. 1968). The poor agreement between the carotid and the facial artery was surprising, however could be due to the facial artery being a branch of the linguofacial trunk, rather than a direct branch of the external carotid. This may result in more sites of wave reflection, contributing to the discrepancy between the readings.

It was surprising that the agreement between all the arterial sites was not better considering this was an experimental study performed under standardized conditions. The LOA in this study were smaller than in the results reported by Gent et al. (2015) in ponies, who were also surprised by the poor agreement observed. The physical factors that can contribute to discrepancies between readings such as the position of the transducers and formation of blood clots or presence of bubbles in the line were all reduced in this study. Each catheter was flushed using a constant flow of saline pressurised to 300 mmHg to prevent clotting and air bubble formation. In addition, each transducer was verified by a laser spirit level to be at the level of the scapulohumeral joint. Technical errors were also excluded by confirming accuracy of equipment prior to and during use. As differences in damping within each measurement system can contribute to poor agreement between arteries, the effect of damping was reduced by using an identical measurement system for each artery. The lack of difference in the calculated damping coefficient between each transducer and fluid line was also highly supportive that this factor was unlikely to have contributed to the poor agreement. As this was an experimental study, there was no excessive electrical activity from surgical instruments or manipulation of the vascular tree due to surgery that could have interfered with the data.

Systolic amplification, a physical phenomenon causing overestimation of systolic pressures by the peripheral arteries, may have contributed to the lack of agreement. Systolic amplification has been documented in dogs and children with the effects of increasing age decreasing its presence (Nichols & O'Rourke 1998; O'Rourke et al. 2000; Wojciechowska et al. 2012). Although the worst agreement observed in this study was the systolic pressures for both combinations with the carotid and between the facial and the metatarsal, both over and underestimation of the more central arterial site occurred. This is consistent with other studies in humans, horses, ponies and dogs where over and underestimation of the SAP by the more peripheral artery was present. (Mignini et al. 2006; Monteiro et al. 2013; Acierno et al. 2015; Gent et al. 2015; Wilson et al. 2017) It is also possible that age related changes could have contributed to poor agreement due to the increasing stiffness of the carotid artery with increasing age, as two of the horses in this study were > 20 years old (Endoh et al. 2017). However, separate analysis with Bland-Altman plots of the two older horses revealed a similar haphazard pattern of agreement as the younger animals. This suggests that age related vascular changes did not influence agreement in this study.

Another possible factor contributing to poor agreement is attenuation, which occurs as a result of partial blood flow obstruction due to the presence of a catheter in the lumen of an artery. This phenomenon, as opposed to overdamping, was demonstrated in an ex vivo model where erroneous low SAP and DAP readings were observed, especially during times of low SVR (Ercole 2006). This phenomenon could perhaps explain the results in dogs where the more peripheral artery underestimated the SAP of the carotid during hypotensive conditions (Monteiro et al. 2013). However, in our study, visual inspection of the Bland-Altman plots did not show underestimation at lower pressures and regression analysis did not reveal any influence by SVR on the difference between measurements. One of the reasons for the lack of attenuation in our study could be the catheter size, resulting in a relatively small proportion of the carotid artery lumen being occupied. Thus, there was less obstruction to flow in the carotid artery compared to the peripheral arteries (Ercole 2006). Unfortunately, in this study vessel size in relation to catheter occupancy was not measured.

The lack of detectable influence of SVR on agreement, may also reflect the method used to measure cardiac output. In our study, cardiac output was measured using the lithium dilution technique. There is evidence in the literature that the administration of certain drugs can influence the function of the lithium sensor. Recently, Hopster et al. (2017) demonstrated a large bias between lithium dilution and thermodilution during administration of high doses of phenylephrine. However, in an older study at doses similar to those used in the current study, a small bias was observed between lithium dilution and thermodilution during administration of phenylephrine and sodium nitroprusside (Linton et al. 2000). Moreover, the potential error induced by overestimation of measurements was irrelevant to the outcome of the study as we were not investigating the absolute values of cardiac output.

In the study by Gent et al. (2015), administration of dexmedetomidine caused all but the SAPm to have improved agreement with the carotid in comparison to saline administration. The authors hypothesized that these observations were as a result of vasoconstriction by dexmedetomidine, increasing the damping of the pressure waves in a smaller vessel further away from the heart. This also could be explained by the phenomena described by Ercole (2006) with less attenuation during vasoconstriction.

This was not evident in our study, in fact the opposite was observed with the administration of phenylephrine causing a trend of worsening agreement between the MAPm with the MAPc as pressures increased.

The agreement between IBP measured at the facial and metatarsal was also evaluated. In this study we observed better agreement between SAP, MAP and DAP measured at the facial and the metatarsal than in a previous study (Wilson et al. 2017). In addition, the positive bias of the MAP and DAP indicated the more peripheral artery underestimated the pressures of the more centrally located artery in contrast to the non-systematic, haphazard agreement seen in the clinical study. The differences in these results could be explained by the current study being performed under standardized experimental conditions.

There are aspects of the experimental design that may have influenced results and need to be considered when interpreting the data. Firstly, the horses were positioned in dorsal recumbency and thus it is not known if the results would be similar in lateral recumbency. In particular, it is not known the impact on pressure measurements when the position of the metatarsal artery is greatly higher than the carotid. This could explain the differences observed between our study and that of other studies where agreement was assessed in ponies positioned in lateral recumbency (Gent et al. 2015). The decision to perform the current study in dorsal recumbency was to enable us to catheterize the carotid artery and the contralateral facial artery, so that flow and pressure in the facial artery was not impacted by the presence of a catheter in the upstream carotid. The use of contralateral arteries also contrasts the study by Gent et al. (2015) where the facial and carotid from the same side was used. Secondly, in our study the carotid arteries were not permanently translocated to a subcutaneous position. It was decided to place the catheter using surgical exposure of the artery to prevent changes in blood flow and thus pressure that could occur due to changes in anatomical alignment. However, it is possible that the cut down technique removed some of the surrounding soft tissue supporting the artery. This could have resulted in changes to elasticity/radial traction of the vessel and resulted in higher systolic pressure and lower diastolic pressure, affecting agreement between the peripheral sites.

Finally, the vasoactive agents phenylephrine and sodium nitroprusside were used to manipulate vascular tone to change IBP in order to assess agreement over a wide range of pressures. However, in clinical situations these agents are rarely used and the influence of these drugs cannot replicate clinical situations when changes to vascular tone and cardiac output are due to systemic disease.

Future studies are needed to assess the agreement between IBP measured between central and peripheral in clinical situations in different recumbencies.

Conclusion and clinical relevance

In conclusion, MAP and DAP of the carotid was generally higher compared to the facial and the metatarsal arteries, which may lead to overzealous treatment of hypotension in clinical cases, albeit maintaining central pressures. Cardiac output and systemic vascular resistance did not largely influence the difference between sites. Mean arterial pressure was closer to the carotid when measured at the facial artery compared to the metatarsal artery in dorsally recumbent horses under isoflurane anaesthesia.

References

Acierno MJ, Domingues ME, Ramos SJ et al. (2015) Comparison of directly measured arterial blood pressure at various anatomical locations in anaesthetized dogs. Am J Vet Res 76, 266–271.

Bland J, Altman D (2007) Agreement between methods of measurement with multiple observations per individual. J Biopharm Stat 17, 571-582.

Endoh C, Matsuda K, Okamoto M et al (2017) Morphometric changes in the aortic arch with advancing age in fetal to mature thoroughbred horses. J Vet Med Sci 73, 661-669.

Ercole A (2006) Attenutation in invasive blood pressure systems. Br J Anaes 96, 560-562.

Dorman T, Breslow MJ, Lipsett PA et al. (1998) Radial artery pressure monitoring underestimates central arterial pressure during vasopressor therapy in critically ill surgical patients. Crit Care Med 26, 1646 - 1649.

Drynan EA, Schier M, Raisis AL (2016) Comparison of invasive and non-invasive blood pressure measurements in anaesthetised horses using the Surgivet V9203. Vet Anaesth Analg 43, 301-308.

Gent TC, Schwarz A, Hatz LA et al. (2015) Evaluation of accuracy of invasive and non-invasive blood pressure monitoring in relation to the carotid artery pressure in anaesthetised ponies. Pferdeheilkunde 31, 33-38.

Grandy JL, Steffey EP, Hodgson DS et al. (1987) Arterial hypotension and the development of postanesthetic myopathy in halothane-anesthetized horses. Am J Vet Res 48, 192–197.

Hopster K, Ambrisko TD, Kaster SBR (2017) Influence of catecholamines at different dosages on the function of the LiDCO sensor in isoflurane anaesthesized horses. J Vet Emerg Crit Care 27, 651-657.

Johnston GM, Eastment JK, Wood JLN et al. (2002) The confidential enquiry into perioperative equine fatalities (CEPEF): mortality results of Phases 1 and 2. Vet Anaesth Analg 29, 159-170.

Linton RA, Young LE, Marlin DJ et al (2000) Cardiac output measured by lithium dilution, thermodilution, and transesophageal Doppler echocardiography in anaesthetized horses. Am J Vet Res 61, 731-737.

Mignini MA, Piacentini E, Dubin A (2006) Peripheral arterial blood pressure monitoring adequately tracks central arterial blood pressure in critically ill patients: an observational study. Crit Care 10, R43.

Monteiro ER, Campagnol D, Bajotto GC et al. (2015) Effects of 8 hemodynamic conditions on direct blood pressure values obtained simultaneously from the carotid, femoral and dorsal pedal arteries in dogs. J Vet Card 15, 263-270.

Nichols WW, O’Rourke MF (1998) McDonald’s Blood Flow in Arteries: Theoretical, Experimental and Clinical principles (4th edn). Edward Arnold, UK.

O'Rourke MF, Blazek JV, Morreels CL et al. (1968) Pressure wave transmission along the human aorta. Circ Res 23, 567-579.

O’Rourke MF, Vlachopoulos C, Graham RM (2000) Spurious systolic hypertension in youth. Vasc Med 5, 141-145.

Wilson KAT, Raisis AL, Drynan E et al. (2017) Agreement between invasive blood pressure measured at different peripheral arteries in anaesthetized horses. Vet Anaesth Analg. DOI 10.1016/j.vaa.2017.11.004

Wojciechowska W, Stolarz-Skrzypek K, Tikhonoff V et al. (2012) Age dependency of central and peripheral systolic blood pressures: Cross-sectional and longitudinal observations in European populations. Blood Pressure 21, 58-68.

Figure 1

Bland Altman plots of agreement between invasive blood pressure (IBP) measured between the carotid and the facial arteries. (a) Systolic arterial pressure (SAP); (b) mean arterial pressure (MAP); (c) diastolic arterial pressure (DAP). Solid lines indicate mean difference (bias) and dotted lines indicate limits of agreement (LOA).

Figure 2

Bland Altman plots of agreement between invasive blood pressure (IBP) measured between the carotid and the metatarsal arteries. (a) Systolic arterial pressure (SAP); (b) mean arterial pressure (MAP); (c) diastolic arterial pressure (DAP). Solid lines indicate mean difference (bias) and dotted lines indicate limits of agreement (LOA).

Figure 3

Bland Altman plots of agreement between invasive blood pressure (IBP) measured between the facial and the metatarsal arteries. (a) Systolic arterial pressure (SAP); (b) mean arterial pressure (MAP); (c) diastolic arterial pressure (DAP). Solid lines indicate mean difference (bias) and dotted lines indicate limits of agreement (LOA).

Table 1

Mean ± standard deviation of cardiovascular parameters and blood gas analysis between the combined baselines, each baseline prior to phenylephrine or nitroprusside and treatments with phenylephrine and nitroprusside in eight horses.

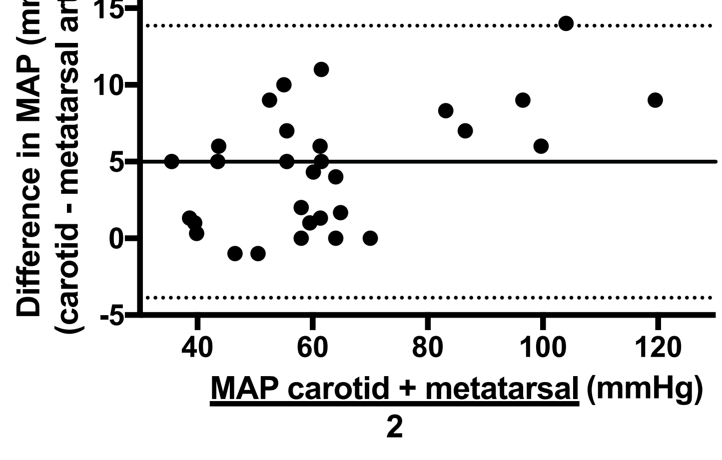
Parameter	**Combined baseline**	**Baseline Phenylephrine**	**Phenylephrine**	**Baseline Nitroprusside**	**Nitroprusside**
SAPc (mmHg)	83 ± 11	79 ± 5	120 ± 15	87 ±14	58 ± 4
MAPc (mmHg)	64 ± 8	61 ± 4	99 ± 14	67 ± 10	43 ± 4
DAPc (mmHg)	51 ± 7	49 ±6	80 ± 14	53 ± 3	36 ± 6
HRc (beats minute^{-1})	35 ± 5	37 ± 4	30 ± 4	33 ± 5	34 ± 4
CVP (mmHg)	4 ± 4	3 ± 4	14 ± 5	4 ± 3	1 ± 3
$\dot{Q}$t (litres minute^{-1})	26 ± 6	26 ± 6	20 ± 5	27 ± 6	23 ± 5
CI (L minute^{-1} m^{-2})	4 ± 1	4 ± 1	3 ± 1	4 ± 1	3 ± 1
SVR (dynes second^{-1} cm^{-5})	187 ± 43	190 ± 48	362 ± 51	183 ± 41	148 ± 36
SVRI (dynes second^{-1} cm^{-5} m^{-2})	1254 ± 288	1244 ± 310	2299 ± 444	1264 ± 285	973 ± 231
PaO_2 (mmHg)	207 ±125		118 ± 62		145 ±105
PaO_2 (kPa)	28 ± 17		16 ± 8		19 ± 14
$PaCO_2$ (mmHg)	56 ± 7		55 ± 7		56 ± 8
$PaCO_2$ (kpa)	7 ± 1		7 ± 1		7 ± 1

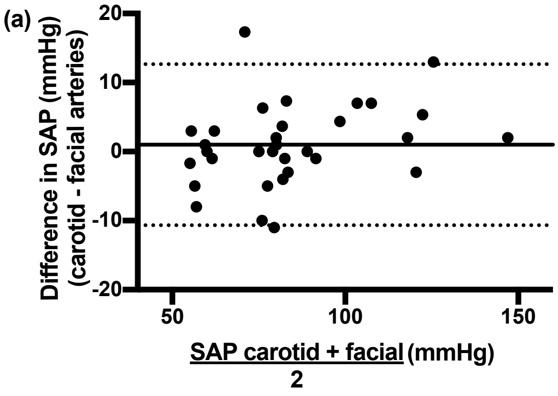
SAP$_{c,}$ systolic arterial pressure measured at the carotid; MAP$_{c,}$ mean arterial pressure measured at the carotid; DAP$_{c,}$ diastolic arterial pressure measured at the carotid. HR$_c$ heart rate measured at carotid; CVP, central venous pressure; $\dot{Q}$t, cardiac output; SVR, systemic vascular resistance; SVRI, systemic vascular resistance index

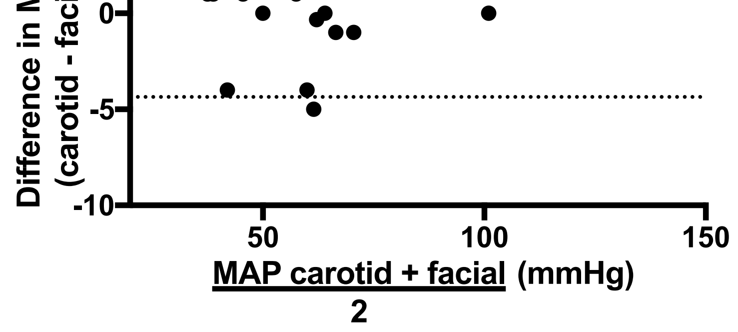
Table 2

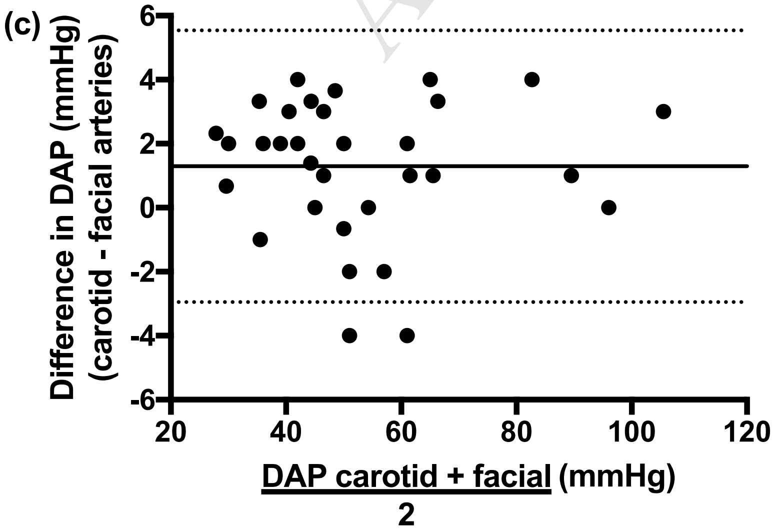
Overall systolic (SAP), mean (MAP) and diastolic arterial pressure (DAP) data with mean difference (bias), precision, limits of agreement (LOA) their 95% confidence intervals (CI) for upper and lower LOA for invasive blood pressure measurements in 8 horses across the carotid, facial and the metatarsal arteries.

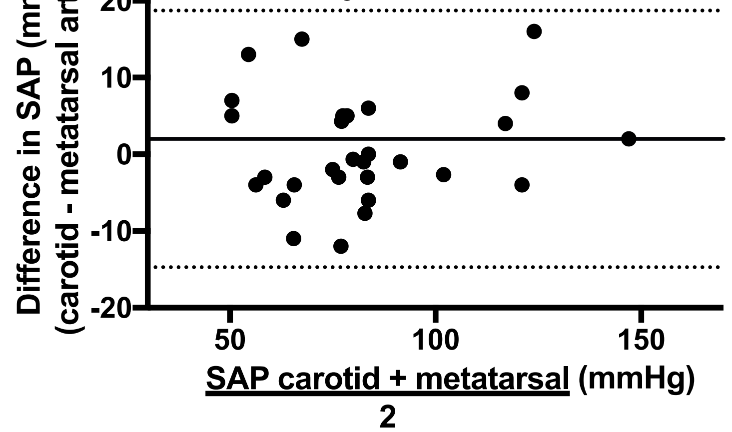
	Parameter	**Bias (mmHg)**	**Precision (mmHg)**	**LOA (mmHg)**	**CI lower LOA (mmHg)**	**CI upper LOA (mmHg)**
Carotid vs Facial	**SAP**	1	6	-11 to 13	-14.to -7	9 to 16
	MAP	2	3	-4 to 9	-6 to -2	7 to 11
	DAP	1	2	-3 to 5	-4 to -1	4 to 7
Carotid vs Metatarsal	**SAP**	2	9	-15 to 19	-20 to -10	13 to 24
	MAP	5	5	-4 to 14	-7 to -1	11 to 17
	DAP	4	3	-2 to 10	-4 to 0	8 to 12
Facial vs Metatarsal	**SAP**	1	9	-16 to 18	-21 to -10	13 to 24
	MAP	3	4	-5 to 11	-8 to -2	8 to 14
	DAP	2	3	-4 to 9	-6 to -2	7 to 11

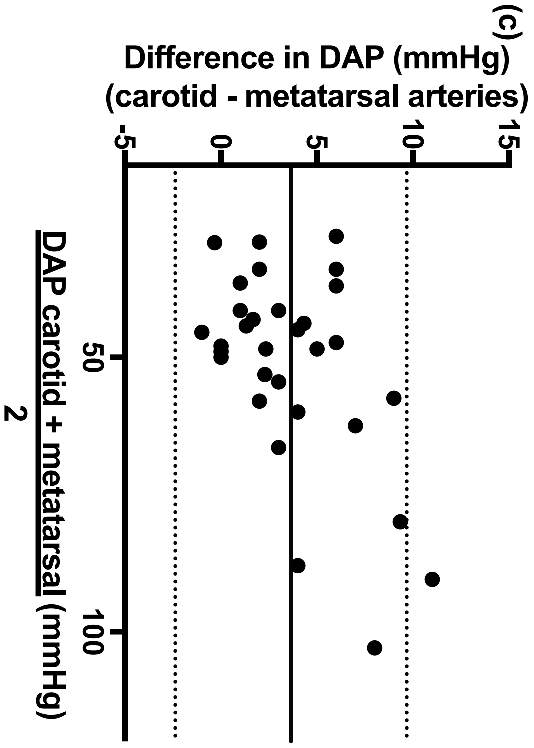

(b)
Difference in MAP (mmHg)
(carotid - metatarsal arteries)
20
15
10
5
0
-5
40
60
80
100
120
MAP carotid + metatarsal (mmHg)
2

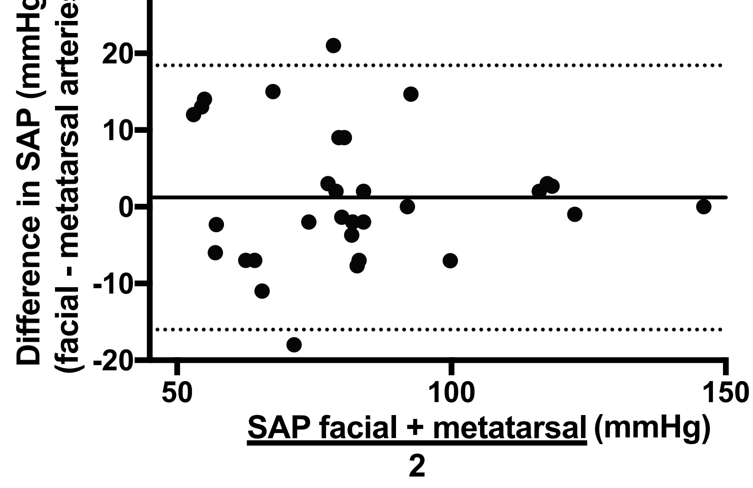

(a)
20
10
0
-10
-20
50
100
150
Difference in SAP (mmHg)
(carotid - facial arteries)
SAP carotid + facial (mmHg)
2

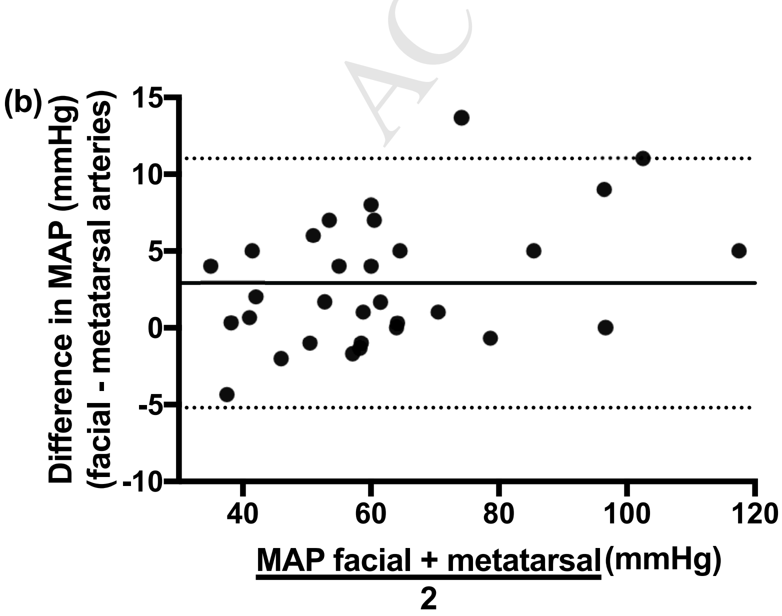

(b)
Difference in MAP (mmHg)
(carotid - facial arteries)
10
5
0
-5
-10
50
100
150
MAP carotid + facial (mmHg)
2

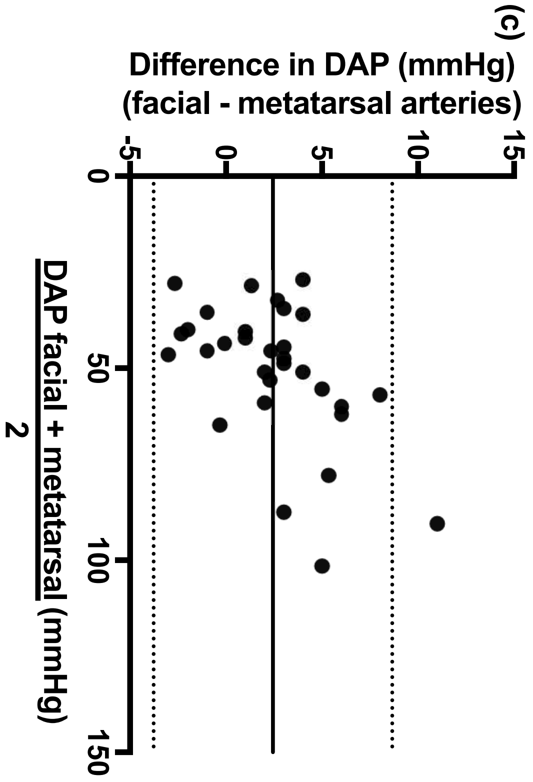

(c)
Difference in DAP (mmHg)
(carotid - facial arteries)
6
4
2
0
-2
-4
-6
20
40
60
80
100
120
DAP carotid + facial (mmHg)
2


(a)
Difference in SAP (mmHg)
(carotid - metatarsal arteries)
30
20
10
0
-10
-20
50
100
150
SAP carotid + metatarsal (mmHg)
2


(c)
Difference in DAP (mmHg)
(carotid - metatarsal arteries)
-5
0
5
10
15
DAP carotid + metatarsal (mmHg)
2
50
100


(a)
Difference in SAP (mmHg)
(facial - metatarsal arteries)
30
20
10
0
-10
-20
50
100
150
SAP facial + metatarsal (mmHg)
2


(b)
Difference in MAP (mmHg)
(facial - metatarsal arteries)
15
10
5
0
-5
-10
40
60
80
100
120
MAP facial + metatarsal (mmHg)
2


(c)
Difference in DAP (mmHg)
(facial - metatarsal arteries)
-5
0
5
10
15
0
50
100
150
DAP facial + metatarsal (mmHg)
2