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Agreement of invasive and non-invasive blood pressure measurements in anaesthetised pigs using the Surgivet V9203

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Title

Agreement of invasive and non-invasive blood pressure measurements in anaesthetised pigs using the Surgivet V9203

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Abstract

The automated oscillometric method is a common method for measuring blood pressure non-invasively and is broadly and confidently used in the veterinary setting. Twenty-one pigs undergoing anesthesia for exploratory laparotomy were enrolled in a study to evaluate the performance of the Surgivet V9203 non-invasive blood pressure (NIBP) monitor. The aim was to compare measurements of arterial blood pressure obtained simultaneously using the Surgivet V9203 oscillometric system and an intra-arterial catheter-transducer system, both at the level of the metatarsus. Invasive blood pressure (IBP) was consistently underestimated by the non-invasive method. Bland-Altman analysis showed poor agreement between the two modalities based on evaluation of mean bias and 95% limits of agreement. The Surgivet V9203 cannot therefore be recommended as a reliable alternative to invasive blood pressure monitoring in anesthetized pigs. As pulse detection is one of the most important factors affecting NIBP accuracy it is likely that our findings may reflect an anatomical or physiological difference in the species that alters the detection of wall movement by the oscillometric technique and additionally, makes the algorithm used by the Surgivet to determine blood pressure parameters unsuitable for use in pigs.

Keywords

anesthesia, arterial blood pressure, pig, non-invasive blood pressure, oscillometric

Abbreviations

DAP diastolic arterial blood pressure

IBP invasive blood pressure

MAP mean arterial blood pressure

NIBP non-invasive blood pressure

SAP systolic arterial blood pressure

1. Introduction

Arterial blood pressure is one of the most commonly measured indices of cardiovascular performance in animals under general anaesthesia. As cardiac output and tissue perfusion cannot be routinely measured in clinical practice, blood pressure monitoring, as a surrogate, contributes to identification of compromise to a patient's cardiovascular system. In our institution the pig is a useful teaching model. The pig is also a common research model for humans due to their numerous similarities in anatomy and physiology (Swindle et al., 2012). In these settings an accurate, but non-invasive method of measuring blood pressure in pigs would be useful, particularly as hypotension is associated with increased morbidity and mortality in many veterinary species, including both companion and farm animals (Aarnes et al., 2014; Deflandre & Hellebrekers, 2008). Thus, early detection and treatment of hypotension is important.

Arterial blood pressure can be measured both directly and indirectly, with the direct or invasive method being widely accepted as the reference method or "gold standard". However, direct blood pressure measurement as a technique, carries risks associated with the placement of a catheter into a peripheral artery, including ischaemic damage, haemorrhage, arterial embolization and infection (Saugel et al., 2014). Additionally, its performance can be technically challenging, particularly in larger pigs where surgical cut-down is often performed to enable catheterisation (Ball and Westhorpe, 2009). Non-invasive techniques, in comparison, are relatively easily performed, are rarely associated with complications and are inexpensive to operate. Therefore, for routine blood pressure measurement in anaesthetised animals, a non-invasive technique is more commonly performed.

The oscillometric method of non-invasive blood pressure measurement is routinely used in both human and veterinary settings and has been in use for over 30 years (Saugel et al., 2014). Oscillometry consists of a cuff with an inflatable bladder that is automatically inflated and deflated over an underlying artery. During deflation, returning blood flow within the underlying artery affects the oscillations generated by the machine within the cuff. Changes in the amplitude of oscillations over the cardiac cycle are detected by the system, resulting in determination of SAP, DAP and MAP intermittently (Alpert et al., 2014). In order to determine whether blood pressure measurements obtained non-invasively in animals using an oscillometric monitor are clinically useful, and therefore considered a less invasive alternative to direct blood pressure monitoring in a species, agreement between the non-invasive monitor and a direct method are compared to current recommendations. The American Association for the Advancement of Medical Instrumentation (AAMI) and the American College of Veterinary Internal Medicine Hypertension Consensus Panel and Veterinary Blood Pressure Society (ACVIM & VBPS) provide these recommendations, but differ in their definitions. A bias of <5 mmHg and a precision of <8 mmHg is considered acceptable variation between measurements obtained using an invasive and a non-invasive technique by the AAMI (Macfarlane et al., 2010) and a bias of ≤10 mmHg with a precision of ≤15 mmHg is considered acceptable by the ACVIM & VBPS (Brown et al., 2007). The AAMI guidelines have been used by manufacturers and clinicians for decades but few studies of oscillometric systems in the veterinary setting have met validation criteria (Binns et al., 1995). Based on the ACVIM guidelines, studies have demonstrated that non-invasive methods, like the oscillometric method, can be meaningful in the clinical anaesthesia setting when used in sheep, dogs and horses (Almeida et al., 2014; Drynan et al., 2016; Drynan, 2013; Drynan and Raisis, 2013; Trim et al., 2013).

The unique anatomy of pigs with their short, thick limbs and tendency to accumulate large amounts of subcutaneous fat means that results for other species cannot be used to reliably interpret blood pressure obtained non-invasively in pigs. So far there have been a small number of studies comparing invasive and automated, non-invasive blood pressure monitoring in pigs, as concerns exist about their accuracy and precision. Cruz et al., (1998) compared an invasive and an oscillometric technique at the metatarsal site in anaesthetised sows, showing consistent underestimation of the reference method by the Dinamap® oscillometric method. The earliest study of the use of oscillometry in pigs showed underestimation of all blood pressure parameters by the Sentry's oscillometric method when performed at the tail, compared to the direct method via a catheter at the metatarsal site (Knaevelsrud and Framstad, 1992). However, as different non-invasive monitors use unique proprietary algorithms to determine blood pressure measurement, the findings and results cannot be extrapolated to the use of other systems.

To the author's knowledge, the Surgivet V9203 NIBP monitor has not been evaluated in anaesthetised pigs. The aim of this study was to assess the agreement of non-invasive blood pressure and invasive blood pressure measured using the

Surgivet V9203 in anaesthetised pigs. Both measurements were performed using the Surgivet V9203, a multiparameter monitor that has been found to be useful in dogs and horses (Drynan et al., 2016; Drynan and Raisis, 2013). The hypothesis of the study was that there would be poor agreement between the invasive and non-invasive (oscillometric) blood pressure measurements obtained by the Surgivet V9203 in anaesthetised pigs.

2. Materials and Methods

The study included a sample of 21 large white pigs (*Sus scrofa*), approximately 10 weeks of age with a mean weight (95% confidence interval) of 20 (10.3-29.8) kilograms, utilised for teaching basic principles of surgery and anaesthesia to undergraduate veterinary students. Ethics approval for all procedures and techniques was obtained by the Animal Ethics Committee of Murdoch University (AEC Permit R2806/16) and the study complied with the National Health and Medical Research Council of Australia code of practice for the care and use of animals for scientific purposes. No overt abnormalities were found in the pigs based on pre-anaesthetic distance examinations. All pigs were anaesthetised with a combination of xylazine (2mg/kg, Ilium Xylazil 100mg/mL, Troy Laboratories

Australia Pty. Ltd., Glendenning, NSW, Australia) and tiletamine and zolazepam (4mg/kg, Zoletil 100, Virbac Australia Pty. Ltd., Milperra, NSW, Australia) administered by intramuscular injection into the hindlimb. Once recumbency was achieved, an intravenous catheter was placed into an auricular vein and, if required, approximately 1mg/kg propofol (1% Norbrook Laboratories Ltd., Victoria Australia) was administered until orotracheal intubation could be performed. Anaesthesia was maintained in all pigs with isoflurane (Attane Isoflurane 1mL/mL, Bayer Australia Ltd, NSW, Australia) delivered in oxygen. If pigs weighed <15 kg a Bain breathing system was used and if >15 kg an adult circle system was used. They were restrained with ropes tied around the forelimbs in order to maintain dorsal recumbency for the entire length of anaesthesia. Pigs were monitored by veterinary students under the supervision of experienced veterinarians involved in teaching veterinary anaesthesia. All pigs in the study underwent an exploratory laparotomy as well as a variety of basic intra-abdominal surgical procedures.

Instrumentation

During preparation of the pigs for surgery, once the pigs had reached an appropriate plane of stable anaesthesia, a 20 gauge or 22 gauge, one inch, over-the-needle catheter was placed percutaneously in the superficial portion of the medial saphenous artery. The arterial catheter was connected via a 3-way stopcock to non-compliant tubing, filled with sterile, heparinised isotonic saline, and a transducer (DTX Plus™, Argon Critical Care Systems, Singapore) to allow a continuous display on the Surgivet V9203 multiparameter monitor (Sound Medical, VIC, Australia). Prior to anaesthesia, the transducer was checked for accuracy and linearity against a column of water according to manufacturer recommendations. Prior to measurement, the transducer was zeroed at approximately the level of the right atrium to eliminate atmospheric pressure from arterial pressure measurements. Patency was ensured with the use of a continuous flushing system using heparinised isotonic saline pressurised to 300 mmHg. A rapid flush test of the system was performed and an estimation of the damping coefficient was made based on the ratio of the induced resonant waves (Kleinman et al., 1992). During the study, intermittent observations of changes in amplitude of the arterial pressure waveform were also performed and if the amplitude was subjectively reduced, the system was flushed. An appropriately sized non-invasive blood pressure cuff, as determined by the metatarsal circumference and manufacturer recommendations (Table A), was placed around the contralateral metatarsus by the same operator in order to measure blood pressure indirectly. Whenever possible, the blood pressure cuff and transducer were both positioned at the level of the right atrium. If this was not possible, the non-invasive measurements were later adjusted for difference in height using the correction of 0.736 mmHg for each centimetre of vertical height difference (Olsen et al., 2016).

In addition to invasive and non-invasive blood pressure monitoring, continuous values for heart rate, oxyhaemoglobin saturation, respiratory rate and end-tidal carbon dioxide were displayed and recorded. At time points determined by the context of the student teaching laboratory that the study was performed in, simultaneous measurements of both invasive and non-invasive blood pressure were collected in triplicate. Data collection for NIBP occurred at 30 second intervals using the STAT-Mode function of the Surgivet V9203. STAT-Mode allows for collection of multiple consecutive measurements of non-invasive blood pressure. Three corresponding measurements of invasive blood pressure were also collected in the same recording period. To ensure data was collected during a haemodynamically stable period of anaesthesia, readings were included only if the observed pulse rates and blood pressure did not vary by more than 5%. Data collection from each pig occurred at three time points: once when the invasive MAP was above 70mmHg, once when MAP was between 60 and 70 mmHg and a third sample when the invasive MAP was below 60 mmHg. All pigs were euthanased by an intravenous pentobarbitone injection at the completion of surgery.

Data Analysis

At each sample time, a measurement of NIBP and IBP was obtained from an average of three consecutive measurements. Variables were checked for normality by examining histograms. The agreement between invasive and non-invasive SAP, DAP and MAP was calculated using Bland-Altman analysis, with the invasive technique being considered the reference method. Data processing and Bland-Altman analysis were performed using a commercially available spreadsheet programme. Information obtained from statistical analysis included relative bias which was calculated as the mean difference between the IBP and the NIBP. A positive bias reflected an underestimation of the IBP by the oscillometric device and a negative value indicated an overestimation. Standard deviation of the difference between the paired results was calculated representing the precision. The 95%

limits of agreement were defined as the calculated bias +/- 1.96 multiplied by the calculated standard deviation.

3. Results

All pigs required a medium size NIBP cuff. Each pig had two or three sets of triplicate measurements of SAP, DAP and MAP taken both invasively and non-invasively resulting in a total of 53 paired sample means for comparison of SAP, DAP and MAP. The mean (95% confidence interval) for all SAP, DAP and MAP measured both invasively and non-invasively are displayed in Table 2. Numerical results of Bland-Altman analysis of the 53 paired sample means are shown in Table 3. These results are also shown in Figure 1 as Bland-Altman plots of the difference against the average of the differences between IBP and NIBP, with lines representing the bias and limits of agreement. Calibre of arterial catheter is represented visually in each plot. Systolic, diastolic and mean arterial blood pressure measurements obtained by the Surgivet NIBP oscillometric method were consistently lower than the IBP for all three blood pressure components. Overall, DAP had the closest agreement with a mean bias of 10 mmHg. The greatest underestimation occurred with the SAP obtained non-invasively with a mean bias of 14.4 mmHg. Based on the figure it can be seen that agreement did not appear to be affected by the size of the arterial catheter.

4. Discussion

This study compared IBP and NIBP measurements obtained simultaneously from a metatarsal site in anaesthetised pigs using the Surgivet multiparameter monitor during exploratory laparotomy. The results of this study showed that NIBP was consistently lower than concurrent measurements of IBP, with the difference being greatest with SAP and least with DAP. The results of our study are consistent with previous work that also demonstrate that NIBP measurements tend to be lower than IBP measurements when used in anaesthetised animals (Almeida et al., 2014; Binns et al., 1995; Branson, 1997; Cruz et al., 1998; Deflandre and Hellebrekers, 2008; Drynan and Raisis, 2013; Knaevelsrud and Framstad, 1992; Sawyer et al., 2004). The better agreement observed for MAP and DAP measurements than SAP in this study is also consistent with that reported in studies of the performance of the Surgivet NIBP function in dogs (Deflandre and Hellebrekers, 2008; Drynan and Raisis, 2013). In contrast to studies in dogs, the agreement between NIBP and IBP observed in our study was poorer; however, when results are compared to analogous studies of oscillometric techniques in pigs, the agreement was better. This suggests the Surgivet produces NIBP measurements in better agreement with IBP than previously studied oscillometric systems used in pigs.

One reason for differences in agreement between studies could be due to differences in technology of oscillometric systems. The unique design of the Surgivet cuff, including a 360 degree bladder, may impact the ability to detect pressure oscillations. The true influence of this factor is unknown in all species. An additional reason for the differences in agreement between studies, particularly in relation to systolic pressure determination, is the differing patterns of cuff deflation employed by oscillometric monitors. Many oscillometric systems use a stepwise cuff deflation method. This can influence the accuracy of measurements depending on the duration of each step. A decrease in the step interval can increase the sensitivity of the system in detecting important events during the deflation cycle, for example the brief peak of the systolic pulse wave (Binns et al. 1995). It could therefore be hypothesised that the slightly lower bias observed in this study may reflect technological differences in oscillometric systems.

There are other reasons for poor agreement between the oscillometric and invasive methods. The oscillometric method is subject to technical errors including the cuff to limb ratio and cuff position. However, these factors were unlikely to be contributing factors in the current study as all were standardised. Because pulse detection is one of the most important factors affecting NIBP accuracy it is likely, assuming the invasive measurements were accurate, that our findings may reflect an anatomical or physiological difference in pigs that alters the detection of wall movement by the oscillometric technique and additionally, makes the algorithm used by the Surgivet to determine blood pressure parameters, unsuitable for use in pigs. The most obvious anatomical difference in pigs compared to domestic animals is their higher amount of subcutaneous fat. This could have an effect on the relationship between invasive and non-invasive measurements in these animals. For example, in people, studies have demonstrated that blood pressure is significantly underestimated in overweight patients and the accuracy of NIBP determination is variable in this population (Araghi et al., 2006).

It is worthy to note that as pigs were non-recovery, no attempts were made to manipulate blood pressure and a consistent depth of anaesthesia was maintained. The blood pressures measured in this study were therefore within the range common for surgery so the findings cannot be extrapolated to situations where extremes of blood pressure may occur. Collectively, the blood pressure measurements included a range of values, but would be limited if the values were to be divided arbitrarily into hypotensive, normotensive and hypertensive states. This is a future area of investigation in pigs. The performance of the Surgivet V9203 oscillometric NIBP monitor is unlikely to be linear and this has been demonstrated in anaesthetised dogs (Drynan and Raisis, 2013).

Although we used direct peripheral arterial blood pressure measurement as our reference method, it is not a perfect tool for assessing true physiological values and is subject to technical errors that could influence results. These include damping, errors due to transducer positioning and factors concerning the catheter used, including size and direction of placement. The damping coefficient was calculated where possible and when optimum damping was not present within the system, the calculated damping coefficient supported an underdamped system. The commercially supplied minimum volume extensions used to connect the catheters to the transducers in our set- up may have contributed to this. The effect of an underdamped system could be reflected in the results of the systolic IBP measurements which showed the largest disagreement with the NIBP measurements. Underdamping would result in the SAP measured invasively being higher than the real SAP, as well as the DAP measured invasively being lower than the real DAP. MAP would be relatively unaffected. Underdamping of the invasive pressure waveform may have contributed to the SAP measured non-invasively being lower than that measured invasively to some degree, however it does not explain why the MAP and DAP measured non-invasively were also lower than their respective invasive measurements. Thus underdamping of the direct measurement system does not fully explain the lack of agreement present in this study. The poor agreement for SAP could also be explained by the placement of the catheter against blood flow. When blood flow impacts the catheter tip, kinetic energy is converted to potential energy and this has the greatest influence on SAP. Two sizes of catheter were used in this study and the effect of more than one calibre is thought to be negligible, as visually, the Bland-Altman graphs show a haphazard distribution of results when both sizes are displayed together graphically. The transducer and cuff were standardised in terms of placement in relation to the right atrium in this study. As the non-invasive and invasive measurements were made from the same artery in contralateral limbs, differences in blood flow due to vessel size and distance from the heart do not explain the poor agreement. This could however explain why agreement was better in our study when compared to studies of other oscillometric systems in pigs where different peripheral sites for cuff and catheter placement were compared. Despite the improvements that were observed in oscillometric blood pressure measurements in pigs, our findings do not support the use of the Surgivet V9203 NIBP system to measure blood pressure using the oscillometric technique at the metatarsal site in the species as the system fails to meet a basic acceptance criteria for validation. Based on the maximum mean difference between paired measurements described by the AAMI or ACVIM & VBPS, the accuracy and precision of this device, as observed in this sample population, were unacceptable. This was due to the bias and standard deviation for SAP and MAP being outside that of the acceptable range that accounts for tolerable error. It is worth noting that these results are specific to the site used in this study and the agreement between NIBP measurements at different sites is required to fully clarify the usefulness of this method in anaesthetised pigs.

In order to interpret results appropriately, it is worth discussing some aspects of study design and analysis. The Bland-Altman technique was determined to be the most appropriate analysis for this type of study. The Bland-Altman analysis is a simple way to evaluate a bias between the methods and using the precision, we can estimate an interval within which 95% of the differences of the second method, compared to the first one would fall. It allows us to consider whether the two methods measure the same thing on average and if not, how one is biased relative to the other (Giavarina, 2015). Simple correlation has been used in previous studies comparing NIBP systems to IBP in pigs. This form of comparison shows the relationship between the modalities being compared, not the differences. This can result in incorrect conclusions being drawn from the data and is not a method for assessing agreement (Giavarina, 2015). However it should be noted that the Bland-Altman analysis was not initially designed for multiple numbers of measurements performed in multiple patients (Bland and Altman, 2007) but as previous work has used this statistical method it was also used in this study to allow comparisons to be made between studies.

In conclusion, the agreement between invasive and non-invasive blood pressure measurements using the Surgivet V9203 in anaesthetised pigs is poor at the metatarsal site. The hypothesis was proven for all parameters when considering the standards of the AAMI. For critical and more complex anaesthetics in the pig, and when accurate figures are required for blood pressure determination, invasive blood pressure measurement would be indicated. The Surgivet V2903 is therefore, in this situation, of limited clinical usefulness and an unsuitable replacement for invasive BP monitoring in anaesthetised pigs.

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Conflicts of interest

None

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Table 1. Surgivet cuff descriptions.

Cuff size	**Circumference of extremity (cm)**
Small	3-9
Medium	5-15
Large	9-25
Extra Large	17-41

Table 2. IBP & NIBP data.

Number	**Parameter (IBP)**	**Mean**	**95% CI**
53	SAP (mmHg)	89.7	63.6-115.9
53	DAP (mmHg)	47.5	29.1-65.9
53	MAP (mmHg)	62.7	40.8-84.5
Number	**Parameter (NIBP)**	**Mean**	**95% CI**
53	SAP (mmHg)	75.4	48.7-102.0
53	DAP (mmHg)	37.5	16.3-58.7
53	MAP (mmHg)	51.8	29.5-74.1

Table 3. Bland-Altman Analysis. Comparison of two methods of measuring blood pressure in pigs.

Number	**Parameter**	**Bias**	**Precision**	**Limits of Agreement**	
				Lower	**Upper**
53	SAP (mmHg)	14.4	12.9	-10.9	39.6
53	DAP (mmHg)	10.0	9.65	-8.92	28.9
53	MAP (mmHg)	10.8	10.8	-10.4	32.1

Figure 1. A. Bland-Altman plot of the difference against the mean of the differences (Direct-Surgivet).

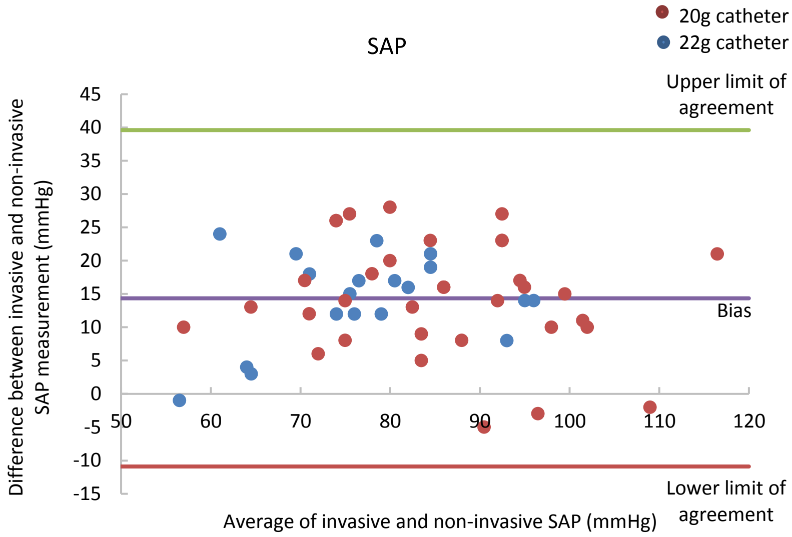


Figure 1. B. Bland-Altman Plot of the difference against the mean of the differences (Direct-Surgivet).

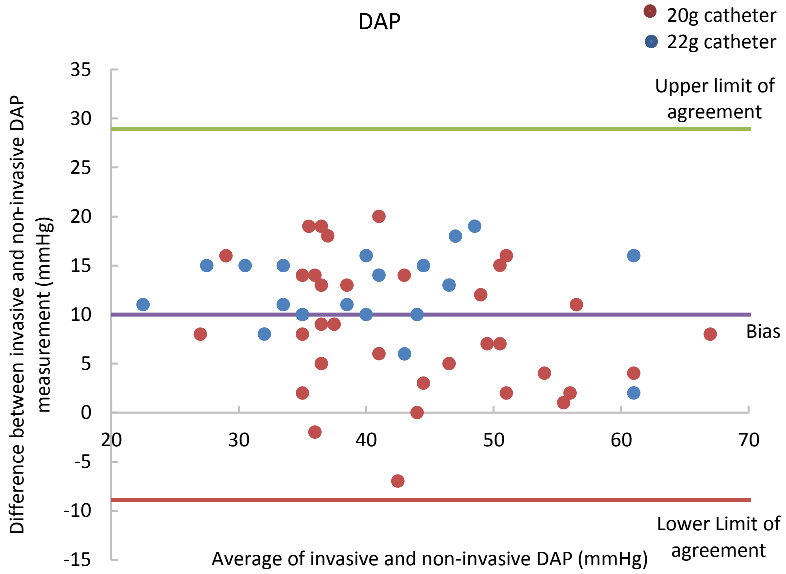
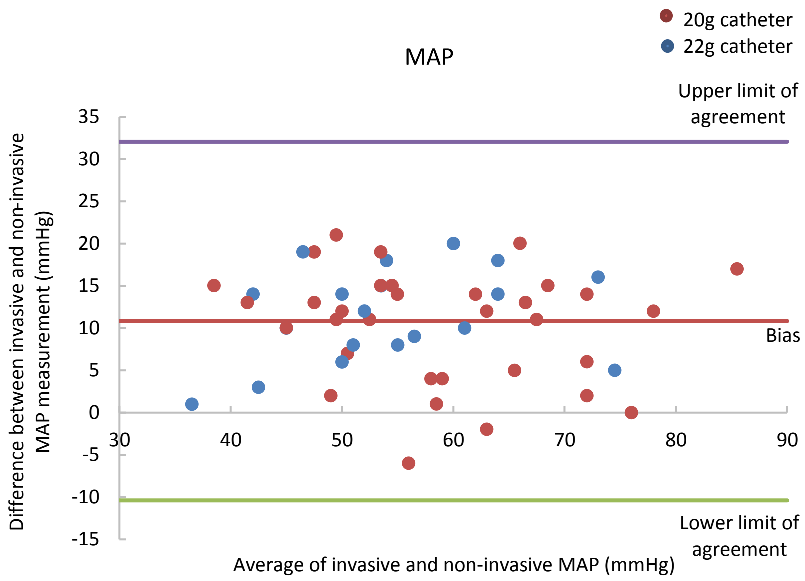


Figure 1. C. Bland-Altman plot of the difference against the mean of the differences (Direct-Surgivet) .



Highlights

- Poor agreement is shown between two methods of blood pressure measurement.
- Arterial blood pressure was consistently underestimated by an oscillometric method.
- Clinical usefulness of Surgivet oscillometry may be limited in anesthetised pigs.