Comparison of blood pressure measurements obtained using non-invasive and invasive techniques, in anaesthetised companion animals

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(Anaesthesia and Critical Care)

This thesis is presented for the degree of Research Masters (with Training) of Murdoch University, 2013
I declare that this thesis is my own account of my research and contains as its main content work which has not previously been submitted for a degree at any tertiary education institution.

…………………………
Eleanor Drynan
Abstract

Measurement of blood pressure is a critical tool in the monitoring of patients undergoing general anaesthesia and has become standard practice within medical fields. Adequate vital organ perfusion is reported to be achieved if a central mean arterial pressure (MAP) is greater than 60mmHg. In clinical practice, peripheral arterial blood pressure (ABP) is used as an estimate of central ABP. Measurement of peripheral ABP can be performed either invasively or non-invasively. While invasive blood pressure measurements (IBP) are considered to be more accurate than non-invasive blood pressure (NIBP) measurements, several studies comparing the two methods have demonstrated that measurements obtained non-invasively are still clinically useful. As the algorithms used for measuring blood pressure vary between different machines it is not possible to extrapolate results from one machine to another and thus each machine must be assessed separately to ensure interpretation of the measurements obtained in clinical patients is appropriate.

The purpose of this thesis was to compare both NIBP and IBP measured using the multi-parameter Surgivet monitor (V9203) in anaesthetised dogs, horses, and sheep. Concurrent measurements of NIBP and IBP were obtained in each species at different pressure levels. These pressure levels were divided into the following categories: hypotension (< 60mmHg), low blood pressure (60-80 mmHg), normotension (80-100mm Hg), high blood pressure (100-120 mmHg), and hypertension (> 120 mmHg). For pooled data and data subdivided based on BP category the relationship between IBP and NIBP was determined using the Bland-
Altman technique. The bias and precision for concurrently recorded IBP and NIBP measurements was calculated.

In all species, NIBP measurements were generally lower than IBP. Overall for both the dog and the horse data, the mean arterial pressure showed the least bias i.e. the greatest agreement between the two methods. Systolic blood pressure tended to show the least agreement between the methods and this was much more evident in the low blood pressure and normotensive blood pressure groups. Interestingly, from the sheep component of the study, the systolic blood pressure had the greatest agreement in each group.

To determine the clinical usefulness of the NIBP measurements the calculated bias and precision was assessed using the guidelines of the American Association for the Advancement of Medical Instrumentation and the American College of Veterinary Internal Medicine Hypertension Consensus Panel (AVCIMHCP). Using these guidelines, the agreement between NIBP and IBP measurements in greyhounds and horses, were found to be within the limits of agreement recommended by the ACVIMHCP for all pressures except systolic blood pressure. This suggests that the Surgivet NIBP can be used to provide a good estimate of IBP for mean and diastolic pressures in these species.

In conclusion, the results of this study demonstrated that non-invasive measurements of diastolic and mean ABP provide a clinically useful alternative to IBP measurements, particularly in the horses and greyhounds. However systolic BP measured using non-invasive techniques does not, and therefore needs to be interpreted cautiously. The results also demonstrate a tendency for NIBP
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Finally, I could not have completed this thesis without the help, and love of my husband, as well as my children. Their support and sacrifice have made this thesis possible.
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Chapter 1: Literature review

Introduction

Measurement of arterial blood pressure, is considered an essential component of monitoring during general anaesthesia in both human and veterinary patients.\(^1\)\(^2\) The importance of blood pressure monitoring is supported by several studies.\(^3\)\(^4\) Blood pressure monitoring has been shown to be crucial for detection of adverse events in anaesthetised human patients.\(^3\) Studies in horses have also demonstrated that monitoring of blood pressure and rapid treatment of low blood pressure have reduced the severity of a myopathy.\(^4\) Hypotension is also reported to one of the most common complications in healthy anaesthetised dogs.\(^5\)\(^6\)

There are numerous techniques available for measurement of arterial blood pressure (ABP) invasively (direct) and non-invasively (indirectly). Invasive measurement of ABP via an arterial catheter is considered the most accurate. Accuracy of non-invasive techniques are generally determined by comparing measurements obtained with the non-invasive techniques with those measured using the invasive technique. To accurately interpret information available on indirect and direct methods for measuring blood pressure it is essential to understand how the complex arterial pressure waveform is generated, how the different techniques measures the pressure produced by this waveform and the technical factors that can interfere with accurate detection and measurement of the arterial pressure.
The following section will discuss the principles of blood pressure generation within arteries and the techniques used to measure arterial blood pressure. In addition, information on the accuracy of the currently available technology in veterinary species will be reviewed.

**What is blood pressure (BP)?**

Blood pressure is defined as the force exerted by the blood on the wall of the vessel. The pressure produced by blood within an artery changes over time due to intermittent pumping of blood by heart and the flow of the blood away from the heart to the periphery. The pressure within the vessel at any point in time will depend on the amount of blood being pumped out of the heart, the compliance of arterial wall and the impedance to flow of the blood to the periphery. Compliance is defined as the change in arterial blood volume ($\Delta V$) due to a change in arterial blood pressure ($\Delta P$), whilst impedance is defined as the resistance to pulsatile flow.

The periodic contraction (systole) and relaxation (diastole) of the heart is described as the cardiac cycle. In clinical practice, blood pressure is measured from the systemic arteries. The systemic arterial blood pressure is influenced by the activity of the left ventricle.

The cardiac cycle as it specifically relates to the left ventricle is as follows. Ventricular systole occurs after filling of the left ventricle is complete. At the start of systole the ventricular muscles contract resulting in an increase in pressure within
the ventricle, when the pressure in the ventricle exceeds that in the atria, the mitral valve closes. Contraction of the myocardium continues resulting in further change in pressure but no change in volume. This is called isovolumetric contraction. When the pressure within the ventricle exceeds that within the aorta, the aortic valve opens. Continued contraction of the myocardium at this point causes ejection of blood from the heart. Initially ejection is rapid (rapid ejection phase), but as systole progresses the contraction of the myocardium decreases and the rate of ejection also decreases. At the end of systole, active contraction of the ventricle ceases and the pressure within the ventricle falls and the aortic valve closes. After closure of the aortic valve, the ventricles rapidly relax. Initially the valves remain closed so there is a decrease in pressure but no change in volume. This is called isovolumetric relaxation. When the pressure within the ventricle falls below that of the left atria, the mitral valve re-opens allowing the ventricles to fill again during ventricular diastole.

**Changes in arterial blood pressure and flow during the cardiac cycle**

During systole, the blood is ejected from the left ventricle into the aorta where it displaces the blood from the previous ejection toward the periphery and also applies an outward force on the arterial wall. The lateral pressure generated within the artery during ejection will depend on the volume of blood ejected (the preload), the compliance of the vessel wall and the impedance to forward flow of the artery. The pressure produced by the ejected blood will be higher if, i) the
volume of blood ejected is greater; ii) the compliance of the arterial wall is decreased and iii) impedance to forward flow of blood is greater.

Due to the elasticity of the arterial wall, during diastole the wall rebounds helping to move the blood towards the periphery in a smoother pattern. This is known as the Windkessel effect. The pressure waveform travels along the artery to the periphery where it is reflected by branching or narrowing vessels. The reflected pressure waveform then superimposes on the forward pressure waveform to produce the final waveform that is typically recorded with monitoring equipment.

The following information can be obtained from the final arterial waveform: systolic, diastolic, mean pressure and the pulse pressure. Systolic arterial pressure (SAP) is the maximum arterial pressure that occurs when the ventricles of the heart are maximally contracted during systole. Diastolic arterial pressure (DAP) is the minimum aortic pressure and occurs when ventricles are maximally relaxed and the heart is filling with blood. The mean arterial blood pressure (MAP) is often described as the average of the pressure measured over the entire cardiac cycle. These variables are those most commonly used in clinical practice.

However the arterial waveform is composed of several superimposed pressure waves with varying frequency and amplitude. Using Fourier transformation the different sine waves that make up the final waveform can be separated. While this is not used in clinical practice, this aspect is important for understanding the techniques used to measure and record the arterial pressure waveform.
Methods for measuring arterial blood pressure

There are two main methods available for measuring arterial blood pressure: invasive (direct) and non-invasive (indirect). Each of the methods has advantages and disadvantages. The following section will discuss the principles of measurement of blood pressure using currently available direct and indirect techniques, the advantages and disadvantages of each technique and the limitations of each technique. The accuracy of the techniques used in veterinary anaesthesia will also be reviewed.

Invasive techniques for measuring blood pressure

Principle of invasive measurement

Invasive blood pressure measurement is considered to be the gold-standard when monitoring blood pressure. The most common method for measuring arterial pressure invasively in clinical practice is via placement of an appropriately sized catheter into a peripheral artery. The catheter can be connected to via fluid filled tubing to either an aneroid manometer (Figure 1.1) or a pressure transducer (Figure 1.2).
Figure 1.1 Aneroid manometer used to measure arterial blood pressure.

Figure 1.2 Becton-Dickinson blood pressure transducer used to determine direct arterial blood pressure.

Aneroid manometer

An aneroid manometer is composed of a metal bellows that changes size when pressure is applied. This turns moves a pointer on a scale. The arterial pressure is transferred to the manometer via a fluid filled line, which is connected to the catheter, and then air filled tubing which attaches to the manometer. Prior to
measurement, the interface between the fluid and air filled line is adjusted to
correspond to the level of the right atrium. This corresponds to a pressure of zero
when compared to atmospheric pressure. At start of measurement, a connector
placed between the artery and fluid line is opened allowing blood to flow into the
fluid filled tubing. The blood flows into the tubing until the height of the column of
water equals the mean arterial blood pressure within the artery. The pressure
within the line at this point is measured by the manometer.

Advantages and disadvantages of the aneroid manometer
The advantage of this method is that it is simple to do, with easily obtained
equipment. The disadvantage of this method is that it only allows the measurement
of mean arterial pressure and not systolic or diastolic pressure. In addition, no
graphical representation of the pressure waveform is produced.

Pressure Transducer

A transducer is used to convert the pressure from the artery into an electrical
signal. The most common type of transducer used for blood pressure
measurement is the Wheatstone bridge.

The Wheatstone bridge is an electrical circuit consisting of four strain gauges with
each pair of strain gauges forming one side of the bridge. The bridge is attached to
a diaphragm made of a flexible elastomeric material which moves in response to
an applied pressure. When no pressure is applied the resistance to current is the same on both sides of the bridge and no current flows.

When the transducer is connected to the artery the arterial pressure is transferred via the fluid filled line to the diaphragm. Distortion of the diaphragm by the applied arterial pressure causes two of gauges on one side of the bridge to compress and the other two to expand. This causes the resistance to an electric current to be different (unbalanced) between the two sides of the bridge and as a result current can flow. The resulting current produces a potential difference that can be measured using a galvanometer. As the potential difference is proportional to the pressure applied to the diaphragm and the associated change in resistance within the circuit, (Ohm's Law), the machine can process the electrical signal to generate a graphical representation of pressure arterial waveform.

As previously discussed, the maximum pressure of the arterial waveform is the systolic pressure, and the minimum pressure is the diastolic pressure. The mean pressure is calculated from the arterial waveform. Different BP monitors use different algorithms to calculate the MAP One method is to calculate MAP as the total area under the pressure waveform. The area represents the change in pressure over a defined period of time. Another method is to calculate MAP using the following formula: Mean blood pressure = diastolic pressure + 1/3(systolic-diastolic pressure).
Advantages and disadvantages of ABP transducer

The advantage of this method is that it provides a beat-to-beat measurement of blood pressure which is imperative for patients where changes in blood pressure are likely to be rapid and significant. Disadvantages of this method include the cost of the transducer, the technical skill required to place and arterial catheter, and the potential creation of a catheter site infection.

Factors that influence accuracy of direct BP measurement

There are many factors that can contribute to inaccurate blood pressure measurements using direct measurement techniques. These include changes in signal resonance or damping, the position of the transducer relative to the heart base, the distance of the catheterised vessel from the heart and placement of the catheter in either a normograde or retrograde position.

Resonance and damping

Resonance is the phenomenon that occurs when a force applied to a material causes it to oscillate at its maximum amplitude. Each transducer and fluid line has a frequency at which it will oscillate maximally, known as natural frequency. As described above, each arterial pressure wave form is a combination of sine waves of various frequencies. If one of the arterial sine waves has a similar frequency, to the natural frequency of the transducer and fluid line the system will oscillate at its maximum amplitude. If this occurs then excessive amplification and distortion of the arterial waveform can occur. Resonance of the BP measurement system can
be assessed using a dynamic pressure response test. In this test the transducer is exposed to pressurised saline. The saline is compressed within an inflatable bag producing a marked increase in pressure within the bag and the fluid line connecting the bag to the transducer. When the transducer is exposed to a sudden application of pressure on the measurement system by being flushed with the pressurised saline, a maximum pressure is registered by the monitoring equipment which should equal that of the applied pressure. If a fluid bag is pressurised to 300mmHg then the maximum pressure registered by the measurement system should be 300 mmHg. Following the maximal pressure, oscillations in pressure will be recorded. The resulting frequency of the pressure oscillations gives an approximate estimation of the resonant frequency of the system. Resonant frequency is equal to one second divided by the length of time required to complete one oscillation and this is normally between 10 and 50Hz. It is important to recognize the resonant frequency as it should be approximately eight times higher than arterial waveform frequency i.e. the pulse rate.

Damping is where the energy within the measuring system is absorbed resulting in reduction in amplitude of oscillations. Some damping (critical or optimal damping level) is required within the transducer system to prevent resonance but still allow accurate reconstruction of the arterial waveform and to ensure the pressure returns to zero promptly. To assess whether the system is optimally damped a fast flush or a square wave test can be done. In this test the catheter is rapidly flushed with pressurised saline, as described above and a square wave form appears. The oscillations of the waveform should disappear and the pressure, return to zero.
within one to two oscillations. By using the amplitude ratio of the first two resulting waves the damping coefficient (the smaller amplitude divided by the larger amplitude) can be calculated. Optimally damped systems have a damping coefficient of approx 0.7.\textsuperscript{9}

If a system is inappropriately damped then erroneous blood pressure measurements, particularly systolic and diastolic BP, are obtained. Inappropriate damping may include under or overdamping.

**Underdamping.**

When damping of the transducer system is small (underdamped), the resonant frequency of the transducer system is equal to the natural frequency of the arterial sine wave forms. This results in superimposition of the oscillations within the transducer on the oscillation produced by arterial pressure waveform. This produces a waveform with a falsely elevated systolic pressure and a falsely low diastolic pressure. The natural frequency of the system is proportional to its stiffness and inversely proportional to its mass, length and diameter.

Underdamping is associated with increased stiffness, reduced length of catheter and/or tubing, decreased fluid density, and increased catheter or tubing diameter.
**Over-damping**

If the system is over damped then the energy within the oscillating system will be reduced and thus the amplitude of the oscillations will be decreased. This results in decreased systolic pressures but increased diastolic pressure. Causes of overdamping include a blocked catheter, air bubbles, vasospasm or kinked/collapsed tubing, use of narrow, long or compliant tubing and use of three way taps.

The diameter of the tubing has the greatest overall effect on the entire system’s performance. Any decrease in the diameter of the tubing will cause damping to increase by the power of a $1/3^{rd}$ of the amount decreased. e.g. if there is a 33 % reduction in the diameter then there will be an increase in damping by 135 %.

**Position of the transducer**

The position of the transducer relative to the base of the heart will also affect the blood pressure measurement recorded. As the arterial pressure within the central arteries, such as aorta, influence the blood flow to the entire body, a measure of this pressure is considered the most clinically useful measurement. To obtain this measurement, the transducer or the fluid-air interface must be placed level with the base of the heart. If using an electronic device, the transducer is then exposed to atmospheric pressure, and the measured pressure reset to zero. Zeroing
eliminates the effect of gravity and the associated changes in hydrostatic pressure that will alter blood pressure measured from an artery that is not at the same level as the aorta. A change in the position of the transducer or air-fluid interface by 10cm in either direction will alter blood pressure readings by 7.4mmHg due to the confounding effect of hydrostatic pressure on the measured arterial blood pressure. If the artery is located below the heart, the measured pressure is higher and if the artery is located above the heart the measured pressure is lower than that in the aorta.

Distance between heart and artery used for measurement

The distance between the heart and the catheterised vessel will also alter blood pressure measurements. As the pressure wave moves towards the periphery the pulse becomes amplified due to the non-uniform elasticity of the peripheral arteries. The systolic pressure is mainly affected and when observing a peripheral arterial waveform the systolic portion becomes narrower and of greater amplitude. As the actual area under the curve does not change, the MAP is less affected by the distance from the heart. In humans the systolic pressure in the peripheral arteries may be up to 20mmHG higher than pressure measured in the proximal aorta.
Blood flow direction

Measurement of BP invasively is also affected by the placement of the catheter relative to blood flow. When the catheter is placed in the artery toward the heart and the direction of blood flow (retrograde), the blood flow will impact the catheter tip. According to Bernoulli’s principle, the total amount of energy must remain constant, thus when the kinetic energy becomes zero, at the time of impact, there must be compensatory increase in potential energy i.e. blood pressure. If the opening of the catheter is at the tip, this will result in an increase in the measured pressure particularly SAP. This has been reported to cause a measured SAP of up to 20 mmHg higher than actual SAP. In contrast, if the opening of the catheter is on the side, it will not be impacted by the blood flow therefore, only the potential energy, which is the lateral pressure acting on the walls, will be measured. This type of catheter may provide a more accurate measure of blood pressure particularly SAP, however these catheters are not commercially available.

Non-Invasive techniques for measuring blood pressure

There are several methods available for measuring arterial blood pressure non-invasively. The principles, advantages and disadvantages, and limitations of each of these techniques will be described briefly in the following review. As the oscillometric method is the only available technique capable of measuring systolic, diastolic and mean ABP in veterinary species, this technique will be discussed in more detail.
**Principle of all non-invasive techniques**

Non-invasive blood pressure measurement is based on the occlusion of blood flow to an extremity by the inflation of a pneumatic (air-filled) cuff. As the cuff is inflated the pressure within the cuff becomes greater than that within the artery and the walls of the artery become so closely opposed that blood flow ceases. The cuff is then gradually deflated in either a linear or a step-down fashion, until the pressure within the cuff decreases enough to allow the walls of the arteries to separate, and blood flow to recommence. The cuff is normally placed around an extremity e.g. a distal limb or a tail. The extremities are chosen as they are approximately cylindrical in shape and provide an even surface for the cuff to encircle. The cuff is then connected via tubing to either a sphygmomanometer or to an electronic machine. These methods of measurement provide intermittent measurements of blood pressure. Methods of obtaining non-invasive blood pressure measurements in this way include auscultation, oscillometric and Doppler techniques.

**Auscultation of Korotkoff sounds**

In human medicine, conscious patients have blood pressure measurement obtained with the auscultation method. This method involves the placement of a RIVA-Rocci cuff (named after an Italian physicist who designed the first sphygmomanometer) around the limb, normally just proximal to the elbow. The cuff is attached to an aneroid sphygmomanometer and a stethoscope is placed over the artery. The cuff is inflated until the pulse within the arm can no longer be auscultated. The cuff is gradually deflated while the operator continues to
auscultate the artery. As the cuff deflates distinct changes in sounds can be detected in association with the certain pressure levels. These five sounds are known as Korotkoff sounds and are described (Table 1.1).

<table>
<thead>
<tr>
<th>Category</th>
<th>Description of Sound</th>
<th>Pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>An initial sharp tapping noise</td>
<td>Pressure in the cuff ($P_{cuff}$) = systolic pressure ($P_{systolic}$)</td>
</tr>
<tr>
<td>II</td>
<td>A succession of murmurs</td>
<td>Diastolic pressure ($P_{diastolic}$) $&lt; P_{cuff} &lt; P_{systolic}$</td>
</tr>
<tr>
<td>III</td>
<td>The disappearance of the murmurs and recurrence of the tapping noise but less distinct</td>
<td>$P_{diastolic} &lt; P_{cuff} &lt;&lt; P_{systolic}$</td>
</tr>
<tr>
<td>IV</td>
<td>Muffling of taps:</td>
<td>$P_{diastolic} \leq P_{cuff}$</td>
</tr>
<tr>
<td>V</td>
<td>Silence</td>
<td>$P_{diastolic} &lt; P_{cuff}$</td>
</tr>
</tbody>
</table>

Table 1.1 Description of the five Korotkoff sounds.

The reasons for the sounds are still not fully understood but it is suggested that they are due either to the arterial wall stretching, turbulence within the vessel, bubble formation as the pressure from the cuff is gradually released, or to a combination of the three.\textsuperscript{15,16}
**Advantages and disadvantages**

The main advantage of this technique is the simplicity of the equipment required i.e. a stethoscope and a sphygmomanometer. The manometer can be either mercury or an aneroid manometer. The use of a mercury manometer is considered gold standard and thus this is the second advantage of this method. It provides an absolute result based on the measurement of the height of a column of mercury which is not affected by drift and does not need to be calibrated. The major disadvantage with the use of this method is that Korotkoff sounds are difficult to detect in dogs and cats and so non-invasive blood pressure measurements cannot be obtained with this method. The reason the sounds are difficult to obtain in dogs is the lack of superficial arteries of a sufficient size to produce the sounds.\(^7\)

**Accuracy of the auscultation method**

This accuracy of this technique in animals has only been reported in horses. In a study that compared invasive to non-invasive BP measurements using the Korotkoff sounds in horses, IBP measurements were obtained via a catheter placed in the facial artery and attached to the Narkovet-E oscilloscope, as well as by using an aneroid manometer attached to an arterial catheter placed in the dorsal metatarsal artery. Non-invasive BP measurements were obtained by using the Korotkoff sounds from a stethoscope placed over a part of the radial artery. The study found that the Korotkoff sounds can be used to track changes of the SAP but that these changes will be consistently higher than those using the IBP oscilloscope method.
Doppler technique

The Doppler method of measurement is based on the concept that the frequency (and so the pitch) of the wave, either light or sound, created by an object, will change as the object moves away from or towards a receiver. This theory can also be applied to blood pressure measurement. In order to measure blood pressure, a piezoelectric crystal is placed over a peripheral artery. The piezoelectric crystal is attached to a Doppler ultrasonic blood pressure machine. When the machine is turned on, an electric current is applied to the piezoelectric crystal which causes the crystal to vibrate and emit sound waves (ultrasonic sound waves). These sound waves travel towards the blood vessel where they are reflected by moving red blood cells. When the crystal comes into contact with the reflected sound waves, the piezo-electric crystal again deforms generating an electrical current which is then transmitted back to the machine. The change in frequency of the reflected sound waves by moving red blood cells can be described using the following formula:

$$\Delta f = \frac{(f_o \times V)}{C}$$

where $\Delta f$ is equal to the change in frequency,

$f_o$ is equal to the original frequency,

$V$ is equal to the velocity of the blood,

$C$ is equal to the speed of sound within the tissue.

The difference between the emitted and reflected sound waves produces an audible signal.
This principle can be used to measure blood pressure. A cuff with an associated sphygmomanometer is placed proximal to the crystal. The cuff is inflated until the audible signal associated with blood flow is no longer evident. The cuff is gradually deflated until the audible signal returns, which is the restoration of blood flow. The pressure within the cuff at this time is considered to be an approximation of systolic pressure, in most species. Mean and diastolic pressures cannot be obtained from this method of measurement.\(^{17}\) The exception appears to be cats as the pressure at which blood flow returns has been reported to closely approximate mean blood pressure.\(^{18}\)

**Advantages and disadvantages**

One of the advantages of this method is that it is extremely sensitive even in low-flow situations e.g. the hypotensive or the very small patient. An added advantage to this method is that by leaving the piezoelectric crystal positioned over the artery, the pulse wave can be heard and a pulse rate obtained. The main disadvantage of this method is that it only measures a single pressure. Measurements may also be difficult to obtain if there is insufficient coupling gel between the probe and the body surface, if there is hair over the site where the measurements are being obtained, if the patient is moving or if there is marked vasoconstriction.\(^{19}\)
**Accuracy of the Doppler method**

Inaccuracies in pressure measurement obtained using the Doppler technique occurred due to incorrect cuff size and placement. The cuff utilised must be the correct size, placed in the correct position and neither too tight or too loose. If the cuff is too narrow then it will give a falsely elevated reading whilst if the cuff is too wide then the reading will be too low.

The tightness of the cuff placement can also affect the reading given. If the cuff is placed too loosely then it will require an increased amount of air to inflate the cuff and therefore will give an extremely high reading while if the cuff is placed too tightly then the cuff itself can occlude the artery underneath and given an erroneously low reading. The reason that this is important is that when measuring the pressure, the reading obtained is actually the pressure within the cuff and not that within the vessel.

The position of cuff can alter the reading. As previously described for transducers, it is important to adjust the position of the cuff approximately level with the base of heart in order to obtain a measure of central arterial pressure. If this is not possible then the measurement needs to be adjusted according to the height above or below the heart base. If the cuff is positioned lower than the base of the heart, e.g. when measuring ABP in a standing large-breed dog, the effect of hydrostatic pressure will cause an increase in the measured arterial pressure relative to the aortic pressure. Conversely if the cuff is placed above the base of heart then the measured pressures will be lower than the aortic pressure.
The position of the inflatable portion of the cuff (bladder) relative to the artery will also affect accuracy of measurements. Some cuffs only inflate certain parts of the cuff i.e. the bladder does not encompass the entire length of the cuff. When using these cuffs, it is essential that the cuff is placed over the vessel so the artery is under the middle of the bladder. Other cuffs, such as those used with the Surgivet V9203 have no specific placement requirements as the entire bladder of the cuff inflates, ensuring that however the cuff is placed, the artery will always be positioned under the inflatable bladder.

**Plethysmography**

Another method of measuring blood pressure non-invasively is the penaz finger technique using optical plethysmography. It is also known as the Finapres technique which is an acronym for Finger arterial pressure.

In this method an inflatable and deflateable cuff is placed around a finger. Within this cuff is a photo-emitting diode which emits an infra-red light that is transmitted through the finger and is detected on the other side by a photocell. The amount of light absorbed by the tissues is proportional to the cross-sectional area of the finger occupied by blood and thus the volume of flow. The change in the amount of light reaching the photocell can be used to calculate change in blood volume within the finger.\(^{21}\) This process of absorption of light associated with a change in distant of travel is based on the Beer-Lambert Law. During each phase of the cardiac cycle the volume of blood flowing through the finger can change i.e. increase in volume during systole and decrease during diastole. This technique is designed to
maintain constant blood flow/volume and thus constant light absorption by changing the pressure in the cuff. The pressure within the cuff has been shown to approximately equal intra-arterial pressure.

Advantages and disadvantages

The main advantage of this method is that it provides an instantaneous, continuous reading of blood pressure instead of an intermittent reading. This method is also simple and easy to perform. However, inaccuracies occur if the cuff is positioned incorrectly, or if the patients have dark pigmentation as light absorption will be difficult to detect. Due to the compression of the finger it also becomes very painful after about 20-30 minutes. Due to these reasons it is rarely used in human patients and it is not used within the veterinary industry as there are no appropriately sized extremities on which to place the cuff.

Oscillometric blood pressure measurement

Principles of measuring blood pressure oscillometrically

The oscillometric method also involves the placement of a pneumatic cuff around the limb over a superficial artery. With this method the cuff is inflated automatically by the oscillometric blood pressure machine. The cuff is inflated above normal systolic pressure resulting in arterial wall compression and absence of blood flow. The cuff is deflated continuously or in a step-wise manner resulting in a gradual decrease in cuff pressure and return of blood flow. Blood flow produces small
oscillations in pressure within the cuff. The oscillations are caused by the movement of the arterial wall produced by the changing lateral pressure observed within the artery during the cardiac cycle. The mean pressure corresponds to the pressure in the cuff when the oscillations/pulsations caused by arterial wall movement are maximal. The systolic and the diastolic pressures are defined using monitor-specific algorithms when each of their oscillation amplitudes are a certain proportion of the maximal oscillation amplitude.

Advantages and disadvantages
One of the main advantages of this method is that it allows the automated measurement of systolic, mean and diastolic pressures to be obtained. In addition pulse rate can be calculated from the time between oscillations. Disadvantages of this method include the expense of the equipment, the length of time it takes to obtain an actual reading, intermittent measurement and the numerous factors that can lead to inaccurate measurement of blood pressure. It is important to recognize that measurement using this method should not be performed at intervals of less than two minutes for a prolonged period of time due to the risk of developing ischaemia in the tissues distal to cuff placement.

Factors that influence the accuracy of the oscillometric technique
Inaccurate measurement can be due to incorrect cuff size and placement, animal or disease factors that interfere with compression of the underlying artery and the method of cuff deflation. The effects of cuff size and position on blood pressure
measurement using the oscillometric technique is the same as that seen when using the Doppler technique (see above).

Animal factors that can interfere with oscillometric methods of blood pressure measurement include dehydration, hypovolaemia, hypervolaemia, hypothermia, stress, movement, oedema, or agitation. Low or irregular heart rates have also been observed to cause failure in blood pressure measurement when using this technique.²²

The method of cuff deflation may be either linear or a step based reduction²³. The method of cuff deflation affects the ability to detect the brief period of peak blood pressure, particularly in hypertensive patients.⁷,²⁴ The stepwise decrease in cuff pressure has the potential to miss the peak systolic pressure if the duration of each step is greater than the duration of the peak pressure. In contrast, machines such as the Datex-Ohmeda Cardiocap monitor²⁵ measures the cuff pressure continuously and thus would be expected to have greater accuracy in detecting the peak systolic pressure non-invasively.

Accuracy of the oscillometric technique in domestic animals

There have been numerous studies that have compared the relative accuracy of invasive measurements of ABP with the oscillometric technique. These studies have compared blood pressure measured by both techniques within both normal and abnormal blood pressure ranges.
In conscious animals, normal systolic pressures is considered to be between 120-160 mmHg, mean arterial pressure between 90 – 150 mmHg, and diastolic arterial pressure between 80 - 130 mmHg with variation between species.\textsuperscript{26}

\textbf{Accuracy of the oscillometric technique in dogs}

There is extensive research investigating the accuracy of different non-invasive techniques for measurement of arterial blood pressure in dogs.\textsuperscript{25, 27-32} Overall, oscillometric measurement is reported to provide a reasonably accurate measurement of blood pressure when compared to that obtained invasively in conscious\textsuperscript{27} and anaesthetised dogs\textsuperscript{28}, particularly if consecutive measurements were averaged.\textsuperscript{27} In general, most of the studies found that the oscillometric method underestimated invasive measurements particularly for SAP and that the agreement between invasive and non-invasive measurements increased with increasing BP. This was again most noticeable for the SAP measurements\textsuperscript{31, 33}. For the remainder of this thesis and for the purpose of this paper, the use of the term NIBP will refer to the oscillometric method of measurement of blood pressure.

Despite the large amount of research in this area, application of the results needs to be performed carefully as the results may not be relevant to all situations. A summary of the methodology used in these studies are presented in table 1.2. Firstly and most importantly these studies used a wide variety of equipment to measure either IBP or NIBP e.g. Cardell\textsuperscript{25, 30, 31}, Dinamap\textsuperscript{29}, Cardiocap\textsuperscript{25}, Datex Ohmenda\textsuperscript{32}, Gould\textsuperscript{31} and PETMAP\textsuperscript{32}. The algorithms used for calculation mean
arterial BP directly may vary between equipment, and the algorithms themselves are unavailable for assessment. In addition the method of cuff deflation used in oscillometric techniques also vary. These equipment differences prevent the findings obtained using one piece of equipment to be extrapolated to use of a different piece of monitoring equipment. There are also other important methodological differences that can alter the relative accuracies of the equipment tested. Different positions were selected for placement of either the NIBP cuff or the arterial catheter. The majority of the studies use the dorsal pedal or dorsal metatarsal artery for obtaining IBP\textsuperscript{25, 30, 32, 34}, however there is a large variation for NIBP position e.g. forelimb\textsuperscript{28, 29, 32}, hindlimb either above the hock\textsuperscript{28, 31, 34}, or around the metatarsus\textsuperscript{28, 31}. Furthermore, the accuracy of NIBP in these studies was determined at different blood pressure levels created pharmacologically using phenylephrine\textsuperscript{30} to increase blood pressure, or increasing isoflurane concentration\textsuperscript{31} to decrease blood pressure. The effect of heart rate on accuracy of non-invasive techniques has not been studied. In addition studies in animals with abnormal blood pressure associated with physiological abnormalities such as hypovolaemia due to blood loss have not been performed. Since hypovolaemia is a common cause of hypotension further investigation is warranted to investigate the accuracy of NBIP in hypovolaemic patients.
<table>
<thead>
<tr>
<th></th>
<th><strong>Invasive BP</strong></th>
<th></th>
<th><strong>Non-Invasive BP</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Machine</strong></td>
<td><strong>Site</strong></td>
<td><strong>Machine</strong></td>
<td><strong>Site</strong></td>
</tr>
<tr>
<td>Gains et al</td>
<td>Physio-Control VSM1 monitor</td>
<td>Sublingual artery</td>
<td>DinaMAP</td>
</tr>
<tr>
<td>Bodey et al</td>
<td>Gould</td>
<td>Metatarsal artery</td>
<td>DinaMAP</td>
</tr>
<tr>
<td>McMurphy et al</td>
<td>MT95000</td>
<td>Lingual a., dorsal pedal artery</td>
<td>Cardell</td>
</tr>
<tr>
<td>Sawyer et al</td>
<td>Gould</td>
<td>Tibial artery</td>
<td>Cardell</td>
</tr>
<tr>
<td>MacFarlane et al</td>
<td>Cardiocap II Datex-Ohmeda</td>
<td>Dorsal pedal artery</td>
<td>Cardell</td>
</tr>
<tr>
<td>Deflandre et al</td>
<td>Datex-Ohmeda S/5 Monitor</td>
<td>Dorsal pedal artery, femoral artery</td>
<td>Surgivet V60046</td>
</tr>
<tr>
<td>Bosiack et al</td>
<td>Datascope Passport</td>
<td>Dorsal pedal artery</td>
<td>Cardell and Datascope Passport</td>
</tr>
</tbody>
</table>

**Table 1.2** Summary of methodology used in studies comparing for measurement of invasive and non-invasive blood pressure in dogs.
**Accuracy of the oscillometric technique in horses**

Recent studies in horses have been limited to foals. Of the few studies, there was good agreement between MAP and DAP but poorer agreement for SAP with a trend for the NIBP to underestimate the IBP. Similar to the studies conducted in dogs, the horse studies also used different machines to measure both IBP and NIBP, as well as using different sites for both the invasive arterial catheter and the NIBP cuffs. A summary of the different methodology used in these studies is presented in table 1.3.
<table>
<thead>
<tr>
<th></th>
<th>Invasive</th>
<th>Site</th>
<th>Non-Invasive</th>
<th>Site</th>
</tr>
</thead>
<tbody>
<tr>
<td>Riebold et al</td>
<td>Aneroid manometer</td>
<td>Facial artery</td>
<td>Electronic sphygmomanometer</td>
<td>Base of tail</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>with piezoelectric crystal</td>
<td>(Coccygeal artery)</td>
</tr>
<tr>
<td>Branson et al</td>
<td>Model 870 Datascope</td>
<td>Facial artery</td>
<td>Vet/BP 6000</td>
<td>Base of the tail</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(Coccygeal artery)</td>
</tr>
<tr>
<td>Nout et al</td>
<td>ProPAQ Encore</td>
<td>Metatarsal artery</td>
<td>ProPAQ Encore</td>
<td>Base of the tail</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(Coccygeal artery)</td>
</tr>
<tr>
<td>Giguere et al</td>
<td>DOT-34 Datex Ohmeda</td>
<td>Metatarsal artery</td>
<td>Cardell and DinaMAP</td>
<td>Base of tail</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(Coccygeal artery),</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>metatarsal artery,</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>median artery</td>
</tr>
</tbody>
</table>

**Table 1.3** Summary of methodology used in studies comparing measurement of invasive and non-invasive blood pressure in horses.
Accuracy of the oscillometric technique in other species

There is not as much literature available for other species when comparing NIBP measurement to IBP measurements. The only other species in which the accuracy of oscillometric technique has been assessed is cats\textsuperscript{17}. There are no studies assessing the accuracy of oscillometric techniques in farm animals.

Conclusions

Due to the differences in methodology used for measuring BP non-invasively, it is not possible to extrapolate results from previous studies to other monitoring units. Despite numerous studies in dogs there are minimal studies investigating accuracy of oscillometric techniques during severe physiological stress such as haemorrhage. Information on oscillometric techniques in other species is also lacking and thus investigation of this technology in different species would also help resolve deficiencies in our knowledge of non-invasive blood pressure monitoring in anaesthetised animals.

Hypothesis

Recently the Surgivet V9203 has been made commercially available in veterinary practice. As the accuracy of this machine cannot be extrapolated from studies using other equipment, the accuracy and clinical usefulness of the Surgivet in clinical veterinary practice warrants investigation. Our hypothesis was that oscillometric measurements of blood pressure obtained using the Surgivet V9203
would have good agreement with blood pressure measurements obtained directly from an arterial catheter.
Chapter 2: Methods and materials

Aims

The study had three primary aims:

1) To investigate the accuracy of the oscillometric technique in greyhounds undergoing general anaesthesia, before and after haemorrhage

2) To investigate the accuracy of the oscillometric technique in horses undergoing general anaesthesia

3) To investigate the accuracy of the oscillometric technique in sheep undergoing general anaesthesia

Measurement of blood pressure

Monitoring of invasive and non-invasive measurements of BP for all three species was performed using a Surgivet V9203 (Sound Medical, VIC, Australia).

Invasive blood pressure measurement

Invasive blood pressure monitoring was performed using a transducer (Becton-Dickinson, NSW, Australia) connected to an arterial catheter via the fluid line provided. To allow re-use, part of the commercially available fluid line was replaced by a 25cm minimum volume IV extension set (Western Biomedical, WA, Australia), which was identical in length and volume to the commercial extension tubing. Both fluid lines demonstrated appropriate damping when the rapid flush test was
performed. Prior to commencement of each study the transducer was connected to an aneroid manometer to ensure accuracy and linearity between 0 and 20 kPa (0-150 mmHg).

Arterial catheterization was performed in greyhounds using a 20 g, 1 ¼ inch catheter (Becton-Dickinson, NSW, Australia) placed percutaneously into the left dorsal metatarsal artery. For horses, a 20 g, two inch catheter (Becton-Dickinson, NSW, Australia) was placed into either the facial or lateral facial artery to measure IBP. For the sheep, a 20 g, one inch catheter (Becton-Dickinson, NSW, Australia) was placed percutaneously into the radial artery. The catheters were all placed in an aseptic manner after clipping and disinfection of the site.

Following catheter placement, the transducer was positioned at the level of the right atrium and zeroed with respect to atmospheric pressure. The site of the right atrium was considered to be at the level of the sternum with the patient in lateral recumbency. When the patient was positioned in dorsal recumbency the site of the right atrium was considered to be at the level of the point of the shoulder. Prior to each measurement, the catheter was flushed with heparin diluted in 0.9% sodium chloride (Baxter, NSW, Australia) (2 iu/ml). Response to the rapid flush was subjectively assessed to ensure the level damping of the system was acceptable. In addition, change in amplitude of the blood pressure waveform was also assessed visually and if reduction of the amplitude was observed, rapid flush of the system was repeated. Quantification of the damping factor was not possible in this study. To ascertain if baseline drift had occurred during the study, the transducer was opened to the atmosphere at the end of each study.
Non-invasive blood pressure measurement

Non-invasive blood pressure (NIBP) measurement was measured oscillometrically with the placement of an appropriately sized cuff. Cuff size was based on Surgivet recommendations.

<table>
<thead>
<tr>
<th>Cuff Size</th>
<th>Circumference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small</td>
<td>3-9 cm</td>
</tr>
<tr>
<td>Medium</td>
<td>5-15 cm</td>
</tr>
<tr>
<td>Large</td>
<td>9-25 cm</td>
</tr>
<tr>
<td>Extra Large</td>
<td>17-41 cm</td>
</tr>
</tbody>
</table>

*Table 2.1 Guidelines for selection of appropriate cuff sizes for use with Surgivet V9200.*

In greyhounds, the cuff was placed around the right metatarsus over the dorsal metatarsal artery. All of the greyhounds included in this study required a medium cuff for blood pressure measurement. After cuff placement, the position of the hind limb was adjusted so the cuff was level with the right atrium and the transducer used to measure blood pressure invasively.

For the horses, the cuff was placed around the base of the tail over the coccygeal artery. To adjust for effects of hydrostatic pressure, the measured height difference in centimeters between the cuff and the heart was converted to mmHg by multiplying by 0.75 (1 cmH₂O of fluid height is equal to 0.75 mmHg). For
measurements obtained from the coccygeal artery, the height in mmHg was then subtracted from the measured blood pressure.

In the sheep, NIBP measurement was measured using a cuff placed around the contra-lateral antebrachium over the radial artery. After cuff placement, the position of the forelimb was adjusted so the cuff was level with the right atrium and the transducer used to measure blood pressure invasively.

**Data collection**

**Studies in anaesthetised greyhounds**

The aim of this study was designed to determine the effect of haemorrhage and body position on the accuracy of the Surgivet V9203.

**Animals**

Thirty-five greyhounds were surrendered to the hospital for blood collection under general anaesthesia prior to euthanasia (Animal Ethics Committee Permit R228609). All greyhounds were surrendered to the hospital at the owner’s request. A physical examination was performed and blood was collected for haematology and biochemistry. Greyhounds with an American Society of Anaesthesiologists (ASA) score\(^{37}\) of I or II were included in the study. The definition of the ASA score are defined in the table below.
ASA Physical Status Classification System

<table>
<thead>
<tr>
<th>ASA Physical Status</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASA Physical Status 1 -</td>
<td>A normal healthy patient</td>
</tr>
<tr>
<td>ASA Physical Status 2 -</td>
<td>A patient with mild systemic disease</td>
</tr>
<tr>
<td>ASA Physical Status 3 -</td>
<td>A patient with severe systemic disease</td>
</tr>
<tr>
<td>ASA Physical Status 4 -</td>
<td>A patient with severe systemic disease that is a constant threat to life</td>
</tr>
<tr>
<td>ASA Physical Status 5 -</td>
<td>A moribund patient who is not expected to survive without the operation</td>
</tr>
</tbody>
</table>

Table 2.2 American Society of Anaesthesiologists (ASA) classification of a patient’s physical status

Anaesthesia

Greyhounds were premedicated with 0.1 mg kg\(^{-1}\) methadone (Methone, Parnell, NSW, Australia) intravenously (IV), 15 minutes prior to induction of anaesthesia. Anaesthesia was induced with a maximum dose of 12 mg kg\(^{-1}\) thiopentone (Ilium Thiopentone, TroyLab, VIC, Australia) IV. Fifty percent of the dose was administered as a bolus and then the rest titrated slowly until depth of anaesthesia was considered adequate to allow intubation. Intubation was performed with a 10 mm cuffed endotracheal tube (ETT) and anaesthesia was maintained with isoflurane (ISO, Veterinary Companies of Australia, NSW, Australia) delivered in 100% oxygen via a re-breathing breathing system. Intermittent positive pressure
ventilation was performed using a volume cycled ventilator (Ohmeda 7000 Ventilator, BOC Health Care). Initially a tidal volume of 10 ml kg\(^{-1}\) and a respiratory rate (RR) of 10 breaths per minute was set. The ventilator settings were adjusted in order to achieve normocapnia (35 – 45 mmHg end-tidal carbon dioxide (EtCO\(_2\))) prior to bleeding. These settings were used for the remainder of the anaesthesia.

**Blood Donation/Collection**

Blood collection was performed via the carotid artery. The neck was clipped and disinfected. The right carotid artery was exteriorised surgically to facilitate blood collection. Blood was collected into sterile citrate infused bags (Fenwal, Lake Zurich, USA). Depending on the operator collecting the blood, needles attached to blood collection bags were inserted either directly into the carotid artery, or into a 14G catheter was placed in the artery. Approximately 60% of the circulating blood volume, based on a blood volume of 80 ml/kg, was collected from each dog. Based on the weight of the dog and the volume of a unit of blood (450 +/- 10%) the number of units to be collected from each dog was calculated. Blood collection was performed over 30 minutes. All greyhounds were euthanased at completion of the study.

**Data Collection**

For data collection, 29 of the greyhounds were positioned in lateral recumbency (Group 1), and six greyhounds were positioned in dorsal recumbency (Group 2).
Once instrumentation and repositioning if required, was performed, baseline data was collected. Three consecutive measurements of NIBP were obtained and averaged using the stat mode on the Surgivet monitor. Stat mode allows repeated measurements, of NIBP continuously for five minutes whilst the automated mode limits repetition of measurements to every 2 minutes. The average of the IBP recorded simultaneously with each measurement of NIBP was also obtained. This produced three corresponding measurements of invasive blood pressure which were then averaged to produce a single measure for comparison with the average NIBP measurement. Blood collection was then commenced. Measurements were then repeated after each unit of blood had been collected. Data was only collected if there was < 5 % variation in observed blood pressure and heart rate during each sample period.

Studies in anaesthetised horses

Animals

6 healthy horses (ASA 1 and II) requiring anaesthesia for elective surgery were included in this study.

Anaesthesia

Horses were premedicated with acepromazine 0.01 mg kg\(^{-1}\) IV. Anaesthesia was induced with 1.1 mg kg\(^{-1}\) xylazine (Xylazine, Ilium, NSW, Australia) IV, followed two minutes later by 2.2 mg kg\(^{-1}\) ketamine (Ketamine, Parnell, NSW, Australia) IV combined with 0.05 mg kg\(^{-1}\) diazepam (Pamlin, Parnell, NSW, Australia) IV. Once
the horses attained recumbency, they were moved into lateral recumbency and intubated with a size 20-26 mm ETT. Horses were then moved using a mechanical hoist from the induction box, into theatre where the horses were placed in dorsal recumbency on a padded surgical table. Anaesthesia of the horses was maintained using isoflurane delivered in 100% oxygen via a re-breathing circle system. All horses were mechanically ventilated with a pressure controlled ventilator (Bird Mark 7 Respirator) throughout their procedure to maintain an ETCO2 of 40-55mmHg.

Data Collection

Three consecutive measurements of both IBP and NIBP were recorded and averaged to obtain one paired sample. These measurements were done at randomly selected time points during anaesthesia when blood pressure and HR demonstrated less than 5 % variation.

Studies in anaesthetised sheep

Animals

Nineteen merino sheep were anaesthetised at the University of Western Australia for laparotomy. Weights were between 54 and 69.5 kg. Blood pressure measurement in these sheep was approved by the University of Western Australia Ethics Committee (RA/3/100/1003).
Anaesthesia

The sheep were premedicated with acepromazine 0.02 mg kg\(^{-1}\) IM and buprenorphine 0.01 mg kg\(^{-1}\) IM. Anaesthesia was induced with midazolam (5 mg/ml) and ketamine (100 mg/ml) combined and administered at a dose of midazolam (0.25 mg kg\(^{-1}\)) and ketamine (mg kg\(^{-1}\)) IV. The sheep were intubated with a size 8.5 mm cuffed ETT and maintained on isoflurane delivered in 100% oxygen via a re-breathing circle system. The sheep were ventilated throughout the procedure with a volume controlled ventilator to maintain an ETCO\(_2\) of 35 -45 mmHg. The sheep were positioned in dorsal recumbency.

Data Collection

Three consecutive measurements of both IBP and NIBP were recorded and averaged to obtain one paired sample. These measurements were done every fifteen minutes during anaesthesia. Blood pressure needed to be stable (maximum 5% variation) before measurements were performed.

Data and Statistical Analysis

Analysis was performed in all species using the pooled BP data and after subdivision of the BP data into the following categories: hypertension (MAP >120mmHg), high blood pressure (MAP 100-120 mmHg), normotension (MAP 80-100mmHg), low blood pressure (MAP 60-80mmHg) and hypotension (MAP < 60mmHg). These categories were chosen to allow comparison with previous
studies. In the greyhounds to assess the effect of physiological changes due to position, data was collected in dorsal and lateral recumbency. In addition to assess the effect of physiological changes associated with blood loss, the data available was further subdivided according to heart rate producing an additional two subgroups for each BP category: normal heart rate (n = 33) and tachycardia (defined as HR > 120 bpm) (n = 45).

The agreement between the systolic, mean and diastolic pressure measurements obtained using the direct and the indirect methods was calculated with Bland-Altman analysis using commercially available software (SPSS 17.0). The Bland-Altman plot examines the agreement between a ‘gold standard’ measurement technique and an alternative. A scatter plot was generated with the x-axis representing the mean of the paired measurements recorded by the two techniques. This is known as the bias. The y-axis represented the difference between the gold standard measurement technique and the alternative measurement. For the purpose of this analysis the invasive technique was considered to be the gold standard. From this graph the following information was obtained: positive and negative bias, and limits of agreement. Limits of agreement are defined as the bias +/-1.96 multiplied by precision, where precision is defined as the standard deviations (SD) of the difference between the paired results.
Chapter 3: Results from anaesthetised greyhounds

Thirty-five greyhounds were included in this study with a mean weight of 30kg and with a mean age of 3.5 years.

Group 1. Greyhounds positioned in lateral recumbency

Pooled Data

Twenty-nine greyhounds were placed in lateral recumbency for the procedure and a total of 84 paired measurements were obtained. A summary of the blood pressure recorded within each category are presented in Table 3.1. Bias, precision, along with the upper and lower 95% confidence intervals obtained from these are also presented in Table 3.1. Graphical presentation of the data is also presented in Figure 3.1. The bias for the systolic BP, mean BP and diastolic BP was 31.54 mmHg, 3.93 mmHg and 7.83 mmHg respectively.

Data subdivided into blood pressure categories

Based on the definition of each category, subdivision of results only produced data in three of the five categories. These included normotension, low blood pressure and hypotension. A summary of the blood pressure recorded within each category are presented in Table 3.2. Bias, precision, along with the upper and lower 95% confidence intervals obtained from these are also presented in Table 3.2 and figures 3.2 – 3.4. Systolic, mean and diastolic pressures obtained oscillometrically, were consistently lower than the IBP measurements in all
categories. In the hypotensive category, the MAP had the greatest agreement i.e. the least bias (1.30 mmHg), while the DAP and the SAP had a bias of 8.33 mmHg and 7.89 mmHg respectively. In the low blood pressure group the MAP had the best agreement with a bias of 4.66 mmHg, with the DAP and SAP being 9.31 mmHg and 30.79 mmHg. Within the normotensive blood pressure group, the MAP has the best agreement with a bias of 5.71 mmHg, DAP had a bias of 5.82 mmHg and SAP had a bias of 55.11 mmHg.

Data subdivided by heart rate

The data was then separated into categories based on HR: < 120 and > 120 and the bias and the precision for IBP versus NIBP were calculated. The results are presented in Table 3.3. These results demonstrate that the agreement for the mean and the diastolic blood pressure in the HR > 120 bpm group in all blood pressure categories, was much poorer than that of the HR < 120 bpm group. In contrast the agreement between systolic blood pressures measured using the two techniques improved when HR increased
**Group 2. Greyhounds positioned in dorsal recumbency**

Six greyhounds were placed in dorsal recumbency for the procedure and a total of 19 paired measurements were obtained. Based on the definition of each category, subdivision of results only produced data in four of the five categories. These included high normal BP, normotension, low blood pressure and hypotension categories. Due to the nature of the procedure and the induced hypovolaemia due to blood collection, there were relatively few results in the high normal group. For the purpose of this analysis data from high normal BP was combined with the normotensive data. Pooled results are presented in Table 3.4. A summary of the blood pressure recorded within each category are presented in Table 3.5. Bias, precision, along with the upper and lower 95% confidence intervals obtained from these are also presented in Table 3.5. The results from each category are also displayed graphically (see figure 3.5 – 3.8). The NIBP consistently underestimated the IBP except for the MAP in the low blood pressure group where the NIBP actually overestimated the IBP. The least bias was seen with the MAP in each of the groups, followed by the diastolic BP. The systolic pressure in each group again had the greatest bias although in the hypotensive group it was less than in the other two groups. The trends in bias from this group (Group 2) were similar to that seen in the greyhounds positioned in lateral (Group 1).
<table>
<thead>
<tr>
<th></th>
<th>Number</th>
<th>Invasive mean (SD)</th>
<th>Non-invasive mean</th>
<th>Absolute Bias</th>
<th>Absolute Precision</th>
<th>Upper 95% limit of agreement</th>
<th>Lower 95% limit of agreement</th>
<th>Relative Bias</th>
<th>Relative Precision</th>
<th>Upper 95% limit of agreement</th>
<th>Lower 95% limit of agreement</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAP</td>
<td>84</td>
<td>121.05 (51.8)</td>
<td>89.51 (28.7)</td>
<td>31.54</td>
<td>26.76</td>
<td>83.96</td>
<td>-20.90</td>
<td>21.72</td>
<td>13.99</td>
<td>49.15</td>
<td>-5.71</td>
</tr>
<tr>
<td>MAP</td>
<td>84</td>
<td>71.81 (25.19)</td>
<td>67.88 (23.90)</td>
<td>3.93</td>
<td>7.36</td>
<td>18.36</td>
<td>-10.50</td>
<td>5.09</td>
<td>10.58</td>
<td>25.83</td>
<td>-15.64</td>
</tr>
<tr>
<td>DAP</td>
<td>84</td>
<td>57.67 (19.90)</td>
<td>49.83 (22.35)</td>
<td>7.833</td>
<td>8.46</td>
<td>24.41</td>
<td>-8.74</td>
<td>15.44</td>
<td>16.53</td>
<td>47.85</td>
<td>-16.96</td>
</tr>
</tbody>
</table>

**Table 3.1** Invasive and non-invasive arterial blood pressures measurements (mmHg) using pooled data from greyhounds positioned in lateral recumbency (mean [SD]), Absolute and relative bias, precision and the 95% upper and lower limits of agreement for invasive and non-invasive measurements is also presented.
<table>
<thead>
<tr>
<th>Hypotensive (MAP &lt; 60 mmHg)</th>
<th>Number</th>
<th>Invasive mean (SD)</th>
<th>Non-invasive mean</th>
<th>Bias</th>
<th>Precision</th>
<th>Upper 95% limit of agreement</th>
<th>Lower 95% limit of agreement</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAP</td>
<td>27</td>
<td>69 (17)</td>
<td>61 (12)</td>
<td>7.89</td>
<td>10.2</td>
<td>27.91</td>
<td>-12.13</td>
</tr>
<tr>
<td>MAP</td>
<td>27</td>
<td>46 (88)</td>
<td>45 10</td>
<td>1.30</td>
<td>5.89</td>
<td>12.84</td>
<td>-10.25</td>
</tr>
<tr>
<td>DAP</td>
<td>27</td>
<td>38 (7)</td>
<td>30 (8)</td>
<td>8.33</td>
<td>7.53</td>
<td>23.10</td>
<td>-6.43</td>
</tr>
<tr>
<td>Low Blood Pressure (MAP 60-80mmHg)</td>
<td>SAP</td>
<td>29</td>
<td>116 (23)</td>
<td>85 (13)</td>
<td>30.8</td>
<td>15.4</td>
<td>61.06</td>
</tr>
<tr>
<td>MAP</td>
<td>29</td>
<td>68 (7)</td>
<td>64 (11)</td>
<td>4.66</td>
<td>6.67</td>
<td>17.73</td>
<td>-8.42</td>
</tr>
<tr>
<td>DAP</td>
<td>29</td>
<td>54 (6)</td>
<td>45 (11)</td>
<td>9.31</td>
<td>7.63</td>
<td>24.27</td>
<td>-5.65</td>
</tr>
<tr>
<td>Normotensive (MAP &gt; 80 mmHg)</td>
<td>SAP</td>
<td>28</td>
<td>176 (39)</td>
<td>121 (18)</td>
<td>55.11</td>
<td>26.77</td>
<td>107.58</td>
</tr>
<tr>
<td>MAP</td>
<td>28</td>
<td>100 (19)</td>
<td>95 (16)</td>
<td>5.71</td>
<td>8.73</td>
<td>22.82</td>
<td>-11.40</td>
</tr>
<tr>
<td>DAP</td>
<td>28</td>
<td>80 (14)</td>
<td>75 (17)</td>
<td>5.82</td>
<td>9.90</td>
<td>25.22</td>
<td>-13.57</td>
</tr>
</tbody>
</table>

Table 3.2 Invasive and non-invasive arterial blood pressure measurements (mean [SD]) subdivided according to magnitude of the BP measurement in greyhounds positioned in lateral recumbency. Bias, precision and the 95% upper and lower limits of agreement for invasive and non-invasive measurements are also presented.
Figure 3.1 Bland-Altman plots of agreement between IBP and NIBP of SAP (graph a), MAP (graph b) and DAP (graph c), obtained from greyhounds positioned in lateral recumbency. Lines indicate mean difference and +/- 2 standard deviations (SDs).
Figure 3.2 Bland-Altman plots of agreement between IBP and NIBP of SAP (graph a), MAP (graph b) and DAP (graph c), obtained from greyhounds positioned in lateral recumbency during hypotension. Lines indicate mean difference and +/- 2 SDs.
Figure 3.3 Bland-Altman plots of agreement between IBP and NIBP of SAP (graph a), MAP (graph b) and DAP (graph c), obtained from greyhounds positioned in lateral recumbency during low blood pressure. Lines indicate mean difference and +/- 2 SDs.
Figure 3.4 Bland-Altman plots of agreement between IBP and NIBP of SAP (graph a), MAP (graph b) and DAP (graph c), obtained from greyhounds positioned in lateral recumbency during normotension. Lines indicate mean difference and +/- 2 SDs.
<table>
<thead>
<tr>
<th></th>
<th>Number HR &lt; 120</th>
<th>Invasive Mean (SD)</th>
<th>Non-Invasive Mean (SD)</th>
<th>BIAS: HR &lt; 120</th>
<th>PRECISION: HR &lt; 120</th>
<th>Number HR &gt; 120</th>
<th>Invasive Mean (SD)</th>
<th>Non-Invasive Mean (SD)</th>
<th>BIAS: HR &gt; 120</th>
<th>PRECISION: HR &gt; 120</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hypotensive</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(MAP &lt; 60 mmHg)</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SAP</td>
<td>6</td>
<td>80 (29)</td>
<td>65 (17)</td>
<td>15.1</td>
<td>13.5</td>
<td>22</td>
<td>65 (12)</td>
<td>60 (10)</td>
<td>5.71</td>
<td>8.29</td>
</tr>
<tr>
<td>MAP</td>
<td>6</td>
<td>47 (10)</td>
<td>47 (13)</td>
<td>-0.17</td>
<td>3.94</td>
<td>22</td>
<td>46 (8)</td>
<td>44 (8)</td>
<td>2.53</td>
<td>6.56</td>
</tr>
<tr>
<td>DAP</td>
<td>6</td>
<td>37 (7)</td>
<td>31 (10)</td>
<td>6.50</td>
<td>3.28</td>
<td>22</td>
<td>38 (7)</td>
<td>29 (8)</td>
<td>9.41</td>
<td>7.95</td>
</tr>
<tr>
<td><strong>Low Blood</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pressure (MAP 60-80mmHg)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SAP</td>
<td>16</td>
<td>126 (17)</td>
<td>92 (12)</td>
<td>34.6</td>
<td>13.5</td>
<td>12</td>
<td>111 (24)</td>
<td>80 (11)</td>
<td>30.9</td>
<td>17.0</td>
</tr>
<tr>
<td>MAP</td>
<td>16</td>
<td>69 (7)</td>
<td>67 (11)</td>
<td>1.50</td>
<td>6.07</td>
<td>12</td>
<td>69 (6)</td>
<td>61 (9)</td>
<td>8.61</td>
<td>4.23</td>
</tr>
<tr>
<td>DAP</td>
<td>16</td>
<td>54 (7)</td>
<td>47 (12)</td>
<td>6.75</td>
<td>7.55</td>
<td>12</td>
<td>55 (5)</td>
<td>44 (10)</td>
<td>11.0</td>
<td>6.93</td>
</tr>
<tr>
<td><strong>Normotensive</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(MAP &gt; 80 mmHg)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SAP</td>
<td>11</td>
<td>180 (20)</td>
<td>115 (9)</td>
<td>65.4</td>
<td>18.3</td>
<td>11</td>
<td>135(28)</td>
<td>106 (18)</td>
<td>28.6</td>
<td>20.1</td>
</tr>
<tr>
<td>MAP</td>
<td>11</td>
<td>93 (6)</td>
<td>89 (8)</td>
<td>4.15</td>
<td>5.95</td>
<td>11</td>
<td>87 (10)</td>
<td>80 (15)</td>
<td>7.21</td>
<td>11.5</td>
</tr>
<tr>
<td>DAP</td>
<td>11</td>
<td>73 (6)</td>
<td>68 (10)</td>
<td>5.15</td>
<td>9.73</td>
<td>11</td>
<td>74 (12)</td>
<td>64 (14)</td>
<td>9.46</td>
<td>9.83</td>
</tr>
</tbody>
</table>

Table 3.3 Invasive and non-invasive arterial blood pressures (mean[SD]) during hypotension, low blood pressure, and normotension, in greyhounds positioned in lateral recumbency subdivided by heart rate. Bias, precision and the 95% upper and lower limits of agreement between IBP and NIBP are also presented.
<table>
<thead>
<tr>
<th></th>
<th>Number</th>
<th>Invasive mean (SD)</th>
<th>Non-invasive mean</th>
<th>Absolute Bias</th>
<th>Absolute Precision</th>
<th>Upper 95% limit of agreement</th>
<th>Lower 95% limit of agreement</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAP</td>
<td>19</td>
<td>110 (29)</td>
<td>86 (22)</td>
<td>24.2</td>
<td>13.29</td>
<td>50.23</td>
<td>-1.88</td>
</tr>
<tr>
<td>MAP</td>
<td>19</td>
<td>68 (19)</td>
<td>65 (20)</td>
<td>3.49</td>
<td>6.68</td>
<td>16.58</td>
<td>-9.60</td>
</tr>
<tr>
<td>DAP</td>
<td>19</td>
<td>57 (20)</td>
<td>49 (20)</td>
<td>7.68</td>
<td>11.48</td>
<td>30.18</td>
<td>-14.81</td>
</tr>
</tbody>
</table>

Table 3.4 Invasive and non-invasive arterial blood pressures (mean [SD]), for pooled BP measurements recorded in greyhounds positioned in dorsal recumbency. Bias, precision and the 95% upper and lower limits of agreement between IBP and NIBP measurements are also presented.
<table>
<thead>
<tr>
<th>Hypotensive (MAP &lt; 60 mmHg)</th>
<th>Number</th>
<th>Invasive mean</th>
<th>Non-invasive mean</th>
<th>Bias</th>
<th>Precision</th>
<th>Upper 95% limit of agreement</th>
<th>Lower 95% limit of agreement</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAP</td>
<td>7</td>
<td>77 (13)</td>
<td>61 (11)</td>
<td>16.38</td>
<td>11.33</td>
<td>39.57</td>
<td>-6.8</td>
</tr>
<tr>
<td>MAP</td>
<td>7</td>
<td>51 (7)</td>
<td>43 (6)</td>
<td>7.47</td>
<td>6.28</td>
<td>19.78</td>
<td>-4.83</td>
</tr>
<tr>
<td>DAP</td>
<td>7</td>
<td>40 (5)</td>
<td>32 (14)</td>
<td>7.95</td>
<td>11.65</td>
<td>30.79</td>
<td>-14.88</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Low Blood Pressure (MAP 60-80mmHg)</th>
<th>Number</th>
<th>Invasive mean</th>
<th>Non-invasive mean</th>
<th>Bias</th>
<th>Precision</th>
<th>Upper 95% limit of agreement</th>
<th>Lower 95% limit of agreement</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAP</td>
<td>7</td>
<td>123 (9)</td>
<td>92 (4)</td>
<td>30.57</td>
<td>6.79</td>
<td>43.8</td>
<td>17.26</td>
</tr>
<tr>
<td>MAP</td>
<td>7</td>
<td>67 (4)</td>
<td>69 (6)</td>
<td>-1.91</td>
<td>3.20</td>
<td>4.38</td>
<td>-8.19</td>
</tr>
<tr>
<td>DAP</td>
<td>7</td>
<td>53 (12)</td>
<td>48 (9)</td>
<td>5.57</td>
<td>14.53</td>
<td>34.06</td>
<td>-22.91</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Normotensive (MAP &gt; 80 mmHg)</th>
<th>Number</th>
<th>Invasive mean</th>
<th>Non-invasive mean</th>
<th>Bias</th>
<th>Precision</th>
<th>Upper 95% limit of agreement</th>
<th>Lower 95% limit of agreement</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAP</td>
<td>5</td>
<td>137 (20)</td>
<td>110 (3)</td>
<td>26.13</td>
<td>18.26</td>
<td>61.92</td>
<td>-9.67</td>
</tr>
<tr>
<td>MAP</td>
<td>5</td>
<td>95 (7)</td>
<td>90 (4)</td>
<td>5.47</td>
<td>6.52</td>
<td>18.25</td>
<td>-7.31</td>
</tr>
<tr>
<td>DAP</td>
<td>5</td>
<td>84 (12)</td>
<td>74 (8)</td>
<td>10.26</td>
<td>7.48</td>
<td>24.92</td>
<td>-4.40</td>
</tr>
</tbody>
</table>

Table 3.5 Invasive and non-invasive arterial blood pressures (mean[SD]) during hypotension, low blood pressure, and normotension, recorded in greyhounds positioned in dorsal recumbency. Bias, precision and the 95% upper and lower limits of agreement for IBP and NIBP measurements are also presented
Figure 3.5 Bland-Altman plots of agreement between IBP and NIBP of SAP (graph a), MAP (graph b) and DAP (graph c), obtained from greyhounds positioned in dorsal recumbency. Lines indicate mean difference and +/- 2 SDs.
Figure 3.6 Bland-Altman plots of agreement between IBP and NIBP of SAP (graph a), MAP (graph b) and DAP (graph c), obtained from greyhounds positioned in dorsal recumbency during hypotension. Lines indicate mean difference and +/- 2 SDs.
Figure 3.7 Bland-Altman plots of agreement between IBP and NIBP of SAP (graph a), MAP (graph b) and DAP (graph c), obtained from greyhounds positioned in dorsal recumbency during low blood pressure. Lines indicate mean difference and +/- 2 SDs.
Figure 3.8 Bland-Altman plots of agreement between IBP and NIBP of SAP (graph a), MAP (graph b) and DAP (graph c), obtained from greyhounds positioned in dorsal recumbency during normotension. Lines indicate mean difference and +/- 2 SDs.
Chapter 4: Results from anaesthetised horses

Six horses were suitable for inclusion in this study. A total of 28 paired measurements were obtained from these horses. The mean age of the horses in the study was 6 ¼ years (4yrs to 11 ¼ yrs), with the mean weight being 515 kg (74 kg). No data was available from the hypertensive category and only two paired measurements were available from the hypotension group. In the hypotensive category, the bias for SAP, MAP and DAP were 16.06, 16.22 and 7.05 respectively. Due to only two readings being obtained, when bias and precision were calculated and graphed, the BP values from the hypotension group were combined with the low BP group. A summary of the BP values pooled as well as from the remaining categories are presented in Table 4.1. Bias, precision, along with the upper and lower 95% confidence intervals are also presented in Table 4.1. The results from each category are also displayed as Bland-Altman figure 4.1 – 4.3. Within the normal blood pressure group, MAP has the least bias followed by DAP and then SAP (7.28 mmHg, 11.94 mmHg, and 13.03 mmHg respectively). In the high blood pressure group, DAP had the least bias (4.43 mmHg), with MAP having a bias of 4.48 mmHg and systolic with a bias of 15.01 mmHg. Systolic, mean and diastolic pressures obtained oscillometrically underestimated the IBP measurements obtained for all paired measurements except for five pairs. Three of these paired measurements were in the normal blood pressure group and two were in the high blood pressure group.
<table>
<thead>
<tr>
<th></th>
<th>Number</th>
<th>Invasive mean (SD)</th>
<th>Non-invasive Mean (SD)</th>
<th>Bias</th>
<th>Precision</th>
<th>Upper 95% limit of agreement</th>
<th>Lower 95% limit of agreement</th>
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<tbody>
<tr>
<td><strong>Pooled data</strong></td>
<td></td>
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</tr>
<tr>
<td>SAP</td>
<td>28</td>
<td>100 (12)</td>
<td>86 (13)</td>
<td>13.53</td>
<td>10.23</td>
<td>33.58</td>
<td>-6.52</td>
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<tr>
<td>MAP</td>
<td>28</td>
<td>72 (11)</td>
<td>66 (14)</td>
<td>6.58</td>
<td>7.39</td>
<td>21.05</td>
<td>-7.90</td>
</tr>
<tr>
<td>DAP</td>
<td>28</td>
<td>59 (11)</td>
<td>49 (15)</td>
<td>10.07</td>
<td>10.34</td>
<td>30.34</td>
<td>-10.20</td>
</tr>
<tr>
<td><strong>Low BP (MAP 60-80 mmHg) + hypotension (MAP &lt; 60 mmHg)</strong></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>SAP</td>
<td>21</td>
<td>94 (7)</td>
<td>81 (10)</td>
<td>13.03</td>
<td>10.23</td>
<td>33.08</td>
<td>-7.01</td>
</tr>
<tr>
<td>MAP</td>
<td>21</td>
<td>67 (6)</td>
<td>60 (10)</td>
<td>7.28</td>
<td>7.23</td>
<td>21.43</td>
<td>-6.89</td>
</tr>
<tr>
<td>DAP</td>
<td>21</td>
<td>55 (7)</td>
<td>43 (11)</td>
<td>11.94</td>
<td>10.57</td>
<td>32.66</td>
<td>-8.77</td>
</tr>
<tr>
<td><strong>Normotension (MAP &gt; 80 mmHg)</strong></td>
<td></td>
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</tr>
<tr>
<td>SAP</td>
<td>7</td>
<td>118 (7)</td>
<td>103 (9)</td>
<td>15.01</td>
<td>11.43</td>
<td>37.41</td>
<td>-7.39</td>
</tr>
<tr>
<td>MAP</td>
<td>7</td>
<td>87 (5)</td>
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<td>4.48</td>
<td>8.04</td>
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<td>-11.27</td>
</tr>
<tr>
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<td>73 (7)</td>
<td>69 (7)</td>
<td>4.43</td>
<td>7.72</td>
<td>19.56</td>
<td>-10.69</td>
</tr>
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</table>

Table 4.1 Invasive and non-invasive arterial blood pressures (mean [SD]), for pooled BP measurements and BP measurements subdivided by Bp magnitude horses positioned in dorsal recumbency. Bias, precision and the 95% upper and lower limits of agreement are also presented.
Figure 4.1 Bland-Altman plots of agreement between IBP and NIBP of SAP (graph a), MAP (graph b) and DAP (graph c), obtained from horses positioned in dorsal recumbency. Lines indicate mean difference and +/- 2 SDs.
Figure 4.2 Bland-Altman plots of agreement between IBP and NIBP of SAP (graph a), MAP (graph b) and DAP (graph c), obtained from horses positioned in dorsal recumbency during normotension. Lines indicate mean difference and +/- 2 SDs.
Figure 4.3 Bland-Altman plots of agreement between IBP and NIBP of SAP (graph a), MAP (graph b) and DAP (graph c), obtained from horses positioned in dorsal recumbency during high blood pressure. Lines indicate mean difference and +/- 2 SDs.
Chapter 5: Results from anaesthetised sheep

Nineteen sheep were suitable for inclusion in this study and a total of 54 paired measurements of BP were obtained. The age of the sheep in the study was approximately 12 months with the mean weight being 60.61 kg (3.69 kg). Based on the definition of each category, data was only available for three of the five BP categories. These included normotension, low BP and hypotension. However as there were only two paired measurements in normotensive pressure group this data was included in the low blood pressure group for analysis. A summary of the BP values grouped by blood pressure category are presented in Table 10. Bias, precision, along with the upper and lower 95% confidence intervals obtained from these are also presented in Table 5.1. The results from each category are also displayed as Bland-altmann graphs (figures 5.1 – 5.4). Within the low blood pressure group, SAP has the least bias followed by MAP and then DAP (4.48 mmHg, 12.22 mmHg, and 15.67 mmHg respectively). In the hypotensive pressure group, SAP had the least bias (-3.19 mmHg) again, with MAP and DAP having a bias of 5.33 mmHg and 9.00 mmHg respectively.
<table>
<thead>
<tr>
<th></th>
<th>Number</th>
<th>Invasive mean</th>
<th>Non-invasive mean</th>
<th>Bias</th>
<th>Precision</th>
<th>Upper 95% limit of agreement</th>
<th>Lower 95% limit of agreement</th>
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</thead>
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<tr>
<td><strong>Pooled data</strong></td>
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<tr>
<td>SAP</td>
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<tr>
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<tr>
<td>SAP</td>
<td>42</td>
<td>86 (7)</td>
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<td>11.09</td>
<td>26.22</td>
<td>-17.26</td>
</tr>
<tr>
<td>MAP</td>
<td>42</td>
<td>70 (7)</td>
<td>57 (9)</td>
<td>12.22</td>
<td>8.23</td>
<td>28.35</td>
<td>-3.91</td>
</tr>
<tr>
<td>DAP</td>
<td>42</td>
<td>60 (7)</td>
<td>45 (9)</td>
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<td>8.48</td>
<td>32.30</td>
<td>-0.95</td>
</tr>
<tr>
<td><strong>Hypotension (MAP &lt; 60mmHg)</strong></td>
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<td></td>
</tr>
<tr>
<td>SAP</td>
<td>12</td>
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<td>70 (17)</td>
<td>-3.19</td>
<td>17.62</td>
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<tr>
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<tr>
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<td>36 (7)</td>
<td>9.00</td>
<td>4.67</td>
<td>18.16</td>
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</tbody>
</table>

**Table 5.1** Invasive and non-invasive arterial blood pressures (mean [SD]), for pooled BP data and BP measurements subdivided according to magnitude of BP recorded in sheep positioned in dorsal recumbency. Bias, precision and the 95% upper and lower limits of agreement between IBP and NIBP measurements are also presented.
Figure 5.1 Bland-Altman plots of agreement between IBP and NIBP of SAP (graph a), MAP (graph b) and DAP (graph c), obtained from sheep positioned in dorsal recumbency. Lines indicate mean difference and +/- 2 SDs.
Figure 5.2 Bland-Altman plots of agreement between IBP and NIBP of SAP (graph a), MAP (graph b) and DAP (graph c), obtained from sheep positioned in dorsal recumbency during hypotension. Lines indicate mean difference and +/- 2 SDs.
Figure 5.3 Bland-Altman plots of agreement between IBP and NIBP of SAP (graph a), MAP (graph b) and DAP (graph c), obtained from sheep positioned in dorsal recumbency during low blood pressure. Lines indicate mean difference and +/- 2 SDs.
Chapter 6: Discussion

This study compared invasive and non-invasive measurements of arterial blood pressure measured from anaesthetised greyhounds, horses and sheep. Interpretation and discussion of the findings of the results can be divided into several areas including i) the type of agreement observed between measurements obtained in this study and how the results compare to previous work ii) the usefulness of non-invasiveness measurements of BP as an alternative to invasive measurements in clinical practice based on current recommendations and iii) factors that influenced the agreement and usefulness of measurements.

Agreement between non-invasive and invasive measurements

In all species, the non-invasive technique resulted in BP measurements that were lower than measurements of BP recorded using the invasive or direct technique. For the greyhounds and horses, the agreement between non-invasive and invasive measurements was better for MAP and DAP and poorer for SAP. In contrast, in sheep, the best agreement was observed for non-invasive and invasive measurements of systolic blood pressure. A more in depth discussion of the findings in each species is presented below.

Agreement between measurements recorded in greyhounds

The relationship between invasive and non-invasive measurements of MAP and DAP observed in greyhounds in the current study is consistent with results of previous studies, with only one of these\textsuperscript{33} using a Surgivet machine, albeit a different model to the one used in this current study.\textsuperscript{25, 30, 31, 33} However, the poor
agreement observed between non-invasive and invasive measurements of SAP in the current study was much greater than previous studies.

When the BP measurement was assessed in the current study, the same relationship as that described for the pooled data was present in each of the categories. The non-invasive measurements were nearly always lower than invasive measurements with the best agreement being observed for the majority of MAP and DAP measurements, and the worst agreement being observed for SAP. Another finding in the current study was the tendency for the agreement to decrease (i.e. the bias to increase) with increasing blood pressure. This was particularly noticeable for the SAP measurements.

Previous studies in dogs have also reported that the non-invasive BP measurements are lower than the invasive measurement in the majority of comparisons. Many of these previous studies also reported similar limits of agreement to those observed in the current study with better agreement between MAP and DAP and poorer agreement between SAP measurements particularly at higher BP. A summary of the findings in previous and the current study are presented in table 6.1. There were some interesting findings from other studies that are worthy of note. Gains et al (1995) observed that although the oscillometric method underestimated the measurements obtained from the IBP method at a light plane of anaesthesia, and overestimated IBP measurement at a deep plane of anaesthesia, it still produced a relatively accurate estimation of direct systolic, diastolic and mean blood pressure. Bodey et al (1994) found that indirect blood pressures were more likely to approximate direct measurements if a number of
consecutive measurements were recorded and averaged. These authors also reported a greater difference between direct and indirect pressure techniques for SAP. MacFarlane et al (2010) found that although the overall agreement was good between the IBP and the NIBP measurements for systolic, diastolic and mean, the variation for individual results was large and care needed to be taken when interpreting NIBP results. The most notable difference between the current study and previous reports was the magnitude of the bias reported between non-invasive and invasive measurements of SAP and the magnitude of the change in bias observed with increasing BP.

While some of the previous studies demonstrated an increase in bias with increasing blood pressure, the increase was not as marked as in the current study. It is important to note that none of the dogs in the current study were categorised as high BP or hypertension. The absence of data in these categories in the current study does limit the ability to compare the results that were obtained in the current study to that of previous studies. However the magnitude of the increase in bias between the hypotensive and normotensive dogs in the current study is much greater than the change in bias reported between hypotensive and normotensive dogs\textsuperscript{31} and is also much greater than the change in bias reported between normotensive and hypertensive dogs.\textsuperscript{30, 33}
Table 6.1 Summary of calculated bias between NIBP and IBP measurements reported in previous canine studies. Bias from current study is presented for comparison.

Possible reasons for poor agreement between SAP in the dogs in the study will be discussed below.

Agreement between measurements recorded in horses.

The results from the anaesthetised horses were similar to those recorded in greyhounds with, the best agreement between the two methods observed for the MAP and DAP. In contrast, although the bias for the systolic BP was greater, the markedly elevated bias that was evident in the greyhounds was not seen in the horses. A summary of the findings in previous and the current study are presented in table 6.2. Although data is limited, it appears that the agreement observed in the horses in the current study is comparable to most of the previous work.
Table 6.2 Summary of calculated bias between NIBP and IBP measurements reported in previous equine studies. Bias from current study is presented for comparison.

<table>
<thead>
<tr>
<th></th>
<th>Drynan</th>
<th>Nout</th>
<th>Giguere</th>
<th>Giguere</th>
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</tr>
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<tr>
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<td>Foals</td>
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</tr>
<tr>
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<td></td>
<td>horses</td>
</tr>
<tr>
<td>Pooled</td>
<td>SAP</td>
<td>13.53</td>
<td>8.0</td>
<td></td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>MAP</td>
<td>6.58</td>
<td>-1.1</td>
<td>4.5</td>
<td>-0.5</td>
</tr>
<tr>
<td></td>
<td>DAP</td>
<td>10.07</td>
<td>-1.3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Agreement between measurements recorded in sheep.

In the sheep component of the study, the best agreement between the methods was observed for SAP. This finding differed from that observed in the other species studied. Interestingly, the MAP obtained non-invasively appeared to consistently provide a closer approximation of the invasive DAP measurement. Assuming the invasive measurement is accurate, this finding may reflect an anatomical or physiological difference in sheep that alters the detection of wall movement by the oscillometric technique. Unfortunately there are no other studies comparing oscillometric and invasive BP measurement in sheep and further studies in this species are needed to investigate this finding.
Due to the lack of previous studies in sheep, we were unable to compare our study results to those of previous studies.

**Clinical usefulness of the Surgivet V9203**

To put the results of this study into context, it is important to determine whether the non-invasive blood pressure measurements recorded using the Surgivet V9203 provides a clinically useful alternative to invasive measurements. This can be determined by comparing the bias and precision of measurements recorded in this study to the recommendations of the American Association for the Advancement of Medical Instrumentation and the American College of Veterinary Internal Medicine Hypertension Consensus Panel & Veterinary Blood Pressure Society.

The American Association for the Advancement of Medical Instrumentation (AAMI)\(^3\) state that a mean difference (bias) of < 5 mmHg with a standard deviation (precision) of < 8 mmHg is acceptable variation between measurements obtained using invasive and non-invasive techniques. However the American College of Veterinary Internal Medicine Hypertension Consensus Panel & Veterinary Blood Pressure Society (ACVIM & VBPS) states that a bias of ≤ 10 mmHg with a precision of ≤ 15mmHg is also acceptable. Their guidelines also suggest that the following conditions should be met at the same time in order for the system to be validated:
1) The correlation between paired measures for systolic and diastolic pressures treated separately is > 0.9 across the range of measured values of BP;

2) 50% of all measurements for systolic and diastolic pressures treated separately lie within 10 mm Hg of the reference method;

3) 80% of all measurements for systolic and diastolic pressures treated separately lie within 20 mm Hg of the reference method; the study results have been accepted for publication in a referred journal;

4) The subject database contains no fewer than 8 animals for comparison with an intra-arterial method or 25 animals for comparison with a previously validated indirect device.

The higher values for bias and precision described by the ACVIM & VBPS were based on what is considered to be a tolerable error on the basis of clinician input.\textsuperscript{40} The AAMI also suggest that an average of three readings be taken. Of the many blood pressure studies performed, relatively few are validated.\textsuperscript{24}

**Clinical usefulness in greyhounds**

Based on the recommendations of the AAMI, assessment of pooled data suggested that only the mean arterial pressure measured non-invasively was an acceptable alternative to invasive measurements. This was the same in greyhounds in each group. When the data was separated into different blood pressure categories, only the non-invasive measurements of mean in the
hypotensive and low blood pressure groups was considered an acceptable alternative to invasive measurements. Assessment of the effect of heart rate on the accuracy of the blood pressure measurements revealed that when HR is < 120, only MAP recorded non-invasively in all pressure categories would be considered an acceptable alternative to invasive MAP. When HR was > 120, only the MAP in the hypotensive group was considered accurate.

Assessment of data using the recommendations of ACVIM and VBPS revealed that non-invasive measurements of mean and diastolic pressures in all pressure categories were considered acceptable alternative to invasive measurements. In addition, non-invasive measurements of SAP in hypotensive animals were also considered clinically useful. When the effect of heart rate on the accuracy of blood pressure measurements was assessed, both non-invasive MAP and DAP would be considered clinically acceptable according to ACVIM and VBPS at normal and high HR. This was in contrast to the SAP which was considered clinically useful only when HR was > 120 bpm.

Thus depending on the recommendations used, it would appear that MAP and possibly DAP measured non-invasively with the Surgivet V9203 provide clinically useful measurements for monitoring blood pressure although greater care is recommended when interpreting BP recorded at higher heart rates. It would also appear that non-invasive measurements of SAP recorded in anaesthetised greyhounds have limited clinical usefulness.
Clinical usefulness in horses

Based on the AAMI validation criteria the only measurements that could be validated within our study was the diastolic BP in the normal blood pressure group. However if we utilised the ACVIM & VBPS recommendations then the mean blood pressure in the pooled groups, as well as MAP in the normotensive group, and the mean and the diastolic in the high blood pressure group would be validated. Thus, the non-invasive MAP appears to be the only consistently useful measure of pressure that can be used as an alternative to invasive measurements in the horse.

Clinical usefulness in sheep

Based on the AAMI validation criteria, the current study indicates that none of the results in the sheep could be validated. If the data is assessed using the ACVIM & VBPS recommendations then the SAP, MAP and the DAP in the hypotensive group and SAP in the low BP group could be validated. Thus SAP appears to be the most reliable measurement obtained using the oscillometric technique in this species. The reason for the difference between sheep and the other species in this study is not readily apparent.
Factors affecting the agreement and clinical usefulness of measurements

In the current study, there was poor agreement between non-invasive and invasive SAP in both the greyhounds and horses. According to current recommendations the large bias obtained makes the non-invasive measurement of SAP an unsuitable replacement for invasive measurement. In contrast, in the sheep studies, the agreement for SAP measurements supported the clinical usefulness of the non-invasive measurement of SAP from the radial artery. However the agreement between measurements of MAP and DAP particularly from the low pressure group did not support clinical usefulness. Possible reasons for the poor agreement in these measurements are discussed in the following section.

Factors contributing to poor agreement in SAP measurement in greyhounds and horses.

There are several possible reasons why the agreement between invasive and non-invasive SAP measurements was poor in horses and greyhounds in the current study. These include i) technical factors associated with measurement of BP, ii) measurements of invasive and non-invasive blood pressure from arteries at varying distance from heart, iii) the direction of the catheter relative to blood flow; iv) the position of the animal; v) the method by which blood pressure was altered and the associated heart rate changes that may have occurred, and vi) breed and species variation. A discussion of each of these factors is presented below.
Technical factors affecting BP measurement

In the current study, it is possible that technical factors could in part explain the differences observed between invasive and non-invasive BP measurements. As only one monitor was used in this study for both invasive and non-invasive measurements, there was no way to assess the intrinsic performance of the monitor and this itself may have had an effect on the results.

Technical factors affecting non-invasive pressure measurement

Technical factors that can affect accuracy of measurements of BP obtained using the oscillometric technique include cuff size and position relative to the heart, the method of cuff deflation and the type of cuff used. In the current study the effect of cuff size and position was minimised by selecting the cuff for each patient based on the manufacturer’s recommendations and by either ensuring the cuff was positioned level with the heart base or adjusting the measurement based on measured distance between heart base and cuff. If these factors contributed to inaccurate measurements, it would be expected that agreement for MAP and DAP would also have been poor.

Differing methods of cuff deflation used by the different oscillometric BP monitors could account for the discrepancy between the current study and other work. The method by which the cuff is deflated could influence the accuracy of BP measurement particularly the SAP, particularly in hypertensive patients. The stepwise decrease in cuff pressure has the potential to miss the peak systolic pressure if the duration of each step is greater than the duration of the peak
pressure. If the step wise decrease in cuff deflation used by the Surgivet V9200 is too long, this could explain the poor agreement between invasive and non-invasive measurement of SAP and the increasing bias observed as blood pressure increased. Better agreement for SAP in other studies would be expected if a different method of cuff deflation such as continuous deflation was used. Unfortunately it is not possible to ascertain the algorithms used for cuff deflation in all of the currently available BP equipment.

An obvious difference between the oscillometric method used in the current study and that of previous studies is the cuff design. The cuff used with the Surgivet is a unique design with the bladder of the cuff extending the entire length of the cuff (360 degree bladder). This contrasts to other cuffs that have a small bladder, and require that the centre of the bladder be placed directly over the artery. Whether this cuff design could impact the ability to detect the initial peak pressure is not known.

**Technical factors affecting invasive measurements of BP**

There are also factors that can reduce the accuracy of blood pressure measured invasively and these factors also need to be considered when interpreting the results of this study. These include position of transducer relative to heart, damping of the signals, and direction of catheter placement relative to blood flow.

In the current study, transducers were always zeroed to atmospheric pressure when positioned level with the base of the heart. This precluded the effects of position on inaccuracies in measurement.
Underdamping and over damping of the pressure waveform can result in erroneous blood pressure measurements. If the system is under-damped then the frequency response of the measurement system is identical to one of the harmonics of the pulse-pressure waveform. When this happens, the amplitude of recorded waveform will be exaggerated and the systolic will be too high and the diastolic too low. All commercially available blood pressure transducers are supplied with minimum volume extension tubing to connect the catheter to the transducer. The ideal tubing for IBP measurement should be wide-bore, non-compliant tubing. The small diameter of the minimum volume extension tubing may have caused a degree of underdamping which would then be expected to be seen in systolic, diastolic and mean BP measurements. However, the poor agreement was predominantly observed with SAP measurements only, with good agreement observed for DAP measurements. A rapid flush test was also performed at the start of each study to assess the level of damping and resonance within the measurement system. While the damping factor was not calculated, there was no subjective evidence of over or underdamping within the measurement systems used in each part of the study. These factors suggest that over or underdamping of the measurement system was not a major contributing factor to the high bias present for SAP measurements in this study.

In the current study, “apparent” overdamping at low blood pressures may explain the resultant better agreement for non-invasive and invasive measurements of SAP. As the agreement between DAP measured non-invasively and invasively did not deteriorate and the response to rapid flush was unchanged, it is likely that this
apparent overdamping was actually due to the effects of physiological changes rather than a technical problem with measurement. The change in the pressure waveform was likely due to the low blood volume caused by haemorrhage. The changes caused by haemorrhage could also have been exacerbated by the current vasodilation that would be expected with isoflurane administration. The improved agreement at low blood pressures was unexpected but may be explained by the wider systolic component of the pressure waveform. These changes may have resulted in more accurate detection of the peak systolic pressure by the Surgivet non-invasive oscillometric monitor.

**Distance of artery from the heart.**

Arterial blood pressure is measured in a variety of peripheral arteries that are at varying distance from the heart. As the pressure wave moves towards the periphery the pulse becomes amplified due mainly to the non-uniform elasticity of the peripheral arteries resulting in increasing systolic and decreasing diastolic pressures. ¹¹, ¹²

Measurement of BP from different peripheral arteries may contribute to discrepancies between measurements. In the current study, the same peripheral artery, but in contralateral limbs, was used for measurement of invasive and non-invasive blood pressure in greyhounds and sheep. Thus this factor is unlikely to have contributed to the poor agreement in SAP observed in the greyhounds in this study. It is a possible contributing factor to the differences in the current study
when compared to other studies. Deflandres et al (2008) compared NIBP from the dorsal pedal to invasive measurements obtained from the femoral artery in an unknown number of dogs. As the femoral artery is larger and closer to the heart, the SAP would be expected to be lower than that in the dorsal pedal artery. If the oscillometric technology used in their study has the same limitations for detecting the peak systolic pressure as is suspected in the current study, this may have resulted in the better agreement observed between invasive and non-invasive SAP. However, if site of measurement produced a significant effect of the agreement between IBP and NIBP, the DAP would also be expected to be affected. However the bias for DAP reported by Deflandres et al (2008) was the same as the current study suggesting that the use of different sites of measurement does not explain the differences observed between studies.

Different peripheral arteries were used in the anaesthetised horses for invasive and non-invasive measurement of BP. The non-invasive measurements in the horses were performed using larger arteries in the tail compared to invasive measurements in the smaller facial arteries; the SAP in the facial artery would be expected to be higher than in the coccygeal artery. This may account for the greater bias between invasive and non-invasive SAP in this species, however a similar bias would be expected in the DAP measurements if distance from heart and vessel size played a significant role. Furthermore, the bias between the SAP measurements in horses was much smaller than that in greyhounds. It would appear the use of different arteries for BP measurements does not fully explain the discrepancies observed in the current study.
Direction of catheter relative to blood flow

Measurement of BP invasively is also affected by the direction of placement of the catheter relative to blood flow. When the catheter is placed retrograde, the blood flow impacts on the catheter tip and the kinetic energy of the blood flow is converted to pressure resulting in a higher SAP measurement. This has been reported to cause a measured SAP of up to 20 mmHg higher than actual SAP in the aorta.\textsuperscript{14} The impact of blood flow on catheters placed against the direction of flow, in peripheral arteries has not been clearly identified and the effect may be much less than the reported 20 mmHg in the aorta.

In the current study, the difference between the non-invasive and invasive SAP recorded in the greyhounds was much greater than 20 mmHg. This would suggest that while this factor may have contributed to the higher invasive SAP, it was not the sole reason for the bias reported in this study. Furthermore, if this was a major contributing factor, a similar bias would be expected in other studies in dogs.

Interestingly in the horses, the bias between the invasive and non-invasive SAP is less than the reported 20 mmHg increase in BP that can occur when kinetic energy is converted to potential energy. The small bias between invasive and non-invasive SAP in the sheep also suggests that effect of kinetic energy had minimal effect on invasive SAP despite the catheter being placed in a retrograde direction. Whether the above represents a species difference in pressure measurement or impact of other technical factors in unclear.
Position of the animal

The effect of animal position on blood pressure measurement was also examined. In the current study, the greatest bias for SAP was initially seen in the greyhounds positioned in lateral recumbency while less bias was observed in the horse and sheep studies which were performed in dorsal recumbency. This prompted the question as to whether the position of the animal was a contributing factor to the large bias in SAP measurements. The greyhounds were positioned in left lateral recumbency with the IBP was always being measured in the dependant limb and NIBP always being measured in the non-dependant limb. As the non-dependant limb lies on top of the dependant limb it was postulated that compression of the vessels in this region may have altered haemodynamics in the lower limb. The greyhounds were also placed in dorsal to assess affect of positioning and when the bias reported in greyhounds in lateral recumbency were compared to those greyhounds in dorsal recumbency the result was similar in all groups except the normotensive group. As part of this thesis, the effect of positioning was only assessed in greyhounds and not in the sheep or horses, preventing the assessment effect of positioning on blood pressure in horses and sheep.

Bodey et al (1996) stated that in standing dogs the proximal forelimb was the most closely correlated with IBP measurement, followed closely by the cuff placed around the tail. When the conscious dogs were restrained in lateral, all cuff readings except that from the mid-metatarsus were closely correlated with direct measurement. Bodey et al (1994) found that the cuff positioned around the tail of
anaesthetised dogs, had the greatest correlation with IBP, especially for systolic pressure.²⁸

**Methods used to alter blood pressure and the effect of changes in heart rate**

A physiological factor that could contribute to the discrepancies is the associated changes in heart rate and/or vascular tone that may occur when blood pressure is altered. As marked changes in heart rate can alter the accuracy of oscillometric method of measuring BP, the method used to alter BP may also affect the accuracy of the measurements obtained. In the current study the most marked changes in HR were observed in the greyhounds following blood loss. This allowed the effects of HR on BP measurement to be assessed in this part of the study. In the horse and sheep component of the study variation in HR was not as evident and thus was not assessed.

In the greyhound component of this study, decreases in blood pressure were produced by blood loss. This was accompanied by a marked increase in HR. A previous study³¹, used increasing inspired concentration of isoflurane to decrease BP. Isoflurane causes dose dependant decreases in blood pressure predominantly due to vasodilation and additionally causes depression of the baroreflexes and thus heart rate can be unchanged or decreased. Unfortunately HR was not reported and thus the effect of HR on the agreement recorded in this study is not known.
It was postulated that the increase in HR in the current study may have contributed to the greater bias in SAP when compared to this and other studies. When analysis was performed on blood pressure measurements subdivided according to HR, improved agreement in SAP was seen in the dogs with higher heart rates particularly in the hypotensive group. The reduced bias in the SAP at higher HR was not expected and the reason for this was not apparent. However as the increasing HR did not explain the discrepancies between the current study and previous reports, it would appear that other factors were responsible. Interestingly the bias for MAP and DAP did increase at higher HR although the increase did not preclude the usefulness of these measurements.

An interesting finding with regard to heart rate was also evident in the horse studies. Horses have markedly lower heart rates than other species. Generally oscillometric techniques are considered less reliable in animals with low heart rates, however in the current study measurements were able to be recorded in horses with HR of 30-40 bpm. This supports the clinical usefulness of the Surgivet in species such as horses that have low resting HR.

**Species and breed.**

The last possible reason for the discrepancies observed in the current canine study and previous work is the use of greyhounds. This breed has been recognised to have a higher systemic arterial BP when compared to other breeds of dogs. One
study postulated that this was associated with differences in arterial wall mechanics. A difference in arterial wall mechanics could potentially affect the ability of oscillometric techniques to detect wall oscillations. If this is the case it is not unreasonable to expect that the impact would be greater for the measurement of SAP where the ability of the technique to detect the brief systolic peak can have a dramatic effect on accuracy of this measurement. More studies using this model of the Surgivet is required in non-greyhound breeds to ascertain if the agreement is similar to that recorded in the greyhounds in this study or not.

**Reasons for poor agreement in MAP and DAP measurement in sheep.**

In the current study, measurement of SAP demonstrated the smallest bias and precision, while measurements of DAP and MAP had the greater bias and precision. In fact in the low BP category measurements of DAP and MAP were not found to be clinically useful. Interestingly, inspection of the actual values for invasive DAP and non-invasive MAP showed that there were in fact very similar.

One possible reason for these findings could be over damping of the arterial waveform. Damping would decrease the amplitude of the waveform and result in a lower SAP and higher DAP. A lower invasive SAP due to damping could have resulted in the better agreement between invasive and non-invasive SAP in the sheep, while a higher DAP could explain why it approximated the non-invasive MAP.

As the same measurement system was used in the study in sheep and there was no evidence of damping in the other species, it is considered unlikely that the
measurement system (transducer, fluid line, or catheter) was responsible. The only other possibility is the anatomical arrangement of the radial artery. If the artery had a branch or change of direction in the region of the catheter tip, some obstruction to blood flow and pressure at the tip may have resulted in damping of the signal.

**Limitations**

There are several limitations of this study which need to be considered when interpreting the results of this study. Firstly, the number of measurements within each of the categories of BP investigated in this study was limited. In all species there was a lack of measurements in the high BP and hypertensive category and thus the accuracy of the Surgivet for measuring non-invasive BP at these levels is not known. In the horses there were very few animals in the hypotensive category which, while in the best interests of the clinical patients, limited the ability to assess the usefulness of this monitor at lower pressures in this species. Secondly, in each animal study invasive method was compared to non-invasive measurements from one site only. For the greyhounds and sheep the contralateral limbs were chosen in attempt to reduce variability in the study results due to arterial location. However further studies need to be performed to determine if non-invasive measurements from periphery arteries are more or less accurate. IN the horses, different sites were used for IBP and NIBP i.e. facial artery and coccygeal artery as this is generally what is done in clinical practice. It is possible that by using the NIBP cuff in a different position and placing the arterial catheter in a different artery, that different results may have been obtained.
One final limitation that needs to be discussed is the use of the Bland Altman method of analysis. The Bland-Altman analysis was initially designed for two sets of measurements done on one occasion from one subject, not, as in this thesis, multiple measurements from multiple subjects. To complicate it further, there were different numbers of measurements obtained from each subject. By averaging the results obtained in this study, the standard deviation and therefore the limits of agreement may be slightly altered, Bland and Altman have suggested an alternative method for assessing multiple measurements per individual.\textsuperscript{42} However, this thesis was written with the purpose of being able to compare our results to that of previous studies. Since the criteria for validating blood pressure machines as well as previous studies have used the original (albeit incorrect) method of Bland Altman analysis, we made the decision to use the same statistical methods so that the results could be compared to similar studies.

**Conclusion**

Overall the results of these studies show that the non-invasive oscillometric technique using the Surgivet V9203 is less accurate than the invasive method, and tended to underestimate the invasive arterial pressure. However the mean and diastolic pressures obtained non-invasively have been shown to be a good estimation of invasive blood pressure at all blood pressure states investigated in the greyhound and horse component of the current study, The Surgivet V9203 therefore, appears to be a useful non-invasive blood pressure monitor particularly
when monitoring the critically ill hypotensive dogs. More work is required in horses and other species to investigate the effect of using different sites for measurement.

One of the most important findings in this study was that while considered clinically useful, the MAP and DAP measured using the oscillometric technique will tend to underestimate the pressures measured invasively. This has implications on the clinical management of anaesthetised animals as there may be an increased chance of falsely diagnosing and treating hypotension. However, treating suspected hypotension slightly early is, for the majority of cases, a safer option than incorrectly recording a normal blood pressure from a hypotensive patient.
References


