ABDOMINAL PRESSURE PROFILING IN ADULT HORSES

THESIS

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By

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Abstract

Measurement of intra-abdominal pressure (IAP) is essential for documentation and monitoring of intra-abdominal hypertension (IAH) and abdominal compartment syndrome (ACS). IAH and ACS are two linked conditions significantly associated with morbidity and mortality in critically ill humans. Documented risk factors for the development of ACS in people may be applicable to horses and IAH has been described within the equine literature. Consensus statements are available in human critical care advising on optimal IAP acquisition methodologies and monitoring because many variables can affect the results obtained. Guidelines are also published for the treatment of IAH and ACS in people. Such information is currently unavailable in equine medicine. The purpose of this study was to undertake abdominal pressure profiling in normal horses to investigate species-specific characteristics. We hypothesized that intra-abdominal pressure is both location and body position dependent in normal horses. We further hypothesized that sedation would not affect IAP in normal standing horses.

Direct abdominal pressures were measured from 3 different locations in nine healthy, standing, adult horses (2 flank positions and the ventral abdomen). Direct arterial blood pressure was concurrently obtained. Abdominal perfusion pressure was calculated (mean arterial pressure – IAP). Identical variables were recorded after administration of
intravenous sedation (xylazine hydrochloride). Each horse then underwent short-term total intravenous anesthesia (diazepam, ketamine, guaifenesin guaiacolate) to facilitate patient positioning. All hemodynamic and abdominal pressures were measured with horses in left lateral/right lateral (LR) and dorsal recumbencies (DR).

We demonstrated that flank IAP was subatmospheric and significantly lower than ventrum IAP in standing horses (P < 0.001). Ventrum calculated abdominal perfusion pressure (APP) was lower than flank calculated APP (P = 0.029). Administration of intravenous sedation did not affect IAP, APP, direct arterial blood pressure, heart rate or respiratory rate in normal standing horses (P > 0.05 for each variable). Ventrum IAP was significantly lower (subatmospheric) with horses in DR compared to values obtained in LR (P < 0.0001). Ventrum APP was not different with horses in all 3 recumbencies. MAP was significantly lower when horses were positioned in DR compared to LR (P < 0.0001). Flank (left and right) IAP was significantly lower and flank (left and right) APP was significantly higher with horses in LR compared to DR (P ≤ 0.002 for all comparisons).

The abdominal pressure profiling undertaken in this study showed that direct IAP and APP are both location and body position dependent in normal horses. Direct arterial blood pressure also varies with recumbency. Sedation with xylazine hydrochloride does not affect hemodynamic and abdominal pressures in standing normal horses. These
effects should be considered when evaluating abdominal pressure profiles and visceral perfusion in horses.
Dedicated to my parents for their love, endless support and encouragement.
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Poster Presentations:


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Field of Study

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Chapter 1: Introduction and Literature Review

1.1 Intra-abdominal hypertension and abdominal compartment syndrome in human critical care medicine

Intra-abdominal hypertension (IAH) is defined in people as sustained or repeated intra-abdominal pressure (IAP) measurements of ≥ 12 mmHg. IAH has been recognized since the early 1900s, however only more intensively studied within the last 10 years. Complications associated with protracted IAH include reduced microcirculatory blood flow to viscera, development of organ dysfunction, and possibly organ failure. Abdominal perfusion pressure (APP) is a calculated index of abdominal blood flow (mean arterial pressure [MAP]-IAP), which has been proposed to be an accurate predictor of visceral perfusion and end point for resuscitation. Abdominal compartment syndrome (ACS) describes the natural progression of pressure-induced end organ changes that develop if intra-abdominal hypertension is not recognized and treated in a timely manner. ACS is defined as sustained IAP > 20 mmHg (with or without an APP < 60 mmHg) that is associated with new organ dysfunction or failure.
The pathophysiology of developing ACS from IAH is the same as that documented for other compartment syndromes (such as extremity compartment syndrome [ECS] and thoracic compartment syndrome [TCS]). It is widely accepted that excessive pressure within the compartmental organ/tissue microcirculation leads to inadequate perfusion and oxygenation. Anoxia is agreed to be the final common pathway of IAH-induced organ failure, however there are two proposed theories to account for this physiology. The first is known as the “arteriovenous pressure (AV) gradient theory” and is the most widely accepted because of early experiments and studies corroborating the described mechanism of theory. The AV theory proposes that an increase in interstitial pressure within a tissue leads to an increase in venous pressure and then a subsequent decrease in the arteriovenous gradients. The result of this reduced pressure gradient is decreased perfusion and reduced oxygen delivery (ischemia) to the organ in question. The second theory is known as the “ischemia-reperfusion syndrome theory”, which similarly states that an increase in interstitial tissue pressure leads to impairment of perfusion within the organ of question. However, this theory also accounts for reperfusion injury and a massive production of reactive oxygen species when blood flow is restored. Free radicals, in addition to the original decreased tissue oxygen delivery allow for a vicious cycle of hypoxia, anaerobic metabolism, vasoconstriction and cellular damage to ensue. This process is irreversible without intervention. Compartment syndromes, in general, can be classified as primary (whereby the pathology/injury is within the compartment affected) or secondary (no primary pathology or injury within the compartment affected).
Patients with a variety of both medical and surgical conditions may develop increased abdominal pressure and IAH. Risk factors for IAH include: diminished abdominal wall compliance (tight surgical body wall closures), increased intra-abdominal contents (intra- or extra- luminal - examples include ileus, ascites or hemoabdomen) and capillary leak syndrome secondary to large volume fluid resuscitation with fluid extravasation into the peritoneal space. Human patients undergoing emergency gastrointestinal surgery are also more likely to suffer from IAH than those undergoing an elective procedure, or any other type of surgery. Human consensus suggests that patients should be screened for IAH/ACS risk factors upon admission to ICU and additionally at times of either new or progressive organ failure. If two or more risk factors are identified, then a baseline IAP measurement should be obtained. If IAH is present, then serial IAP measurements should be obtained throughout the patient’s illness. A grading system for ranking severity of IAH has been published, which can be used to guide clinician decisions for both monitoring and intervention.

In critically ill humans, intra-abdominal hypertension has been shown to be an independent risk factor for organ failure and mortality. Mortality rates associated with ACS in critically ill adults and children range from 50 - 60%, with some studies reporting up to 100%. Body systems that may be affected include: the cardiovascular, pulmonary, gastrointestinal, hepatic and central nervous systems. Cardiovascular changes occur due to compression of the caudal vena cava, resulting in decreased venous return to the heart, decreased ventricular filling and decreased cardiac output. Impaired
pulmonary function is the result of reduced diaphragmatic excursion and decreased functional residual capacity of the lung. Atelectasis follows and there is an increase in functional dead space. Hypoxia secondary to increased shunt fraction may develop, and activation of the hypoxic vasoconstriction reflex results in pulmonary hypertension. Increased intra-thoracic pressure can also cause obstruction of cerebral venous blood flow and along with decreased cardiac output; this can cause reduction in cerebral perfusion pressure. The effect of ACS on the renal system can give rise to oliguria or anuria. Glomerular filtration decreases due to the reduction in cardiac output and renal blood flow, direct compression of renal blood vessels and renal parenchyma, increased renal vascular resistance and redistribution of blood flow within the kidneys. The direct compression of the ureters is not thought to play a major role in renal dysfunction. Impaired wound healing and gut edema can also occur as a result of IAH and ACS. Rodent models of ACS additionally show an increased incidence of bacterial translocation from the gastrointestinal tract. As with other organs within the abdomen, the liver can also suffer from hypoxia and edema. The effects of IAH and ACS are widespread throughout the body and can cause either permanent or temporary dysfunction of a number of organs. The symptoms of ACS are specific to the organ whose function has been impaired. Recognition of the widespread prevalence of elevated intra-abdominal pressure in critically ill people, combined with advances in both the diagnosis and management of IAH and ACS, have yielded significant improvements in patient survival associated with these clinical syndromes within the last decade.
A standardized therapeutic approach to IAH and ACS is difficult in human critical care medicine due to the wide variety of causal disease processes and disparate patient populations. Several fundamental management concepts remain appropriate, however. While surgical decompression is commonly considered to be the most targeted treatment of IAH/ACS, non-operative medical management strategies are also recognized to play a vital role in both the prevention and treatment of organ dysfunction due to increased IAP.7,11 There are four general principles for management of IAH and ACS: (a) serial monitoring of IAP, (b) optimization of systemic perfusion and organ function in the patient with elevated IAP, (c) institution of specific medical procedures to reduce IAP and the end organ consequences of IAH/ACS, and (d) prompt surgical decompression for refractory IAH.7 Areas of potential medical intervention for targeted treatment include: sedation, analgesia and neuromuscular blockade (to reduce abdominal muscle tone), manipulation of body position, nasogastric/colonic decompression and gastrointestinal promotility agents (for evacuation of intraluminal contents), fluid resuscitation, diuretics and renal replacement therapies as well as percutaneous catheter decompression. Algorithms have been developed in human critical care for the assessment and management of increased IAP in people.
1.2 Overview of techniques for abdominal and hemodynamic pressure acquisition

Physical examination has been proven to be an inaccurate predictor of ACS with a sensitivity and positive predictive value of approximately 40-60%. Radiographic screening, abdominal ultrasound and computed tomography are also insensitive predictors, although these methods do provide information regarding the presence of ascites, ileus, intestinal distention and space occupying masses. Accurate measurement of IAP is therefore required for identification of IAH and ACS. Methods of IAP acquisition may be direct or indirect, intermittent or continuous.

The gold standard technique is direct measurement of intra-peritoneal pressure, using either a catheter or cannula that is inserted into the abdomen and connected to a saline manometer or pressure transducer. Examples of abdominal catheters that provide accurate readings include: the piezoresistive catheter, the air-capsule catheter, the water-capsule catheter and the Stryker intra-compartmental pressure monitor. Abdominal drains have also been used to investigate postoperative IAP measurements and laparoscopic procedures may additionally be exploited to obtain peritoneal pressures (this is less applicable in critically ill non surgical patients).

Indirect methods of IAP acquisition include trans-vesicular, trans-gastric and trans-rectal techniques. Urinary bladder estimation of peritoneal pressure is the most common and most accurate indirect methodology used in both human and small animal practice.
The bladder wall is compliant and acts as a passive transducer of pressure. Therefore, changes in intra-vesicular pressure (IVP) reflect changes in IAP. The intra-vesicular technique was applied by Kron in 1984 and validated against direct measurements by Iberti in 1987. The IVP methodology has undergone many developments since the original open, single measurement system and is now frequently used as a closed, continuous system (although many modifications of this system type exist).

The original technique for IVP measurement necessitated disconnection of the patient’s urinary catheter (breach of an otherwise closed system) for installation of 50-100 ml of saline into the bladder. Such disruption of the urinary collection system may lead to an increased risk for development of urinary tract infection and also exposes health care providers to bodily fluids. Cheatham and Safcsak subsequently revised this methodology in 1998 in order to maintain the patient’s urinary catheter as a closed, needle free system. This modified technique is faster, but potential complications remain possible. Other closed methodologies that were developed for IVP measurement thereafter include: the Malbrain technique, the continuous 3-way catheter technique, the U-tube technique and the foley manometer technique. Each of these has its own set of advantages/disadvantages for any given clinical setting.

The stomach can also act as a pressure transmitter (similar to the bladder) and so in cases of bladder disease, intra-gastric pressure is used in human critical care medicine to estimate IAP. Intra-gastric pressures have been found to correlate well with IVP in
Different methodologies for acquisition of intra-gastric pressure include the Collee technique,\textsuperscript{21} the balloon-tipped gastric tonometry catheter technique and the esophageal balloon catheter technique. Continuous monitoring can be performed using balloon tipped IAP catheters (Spielberg IAP catheter; CiMON catheter) and this has recently become the more commonly researched intra-gastric IAP method in people.\textsuperscript{17}

In veterinary medicine, the intra-vesicular technique for IAP determination is the most commonly utilized in small animal patients (dogs and cats); however further studies are required to standardize this methodology. In contrast, bladder pressures in horses have a low correlation with direct IAP and show poor repeatability in measurements between individuals.\textsuperscript{25} One study in dogs has reported a high correlation between intra-gastric pressure (using gastric tonometry catheters), IVP and direct IAP,\textsuperscript{26} but clinical trials evaluating intra-gastric pressures as an indirect method of IAP acquisition have not been undertaken in small animal patients and are warranted.\textsuperscript{17} Two methods of gastric pressure measurement have been evaluated in horses thus far (utilizing a U-tube manometry technique\textsuperscript{27} and an esophageal/gastric balloon catheter\textsuperscript{28}). Both show that this indirect method does not correlate well with direct IAP values. A direct IAP technique has been proposed in horses,\textsuperscript{25} which represents modification of the commonly used abdominocentesis procedure within equine practice. The site of pressure measurement is midway between the height of the tuber ischii and the height of the point of shoulder (cranial eminence of the greater tubercle of the humerus), at a flank position 12cm caudal to the rib (\textbf{Figure 1.1}). Insertion of the cannula into the abdomen is routine. This site
has not been fully validated, but was chosen with the aim of limiting as many external variable factors as possible in the standing horse. The region of this cannula position has been used in a number of equine studies evaluating abdominal pressures and IAP in normal standing horses attained from this site is reported to be sub-atmospheric. Given the lack of correlation between direct IAP and various indirect techniques in horses, the recommended methodology for equine abdominal pressure profiling has to remain as the modified direct abdominocentesis at this time.

The reference point for measurement of abdominal pressure can significantly affect values obtained. As such, consensus guidelines in people state that the site to be used is the mid axillary line at the level of the iliac crest. This is a bony structure that is easy to palpate in human patients of almost all shape and body mass. The reference points that have been used in dogs for measurement of IVP are: the level of the vulva (similar to the neck of the bladder), midway through the pelvis, and the symphysis pubis (dogs and cats). Further work is required to better define optimal reference points in small animals. In horses, the direct IAP reference points utilized have been either the site of cannula/catheter insertion or the right atrium. Indirect methods have used the scapulohumeral joint (gastric pressure), the humeroradial joint (gastric pressure), and the tuber ischi (bladder pressure). As with the other veterinary species, consensus of an optimal reference point to provide an accurate reference range for IAP in horses is yet to be determined. Regardless of the exact technique used to measure IAP, all previously reported methodologies use a reference point that is very similar to the level (height) of
instrument insertion into the abdomen, in order to minimize the effect of gravitational forces on values obtained. Nomination of a consensus reference point requires identification of a site that is easily identifiable, shows minimal inter-individual variability and accounts for the above phenomenon. Other variables that have been reported to influence IAP values include: body positioning, obesity, gastrointestinal fill, abdominal muscle contractions and the volume of infusate that is used for indirect methods.

The reference interval for IAP in people ranges from 0 to 5–7 mmHg and values acquired may vary with BMI, pregnancy, and recent abdominal surgery. IAP also fluctuates with physiologic functional conditions such as phase of breathing, coughing, defecation, and exercise. IAP is not a constant value, but small variations occur with movement of the diaphragm during respirations (IAP increases during inspiration and decreases during expiration). Despite this, IAP tends to remain within the reference interval and fluctuates by only approximately 2 mmHg during sequential cycles. Intermittent measurement of IAP only provides a snapshot of information about IAH and ACS; therefore improved assessment and more prompt recognition of these conditions require continuous monitoring techniques. If intermittent IAP acquisition is the only available methodology, then it is proposed that measurements should be performed every 4 hours.
1.3 Intra-abdominal hypertension and abdominal compartment syndrome in veterinary critical care medicine

Animals have been utilized in models of IAH for many years, but the application of IAP monitoring techniques in veterinary medicine has remained limited due to the lack of clinical studies in animals. To date, the measurement of IAP in veterinary patients remains an emerging technique in the ICU. There is a lack of consensus guidelines in veterinary critical care medicine, but reference ranges for IAP have been proposed in dogs and published in cats using indirect methodologies. The ranges of normal values for both species are similar. Quantitative consensus guidelines are similarly unavailable in equine medicine, but values for direct IAP in normal horses have been published. It has been shown that indirect IAP values do not correlate well with direct values.

Veterinary literature describing the incidence and course of IAH and ACS is limited for all species. One study measured IAP using an intra-vesicular technique in dogs both pre and post elective ovariohysterectomy, as well as in dogs with gross abdominal distention undergoing surgery for a variety of diseases. The elective surgical cases showed an increase in postoperative IAP, but this was not associated with any form of morbidity. IAP in all of the dogs with gross abdominal distention was \( \geq 16 \) cmH\(_2\)O (11.8 mmHg) either before or after surgery. Two patients developed ACS (as defined by the current human definition) and developed anuric renal failure. The most recent prospective canine study evaluated transvesical IAP in 14 hospitalized dogs. Patients that were
admitted to the ICU and received bladder catheterization were assigned to either an ‘IAH risk’ group or ‘no risk’ group based on their problem list and fulfillment of the published human consensus risk factors.\textsuperscript{7,40} These investigators found that dogs in the ‘risk’ group had significantly higher mean IAPs than dogs in the ‘no risk’ group. They also reported that intra-observer and inter-observer variability of measurements using this methodology was low. The small animal IAH literature also includes one case report of ACS in a dog with babesiosis that developed sustained increases in IAP concurrent with renal and pulmonary dysfunction.\textsuperscript{43}

Reports of IAH and ACS are sparse in the equine literature, but IAH has been described in a recent case series of two horses.\textsuperscript{32} Brosnanahan \textit{et al} report one horse with urinary/neurological abnormalities (horse 1) and another with castration complications (horse 2). Peritoneal effusion was present in both individuals at the time of IAH diagnosis. A needle was placed under ultrasound guidance into an area of peritoneal fluid at the right lateral region of the abdomen and held in position parallel to the floor. IAP was measured using a pressure transducer and electric manometer. The pressure transducer was zeroed at approximately the ventral margin of the rib cage. Mean IAP values were recorded as 17.2 mmHg and 25 mmHg respectively for horse 1 and horse 2. The IAH in these horses was associated with significant hemodynamic alterations. The paucity of reported IAH and ACS in veterinary species likely reflects poor recognition (from underutilization of IAP monitoring techniques), rather than absence of disease.
since many clinical cases of both small and large animal intensive care units have more than one risk factor for the development of IAH.
1.4 Significance of equine abdominal disease on intra-abdominal and hemodynamic pressures

Colic is the single most common reason for admission into an equine hospital and these horses frequently present with abdominal/visceral distention, shock and hypoperfusion. Many of the risk factors for IAH and ACS are applicable to such clinical cases. Moreover, a number of the surgical and medical interventions commonly used in horses with colic are targeted at ameliorating such risk factors (trocharization, gastric decompression, intravenous fluids and sedative analgesics). This area of equine intensivist medicine remains under-investigated, however. Abdominal pressure profiling in normal horses is first required to establish appropriate species-specific reference ranges. This knowledge may then be applied to clinical cases of abdominal disease to allow for recognition of IAH as well as implementation of improved and tailored treatment with the goal of reducing complications and improving outcome.

The purpose of our first study (Chapter 2) was to establish normal values for direct IAP in normal standing horses, as well as to investigate the effect of the site of measurement on values obtained. In addition, we also sought to evaluate the effect of sedation on hemodynamic and intra-abdominal pressures in normal horses. We proposed that IAP would be location dependent in normal horses and that sedation would not alter the IAP values obtained from any one site in normal standing horses.
The purpose of our second study (Chapter 3) was to investigate the effect of body position on hemodynamic and intra-abdominal pressures when IAP was obtained from varying sites within the abdomen. We proposed that the pressure variables would change in response to changes in recumbency from all sites of IAP measurement.
Figure 1.1: Site of modified abdominocentesis at the flank to measure direct IAP.25

A: Height of the center of the tuber ischii

B: Cranial eminence of the greater tubercle of the humerus

X: Site of modified abdominocentesis for direct IAP measurement

(midway between height A and B, at 12 cm caudal to the last rib)
Chapter 2:

Direct hemodynamic and intra-abdominal pressures in normal standing horses pre and post administration of intravenous sedation

2.1 Materials and Methods

Animals

Nine adult horses (> 1 year of age) of various breeds were used for this study. Horses were non-gravid and considered free of abdominal disease based on a normal physical examination, normal rectal examination, no history of colic or abdominal surgery (≤ 6 months prior) and no detectable abnormalities on trans-abdominal ultrasonography.

Patient preparation

Twenty-four hours before instrumentation, four litres of mineral oil\textsuperscript{a} were administered via nasogastric intubation and food was withheld at this time in an attempt to standardize gut fill amongst the study population. Water was withheld for 6 hours prior to
experimentation. Horses were housed in temperature controlled (25°C) indoor stalls. Just prior to experimentation, all horses were weighed and assigned a body condition score. Additional morphometric data collected for each horse included: trunk circumference at the point of ventrum IAP measurement, caudal abdominal circumference just cranial to the stifles and the dorsal length/ventral length of the horse between these two circumferential points (Figure 2.1).

**Instrumentation**

Horses were placed in standing stocks for instrumentation and not sedated. A 14 gauge 5.25 inch Teflon catheter\(^b\) was placed in the left jugular vein and secured using 2-0 polypropylene suture\(^d\) in all horses for venous access, following 2 mL intradermal mepivicaine\(^e\) instillation. A 20 gauge 1.25 inch Teflon catheter\(^e\) was placed in a transverse facial artery or submandibular artery following 1 ml intradermal mepivicaine instillation for measurement of direct arterial blood pressure (systolic [SAP], mean [MAP] and diastolic [DAP] arterial pressures). The arterial catheter was secured to the face using cyanoacrylate glue and attached to a heparin-0.9% saline primed 84cm-long firm extension set (taped to the horses’ halter). The extension set was connected to a pressure transducer and yearly calibrated electronic manometer.\(^h\)

Intra-abdominal cannulation was performed at three locations in the abdomen; right flank (RFl), left flank (LFl) and ventrum (V). The location of flank cannulas was identical to a previously described method for right flank IAP measurement.\(^25,30\) (Figure 1.1). Briefly,
the site used was midway between the height of the tuber ischii midpoint and the height of the point of the shoulder (cranial eminence of the greater tubercle of the humerus) at approximately 12 cm caudal to the last rib on each flank. The ventrum site (linea alba) was identified by visual inspection of the standing horse and determination of the shortest ground-to-abdomen distance using a measuring tape. A 5 cm x 5 cm area at each site was clipped and aseptically prepared using chlorhexidine gluconate and isopropyl alcohol. Eight milliliters of mepivicaine was locally infiltrated. A stab incision was made into the skin and subcutis using a no. 15 scalpel blade.

Direct IAP was obtained via a three-way stopcock that was attached to a saline primed 10 cm metal teat cannula with the closed position turned toward the cannula end. The cannula was placed through the body wall and peritoneum into the intra-abdominal space and held in position by an assistant as has been reported previously.\textsuperscript{25,30} (Figure 2.2 and 2.3) Entrance into the peritoneal cavity was confirmed by retrieval of peritoneal fluid or by loss of resistance to pressure / lack of resistance to sterile saline flush (< 3 ml). Sterile water-based lubricant\textsuperscript{k} was applied at the site of cannula insertion to avoid entry of air and development of pneumoperitoneum.

**Experimentation**

A 10-minute time interval elapsed prior to data collection to minimize the effect of stress responses associated with instrumentation on systemic cardiovascular indices. The initial baseline data set included IAP measurement from each horse without sedation from the
left flank, right flank and ventrum. Simultaneous blood pressure readings (SAP, MAP and DAP) and heart rate/respiratory rate were recorded whilst IAP was acquired at each site. Direct blood pressure from an arterial catheter was obtained in 7/9 horses and indirect blood pressure using a tail cuff was measured in 2/9 horses.

For IAP acquisition, a sterile heparin-0.9% saline primed 84 cm-long firm extension set was attached to the 3-way stopcock on the cannula, then connected to a pressure transducer and yearly calibrated electronic manometer. The 3-way stopcock was turned to the open position at the cannula end and the transducer was zeroed at the level of cannula insertion into the abdomen. Each pressure was recorded in triplicate at the end of expiration as is standard in human medicine. For blood pressure acquisition, the transducer was zeroed at the level of the point of the horse’s right shoulder. The horse’s head was maintained at the level of the withers throughout the experiment.

All pressure-recording systems used saline primed lines that were visually assessed for the presence of air bubbles prior to connection to the horse. When present, lines were flushed until no bubbles were evident. Furthermore, assessment of dampening in all pressure recording systems was performed via the ‘square-wave flush test’ and visual inspection of the pressure waveform for under- or over-dampening where no appreciable effect of dampening was observed.
Once the initial data set was acquired (IAP, SAP, MAP, DAP, heart rate and respiratory rate) using the above protocol (time-baseline), horses were then moved into a padded induction stall and sedated with 1.1 mg/kg body weight intravenous (IV) xylazine hydrochloride. Following 5 minutes and clinical assessment of adequate sedation, all hemodynamic and intra-abdominal pressure variables were again measured (time-sedation).

All experimental procedures were approved by the institutional animal care and use committee of The Ohio State University prior to the commencement of the study and comply with the NIH standards for the ethical treatment of animals.

**Calculated indices**

The abdominal perfusion pressure (APP) was determined for IAP measured at each location by the following equation:

$$\text{APP}_x = \text{MAP}_x - \text{IAP}_x$$

where $x$ is the RFl, LFl or V location.

The right and left dorsal-to-ventral (D-V) IAP and APP gradients were calculated by the following equations:

$$\text{IAP}_{\text{RFl or LFl}} \text{ D-V gradient} = \text{IAP}_{\text{RFl or LFl}} - \text{IAP}_V \quad \text{and}$$

$$\text{APP}_{\text{RFl or LFl}} \text{ D-V gradient} = \text{APP}_{\text{RFl or LFl}} - \text{APP}_V$$
The left-to-right (L-R) and right-to-left (R-L) IAP and APP gradients were calculated by the following equations:

\[
\text{IAP L-R gradient} = \text{IAP}_{LFI} - \text{IAP}_{RFI} \quad \text{and} \quad \text{IAP R-L gradient} = \text{IAP}_{RFI} - \text{IAP}_{LFI}
\]

\[
\text{APP L-R gradient} = \text{APP}_{LFI} - \text{APP}_{RFI} \quad \text{and} \quad \text{APP R-L gradient} = \text{APP}_{RFI} - \text{APP}_{LFI}
\]

Abdominal volume was calculated using a truncated cone model from the morphometric data collected (Figure 2.4).

**Statistical Analysis**

All hemodynamic and intra-abdominal variables were measured in triplicate for each site of measurement. The averaged values were used for statistical analysis. Statistical testing was performed using commercial software programs. All data were assessed for normality using the Shapiro-Wilk and D’Agostino & Pearson omnibus normality tests and found to be Gaussian in distribution. Data are presented as mean ± standard deviation or 95% confidence intervals unless otherwise stipulated.

Comparisons between IAP and APP determinations obtained at each location were performed using a one-way ANOVA with Bonferroni post-hoc testing. Differences between IAP gradients and APP gradients for each location were performed using an unpaired Students t-test. Effect of sedation on all variables (baseline versus sedated) was assessed using paired t-tests. Correlation between calculated abdominal volume and
morphometric data/abdominal pressures was assessed using a Pearson’s correlation test. Significance was set at $P < 0.05$. 
2.2 Results

Study population

The median (interquartile range) age of horses was 21 (13-25) years with 5 geldings and 4 mares. Breeds included were Quarterhorses (5), Standardbreds (1), Thoroughbreds (2) and a Rocky Mountain Horse (1). The median body condition score was 5/9 (range, 3 to 8). The median (interquartile range) weight of horses was 485 (439-528) kg. Results of preparatory findings showed that all horses had no abnormalities detected by trans-abdominal and trans-thoracic ultrasonography or rectal examination.

Unsedated direct hemodynamic and intra-abdominal pressures in normal standing horses and effect of IAP cannula location

The direct IAP, SAP, MAP, DAP and calculated APP for each location of measurement are presented in Table 2.1. There were no differences in SAP, MAP, and DAP obtained at each location (P = 0.88, 0.94, and 0.95, respectively). There was a significant difference in the measured IAP (P < 0.001) between each flank location and the ventral location, where higher IAP was obtained ventrally. Similarly, the APP$_V$ was significantly lower (P = 0.029) than APP$_{RFI}$ or APP$_{LFI}$. There was no statistical difference between IAP and APP values obtained from the left flank or right flank (P > 0.05).

IAP and APP gradients between locations of measurement are shown in Table 2.2. There was no statistical difference between the left and right D-V gradients for IAP (P = 0.26)
or APP (P = 0.3). There was a difference between the L-R abdominal gradient and R-L abdominal gradient (P = 0.004) where IAP remained sub-atmospheric but was more negative on the right and became more positive towards the left.

Morphometric Data

Table 2.3 shows the mean and 95% confidence interval for morphometric variables measured within the study population. Calculated abdominal volume was strongly and positively correlated with body condition score ($r^2 = 0.83$, $P < 0.01$) but showed no correlation with any other morphometric or abdominal pressure variable (Figure 2.5). Body condition score was not correlated with body weight ($r^2 = -0.15$, $P = 0.7$), but showed a strong positive correlation with right flank APP and ventrum APP ($r^2 = 0.7$, $P = 0.038$ and $r^2 = 0.71$, $P = 0.038$ respectively). Body weight was strongly and positively correlated with left flank APP and ventrum APP ($r^2 = 0.68$, $P = 0.04$ and $r^2 = 0.68$, $P = 0.04$ respectively).

Effect of xylazine sedation on direct hemodynamic and intra-abdominal pressures in horses:

Table 2.4 shows the effect of xylazine premedication on hemodynamic and intra-abdominal pressure variables in normal standing horses. Although all horses were assessed to be clinically sedate, there was no significant effect of sedation on any of the measured variables at 5 minutes following a 1.1 mg/kg bolus of IV xylazine hydrochloride.
2.3 Discussion

We measured hemodynamic variables, IAP and calculated APP in unsedated standing horses at three locations within the abdomen to determine whether IAP and APP are consistent throughout. Intravenous xylazine hydrochloride was then administered to assess the effect of sedation on these direct hemodynamic and intra-abdominal pressure parameters. Based on our findings, these data show that direct IAP and calculated APP are location dependent within the standing horse abdomen. These values, along with blood pressure, heart rate and respiratory rate remain unaffected by a single pre-anesthetic (high) dose of sedation.

It has been speculated many times in the human literature that the abdominal cavity behaves as a homogenous hydraulic fluid system obeying the dynamics of Pascal’s Law.\textsuperscript{1,35,38} Pascal’s law states that the pressure exerted anywhere in a confined non-compressible fluid is transmitted equally in all directions throughout the fluid, such that the pressure ratio (initial difference) remains the same. This is true when all points of the fluid are at the same absolute height, as shown by Pascal’s equation:

\[ \Delta P = \rho g (\Delta h) \]

whereby:

- \( \Delta P \) is the hydrostatic pressure (pascals) or the difference in pressure at two points within a fluid column, due to the weight of the fluid;
\( \rho \) (rho) is the fluid density (in kg/m\(^3\));

\( g \) is the sea level acceleration due to Earth’s gravity (in m/s\(^2\));

\( \Delta h \) is the height of fluid above the point of measurement, or the difference in elevation between the two points within the fluid column (in m).

Such an argument means that IAP should remain constant, regardless of site of measurement. However, Loring et al in 1994\(^{46} \) showed that direct IAP is both location and body position dependent within the dog abdomen and proposed that there are actually three factors involved in the determination of IAP: gravity, visceral shear deformation and visceral compression. Under certain conditions of recumbency in humans and dogs, the effects of gravity and visceral shear are minimal, such that visceral compression correlates directly with intravesicular pressure and therefore IAP.\(^{34} \) In this case, the abdomen behaves as a hydraulic system according to Pascal’s Law. However, for larger species such as the horse, the size and depth of the abdomen means that gravitational forces throughout this compartment need to be considered. Irrespective of any object’s mass, the forces of gravity acting upon it will increase as its distance from the center of the earth decreases. The dorsal and ventral abdomens are at differing heights with respect to the center of the earth and so gravitational forces will also differ at each of these two points. It can therefore be expected that gravity has an increased effect on visceral mass within the ventral (compared to dorsal) abdomen, and that IAP values will be higher at ventral sites to reflect this. Loring\(^{46} \) showed this to be the case for anesthetized dogs that were manipulated into an upright position. A saline filled catheter
yielded significantly lower values for direct IAP at the xiphisternum compared to the caudal abdomen. In the same way, we propose that the effects of gravity can also explain the results obtained from this study - lower (subatmospheric) IAP values were measured from the equine flank (dorsal abdomen) and higher, significantly more positive IAP values were obtained from the ventrum.

The comparable left and right flank IAP values reported by this study, in addition to the lack of difference between left and right D-V gradients implies that the factors causing an increase in ventral IAP are symmetrically distributed throughout the compartment. This is again likely to be due to the effects of gravity because both flank sites of IAP measurement were at an identical height within the abdomen. To further test whether gravity consistently increases IAP in a dorsal to ventral direction, additional study that manipulates the most ventral site of IAP acquisition is required. This can be done by changing body position / recumbency. To investigate the specific effect of visceral mass on IAP APP, further investigation of our measured variables should be performed in fasted versus fed horses.

Our study showed the dorsal abdomen to have subatmospheric IAP. We propose that this may be advantageous to organ perfusion because positive pressure at this site could impede the major vessels within the abdomen. Subatmospheric pressure will have the opposite physiological effect, thus promoting blood flow through the abdominal aorta and optimizing venous return from the viscera to the caudal vena cava. There was a small,
equal but opposite IAP/APP gradient between the left and right abdomen, whereby RFl was more negative than the LFl. The exact reasons for this are unknown but may relate to abdominal organ topography. The spleen is located at the LFl site and may be more likely to exert a pressure on the cannula simply due to its mass and parenchymous nature. However at the RFl, the cecal base should be flaccid and non-distended in a standing normal horse and so less likely to exert transmural pressure to the peritoneal space.

Direct IAP measurements obtained from the flank sites in this study compare similarly to results from previous studies in healthy standing horses.\textsuperscript{25,27,29} The normal data distribution and agreeable absolute values indicate that direct cannulation is a reliable and reproducible method of IAP measurement in normal horses. We chose to also assess IAP/APP in the ventral abdomen to establish normal values that have not previously been reported. Ventral abdominocentesis is commonly performed as part of the evaluation of acute abdominal disease in horses, and may offer a practical and easy method to determine IAP in the clinical setting. Further investigation evaluating ventral IAP in horses with abdominal disease (i.e. colic, hydrops allantois/amnion etc) is required to determine the diagnostic value of ventral IAP measurements and usefulness in clinical decision making for cases considered to be high risk for IAH.\textsuperscript{47}

Our study showed that calculated abdominal volume was positively correlated with body condition score (BCS). Body condition score is assigned according to deposition of body fat over the skeletal musculature. We speculate that increases in this peripheral adiposity
reflect increases in intra-abdominal adiposity, such that horses with high BCS have increased abdominal circumference and calculated abdominal volume compared to individuals of lower body condition. Abdominal circumference is a poor indicator of IAH in people, but increased body mass index (BMI) has been associated with higher IAP values and earlier development of IAH. This study did not identify any linear association between BCS, calculated abdominal volume and IAP (or any other variable), but we did detect a positive correlation between BCS and APP obtained from the right flank/ventrum. APP is a calculated index of abdominal perfusion and accounts for arterial blood pressure as well as IAP. It is possible that horses of high body condition have a degree of relative hypertension to yield increased IAP, however this is speculation only and further investigation is required to reassesses all variables in horses with differing BCS.

Our study additionally showed that body weight was not correlated with either abdominal volume or body condition score. The fact that body weight showed no correlation with any other morphometric variable is likely a reflection of the breed differences within our study population. As such, horses were of varying conformation and stature with differences in depth of distal limb bone and regional adiposity. It is possible that calculated abdominal volume is a proxy of body fat (as BMI is in people), rather than body mass. Further investigation is required.
Sedation has been proposed in human critical care medicine as one form of medical treatment for ACS.\textsuperscript{4,7,40} Sedative medications are reported to decrease IAP by way of increasing abdominal wall compliance.\textsuperscript{49,50} It has been shown that a continuous rate infusion of the alpha-2 adrenoceptor, dexmedetomidine, decreases IAP in cases of severe sepsis after abdominal surgery.\textsuperscript{51} It is also reported that the use of sedatives in people can reduce variability of IAP measurements during continuous monitoring by reducing the variability of abdominal wall compliance changes. As such, we sought to investigate the effect of sedation on IAP in normal horses to provide preliminary information that may be applied to clinical cases of IAH in the future. We found that hemodynamic and intra-abdominal pressures were unchanged for normal horses in response to administration of 1.1 mg/kg bodyweight of intravenous xylazine, despite an observation of desired clinical effect. Our reported effect of sedation on arterial blood pressure, heart rate and respiratory rate is similar to that which has been previously documented in horses.\textsuperscript{49} This is new information regarding the effect of sedation on abdominal pressures because these two variables have not been simultaneously studied in veterinary species previously. Additional investigation of sedative effects in clinical cases of abdominal disease are required to further assess this potential treatment modality for IAH.

In summary, this study showed that intra-abdominal pressures and APP values are location dependent within the normal abdomen in standing horses. Ventral IAP was positive and increased when compared to left or right flank pressures, which were subatmospheric. A small but significant IAP and APP gradient exists between the left and
right dorsal abdomen, where right pressures are more negative. Calculated abdominal volumes strongly and positively correlate with body condition score. Sedation does not affect hemodynamic and intra-abdominal pressures in normal horses. These data provide new information regarding abdominal pressure profiles and pressure gradients in standing normal horses.
2.4 Footnotes

a Butler Schein Animal Health Inc., Dublin, OH, USA

b BD, Franklin Lakes, NJ, USA

c Hospira, Lake Forest, IL, USA

d Covidien, Mansfield, MA, USA

e Terumo Medical, Somerset, NJ, USA

f Akorn Inc, Decatur, IL, USA

g Pfizer Animal Health, New York, New York, USA

h Maquet GmbH & Co. KG, Rastatt, Germany

i Prism, version 5.0, GraphPad Software Inc., San Diego, CA, USA

j Excel, Microsoft Corporation, Mountain View, CA, USA

k First Priority, Inc., Elgin, IL, USA
Table 2.1: Direct intra-abdominal pressure and blood pressure measurements in standing unsedated horses (n = 7).

<table>
<thead>
<tr>
<th></th>
<th>IAP (mmHg)</th>
<th>SAP (mmHg)</th>
<th>MAP (mmHg)</th>
<th>DAP (mmHg)</th>
<th>APP (mmHg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left flank</td>
<td>-3 ± 2.5</td>
<td>144 ± 18</td>
<td>107 ± 12</td>
<td>82 ± 14</td>
<td>106 ± 24</td>
</tr>
<tr>
<td>Right flank</td>
<td>-5 ± 3.0</td>
<td>140 ± 16</td>
<td>104 ± 10</td>
<td>81 ± 10</td>
<td>108 ± 16</td>
</tr>
<tr>
<td>Ventrum</td>
<td>25 ± 3.1*</td>
<td>146 ± 19</td>
<td>108 ± 13</td>
<td>84 ± 14</td>
<td>82 ± 23*</td>
</tr>
</tbody>
</table>

Values recorded as mean ± standard deviation

IAP = intra-abdominal pressure, SAP = systolic arterial blood pressure, MAP = mean arterial blood pressure, DAP = diastolic arterial blood pressure, APP = abdominal perfusion pressure.

^ APP calculated from MAP – IAP; * P < 0.05 between sites of measurement
Table 2.2: Calculated direct intra-abdominal pressure and abdominal perfusion pressure gradients in standing unsedated horses (n = 7).

<table>
<thead>
<tr>
<th>Morphometric Variable</th>
<th>IAP (mmHg)</th>
<th>APP (^{\text{a}}) (mmHg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left D-V gradient</td>
<td>28 ± 3.3(^{\text{a}})</td>
<td>24 ± 2.7(^{\text{a}})</td>
</tr>
<tr>
<td>Right D-V gradient</td>
<td>30 ± 3.7(^{\text{b}})</td>
<td>26 ± 2.8(^{\text{b}})</td>
</tr>
<tr>
<td>L-R gradient</td>
<td>1.9 ± 2.4(^{#\text{ab}})</td>
<td>-2 ± 1.3(^{#\text{ab}})</td>
</tr>
<tr>
<td>R-L gradient</td>
<td>-1.9 ± 2.4(^{#\text{ab}})</td>
<td>2 ± 1.3(^{#\text{ab}})</td>
</tr>
</tbody>
</table>

Values recorded as mean ± standard deviation

IAP = intra-abdominal pressure, APP = abdominal perfusion pressure.

\(^{\text{a}}\)APP calculated from MAP – IAP; \(^{\#}\text{P < 0.05 between gradients; }^{\text{a}}\text{P < 0.05 between left}

D-V gradient and L-R or R-L gradients. \(^{\text{b}}\)P < 0.05 between right D-V gradient and L-R or R-L gradients.

Table 2.3: Morphometric variables and calculated abdominal volume in standing unsedated horses (n = 9)

<table>
<thead>
<tr>
<th>Morphometric Variable</th>
<th>Mean (95% confidence interval)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Body condition score (0 - 9)</td>
<td>5.1 (3.7 to 6.6)</td>
</tr>
<tr>
<td>Calculated abdominal volume (liters)</td>
<td>118 (97 to 138)</td>
</tr>
<tr>
<td>Body weight (kilograms)</td>
<td>502 (441 to 562)</td>
</tr>
</tbody>
</table>
**Table 2.4:** Effect of sedation on hemodynamic and abdominal pressure variables in standing horses (n=9)

<table>
<thead>
<tr>
<th></th>
<th>Baseline</th>
<th>After sedation</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left flank IAP (mmHg)</td>
<td>-3.2 (-5.2 to -3.2)</td>
<td>-5.1 (-7.9 to -2.3)</td>
<td>0.12</td>
</tr>
<tr>
<td>Right flank IAP (mmHg)</td>
<td>-5.1 (-7.5 to -2.8)</td>
<td>-5.1 (-7.0 to -3.3)</td>
<td>0.51</td>
</tr>
<tr>
<td>Ventrum IAP (mmHg)</td>
<td>25 (22 to 27)</td>
<td>25 (22 to 28)</td>
<td>0.54</td>
</tr>
<tr>
<td>SAP (mmHg)</td>
<td>134 (126 to 141)</td>
<td>140 (120 to 160)</td>
<td>0.56</td>
</tr>
<tr>
<td>MAP (mmHg)</td>
<td>103 (92 to 113)</td>
<td>100 (86 to 113)</td>
<td>0.71</td>
</tr>
<tr>
<td>DAP (mmHg)</td>
<td>80 (72 to 88)</td>
<td>81 (63 to 99)</td>
<td>0.92</td>
</tr>
<tr>
<td>HR (beats/minute)</td>
<td>35 (30 to 40)</td>
<td>36 (33 to 39)</td>
<td>0.56</td>
</tr>
<tr>
<td>RR (breaths/minute)</td>
<td>14 (13 to 16)</td>
<td>14 (13 to 15)</td>
<td>0.53</td>
</tr>
<tr>
<td>Left flank APP (mmHg)</td>
<td>106 (95 to 117)</td>
<td>103 (88 to 118)</td>
<td>0.88</td>
</tr>
<tr>
<td>Right flank APP (mmHg)</td>
<td>108 (97 to 119)</td>
<td>103 (89 to 118)</td>
<td>0.71</td>
</tr>
<tr>
<td>Ventrum APP (mmHg)</td>
<td>78 (67 to 89)</td>
<td>73 (59 to 87)</td>
<td>0.65</td>
</tr>
</tbody>
</table>

IAP = intra-abdominal pressure, SAP = systolic arterial blood pressure, MAP = mean arterial blood pressure, DAP = diastolic arterial blood pressure, HR = heart rate, RR = respiratory rate, APP = abdominal perfusion pressure.

Values are expressed as mean (95% confidence intervals).
**Figure 2.1:** Sites of morphometric measurements in standing horses:

- **A:** Trunk circumference at the point of ventrum IAP measurement
- **B:** Caudal abdominal circumference just cranial to the stifles (approx. level of umbilicus)
- **c:** Dorsal length of the horse between the two circumferential points
- **d:** Ventral length of the horse between the two circumferential points
Figure 2.2: Instrument set up for direct IAP measurement:

(metal teat cannula, three-way stopcock, saline primed line and electronic pressure transducer)
**Figure 2.3:** Instrument set up for direct IAP measurement (in situ):

(metal teat cannula, three-way stopcock, saline primed line and electronic pressure transducer)
Figure 2.4: Truncated cone model for calculation of abdominal volume from morphometric data.

Abdominal volume, $V \text{ (cm}^3\text{)} = \frac{1}{3} \times \pi \times h \times (R_1^2 + R_1R_2 + R_2^2)$

where $h$ = average of the dorsum length and ventrum length, in cm

$R_1$ = radius of the cranial circumferential measurement, in cm

$R_2$ = radius of the caudal circumferential measurement, in cm
**Figure 2.5:** Scatter plot of body condition score and calculated abdominal volume (liters) in standing horses (n = 9). Line of best fit and 95% confidence intervals [dotted lines] are shown.
Chapter 3:

Effect of body position on hemodynamic and intra-abdominal pressures in normal horses under short-term intravenous anesthesia

3.1 Materials and Methods

Animals and Patient Preparation

Nine adult horses (> 1 year of age) of various breeds were used for this study. They were the same horses that participated within the study described in Chapter 2. Once the standing and sedated phase of abdominal pressure experimentation was completed, all horses were subsequently enrolled into this study. As stated previously, each horse was non-gravid and considered free of abdominal disease based on a normal physical examination, normal rectal examination, no history of colic or abdominal surgery (≤ 6 months prior) and no detectable abnormalities on trans-abdominal ultrasonography. Patient preparation was otherwise as described in Chapter 2.
**Instrumentation and Experimentation**

Horses were instrumented and IAP acquisition sites were chosen as described in Chapter 2. After administration of xylazine hydrochloride\(^c\) 1.1 mg/kg bodyweight IV and collection of all relevant data (Chapter 2), the abdominal cannulas were subsequently removed. Horses were anesthetised using a standardized intravenous protocol. Anesthetic induction was performed using ketamine hydrochloride\(^g\) 2.2 mg/kg body weight IV and diazepam\(^c\) 0.075 mg/kg body weight IV, then maintained using a continuous infusion to effect of ketamine hydrochloride\(^g\) (2 mg/ml solution) and guaifenesin guaiacolate in 5% dextrose (50 mg/ml solution). The rate of ketamine-guaifenesin infusion was adjusted to maintain a light plane of general anesthesia to facilitate animal positioning (minimal-to-no nystagmus, and no spontaneous limb, head or neck movement). Horses were intubated with a 26-mm cuffed orotracheal tube and spontaneously breathing room air (FiO\(_2\) = 0.21). 2/9 horses that did not receive an arterial catheter whilst standing had one placed immediately after anesthetic induction. Anesthetic monitoring throughout the procedure included ECG in addition to the measured variables. If the total anesthesia time for the experimental protocol exceeded 30 minutes, then additive support of oxygen provision via a demand valve to the orotracheal tube was provided. The TIVA drug protocol was chosen to simulate a protocol that may be employed in the field by equine veterinarians for minor procedures.\(^{52}\)
This was a randomized crossover study with repeated measures design. Horses were initially placed in left lateral recumbency, right lateral recumbency or dorsal recumbency and were placed into each recumbency twice during data collection. Each recumbency was assigned a number (left-1, left-2, right-1, right-2, dorsal-1 dorsal-2) and the order of horse positioning was randomized using a web-based random number generator. If the same position was designated consecutively, the horse was placed into a differing recumbency, and then returned to the designated recumbency before obtaining hemodynamic and IAP measurements. Between recumbencies, a 2-minute period elapsed prior to data collection.

Collection of hemodynamic and abdominal pressure data was performed with horses in each recumbency. Measured variables were: direct IAP, SAP, MAP, DAP, heart rate and respiratory rate. IAP at the right flank was obtained when horses were in left lateral and dorsal recumbency. Ventrum IAP was obtained from horses in all three recumbencies. IAP at the left flank was obtained when horses were in right lateral and dorsal recumbency. All pressure measurements were taken in triplicate and averaged for each position. Details of direct IAP acquisition methodology were as described in Chapter 2. Each pressure was recorded in triplicate at the end of expiration as is standard in human critical care medicine. Between sites of measurement, cannulas were removed, and then reinserted after repositioning of the horse. The transducer for systemic arterial blood pressures was also re-zeroed for each recumbency in each horse (at the estimated level of the right atrium as indicated by the horse’s point of shoulder).
Following data collection, horses were subsequently enrolled into another unrelated study.

All experimental procedures were approved by the institutional animal care and use committee of The Ohio State University prior to the commencement of the study and comply with the NIH standards for the ethical treatment of animals.

**Calculated indices**

The abdominal perfusion pressure (APP) was determined for IAP measured at each location by the following equation:

\[ \text{APP}_x = \text{MAP}_x - \text{IAP}_x \]

where \( x \) is the RF, LF or V location.

**Statistical Analysis**

Statistical testing was performed using commercial software programs. Data were assessed for normality using the Shapiro-Wilk and Kolmogorov-Smirnov normality tests and found to be Gaussian in distribution. The averages of the triplicate hemodynamic and abdominal pressure values were used for statistical analyses. Comparisons of IAP, MAP and APP were made using one-way repeated measures ANOVA with Holm-Sidak post hoc testing to detect the effect of body position on abdominal pressures from the ventrum cannula site. Comparisons of IAP, MAP and APP were made using paired t-
tests to detect the effect of body position on abdominal pressures from the left and right flank cannula sites. Significance was set at P < 0.05.
3.2 Results

**Study population**

The median (interquartile range) age of horses was 21 (13-25) years with 5 geldings and 4 mares. Breeds included were Quarterhorses (5), Standardbreds (1), Thoroughbreds (2) and a Rocky Mountain Horse (1). The median body condition score was 5/9 (range, 3 to 8). The median (interquartile range) weight of horses was 485 (439-528) kg. Results of our preparatory findings showed that all horses had no abnormalities detected by trans-abdominal and trans-thoracic ultrasonography or rectal examination.

**Effect of body position on abdominal pressures**

All horses completed the study protocol and the mean ± standard deviation anesthesia time for data collection was 27 ± 3.4 minutes.

There was ≤ 10 % variability in the mean IAP values obtained for each repeated recumbency (i.e between left-1 and left-2 etc). There was ≤ 12 % variability in the mean MAP values obtained for each repeated recumbency.

**Table 3.1** shows the effect of body position on direct IAP, MAP and calculated APP in normal anaesthetised horses. Ventrum IAP was significantly lower with horses in dorsal compared to values obtained in left or right lateral recumbency (**Figure 3.1**; P<0.001). Ventrum APP was not different with horses in all 3 recumbencies (**Figure 3.2**; P=0.23).
Direct MAP was significantly lower when horses were positioned in dorsal compared to either left or right recumbency (**Figure 3.3**; \( P<0.001 \) when recorded concurrently with ventrum IAP measurements; \( P<0.05 \) when recorded concurrently with flank IAP measurements). Left flank IAP was significantly higher and APP significantly lower with horses in dorsal compared to right recumbency (**Figure 3.1 and 3.2**; \( P<0.001 \) for both IAP and APP). Right flank IAP was significantly higher (**Figure 3.1**; \( P<0.001 \)) and APP significantly lower (**Figure 3.2**; \( P=0.002 \)) with horses in dorsal compared to left recumbency.
3.3 Discussion

We found that by measuring direct IAP, MAP and APP at three locations in the abdomen with horses assuming differing recumbencies under intravenous general anesthesia, intra-abdominal and haemodynamic pressures are directly affected by body position.

Several recent studies in human critical care support these findings.\textsuperscript{33-36,53} Gold standard methodology for measuring IAP in people is reported by the World Society of the Abdominal Compartment Syndrome to be an indirect intra-vesicular technique with patients positioned in supine recumbency (patient lying on their back).\textsuperscript{1} Indirect bladder pressures are reported to correlate well with direct IAP during either laparoscopic or paracentesis procedures in people.\textsuperscript{54-56} Using this accepted indirect methodology, many studies also demonstrate that differing recumbencies (e.g. lateral decubitus) and various semi-recumbent positions (supine positioning with variable head-of-bed elevations) result in significantly increased measurements of abdominal pressure when compared to those obtained from a strict supine position.\textsuperscript{33-36,53,57} The severity of intra-abdominal hypertension can increase by 1-2 pressure-based predetermined grades in such circumstances.\textsuperscript{7,36} IAP in humans is reported to be highest when the patient assumes an upright position.\textsuperscript{58}

It has been speculated that the abdominal cavity behaves as a homogenous hydraulic fluid system obeying the dynamics of Pascal’s Law.\textsuperscript{1,38,54} As discussed previously, Pascal’s
law states that the pressure exerted anywhere in a confined non-compressible fluid is transmitted equally in all directions throughout the fluid, such that the pressure ratio (initial difference) remains the same. Such an argument means that IAP should remain constant, regardless of body position. However, Loring et al. showed in dogs that direct IAP is both location and body position dependent within the abdomen. They proposed that there are actually three factors involved in the determination of IAP: gravity, visceral shear deformation and visceral compression. Gravity and visceral shear are considered to be negligible with patients lying in a supine position and so in such circumstances, visceral compression correlates directly with intra-vesicular pressure and IAP. Supine recumbency therefore allows the abdomen to behave as a hydraulic system and according to Pascal’s Law. However, in certain body positions, shape stable viscera (i.e. the bladder) become deformed and change abdominal pressure dynamics away from a simple hydrostatic system. Exact reasons why changes in body position alter IAP measurements remain incompletely defined, but several interacting forces may explain the heterogeneous behaviour of the abdomen when patients are placed in differing recumbencies. Manipulating recumbencies of the horse changes intra-abdominal cannula height relative to the bulk of abdominal mass and will increase or decrease gravitational and shear forces accordingly for each of the fixed cannula sites we used.

Additional findings of this study included differences in direct MAP obtained from dorsal and lateral recumbencies. We speculate that the variation in direct MAP identified in this study was due to the weight of abdominal organs compressing the caudal vena cava
and causing decreased venous return to the heart as horses were moved from lateral into dorsal recumbency. One study in horses has shown that cardiac output and blood pressure are not significantly different for patients in lateral and dorsal recumbencies under anaesthesia,\textsuperscript{59} although another study has demonstrated that equine cardiac output is in fact slightly lower in dorsal recumbency.\textsuperscript{60} It is important to note however, that both of these experimental protocols did not study the immediate cardiopulmonary effects of changes in body position because horses were recovered and then re-anaesthetised between manipulations of recumbency. Inhalant rather than intravenous anaesthesia was also used for these horses, which constitutes a difference to the protocol adopted here. A more comparable study in dogs\textsuperscript{61} demonstrated that an immediate change in body position results in lower blood pressure, lower systemic vascular resistance, lower ventricular stroke work and higher heart rates from patients in supine recumbency compared to lateral recumbency indicating that body position can directly affect hemodynamic indices.

Calculated APP measurement is a concept analogous to the widely accepted and utilized notion of cerebral perfusion pressure, i.e. the difference between MAP and intracranial pressure [MAP – ICP].\textsuperscript{7} This study showed that when using flank cannula sites as reference points for direct IAP, differing body positions under intravenous anaesthesia resulted in expected changes of APP (such that increased IAP resulted in a decreased APP). However, when using the ventrum cannula site as a point of reference, APP remained unchanged regardless of body position. This is because ventrum IAP increased
and MAP decreased by comparable magnitudes in response to a change in recumbency. The differences in MAP and IAP (i.e. APP) therefore remained unchanged. When using the left/right flank cannula sites as reference points for abdominal pressures, IAP and MAP increased or decreased in opposite directions in response to a change in body position. Therefore, the difference between these parameters (i.e. APP) varied with recumbency. APP has been proposed as an optimal resuscitation endpoint and predictor of outcome in human critical care medicine. However, other studies have shown APP to be a poor indicator of abdominal disease severity. APP has yet to be subjected to a prospective, randomized clinical trial in human medicine and so the interpretation and application of this concept remains in its infancy. All literature in people regarding the effect of body position on IAP did not concurrently evaluate APP, and so there is no information available for species comparison to that which was obtained in this study. The significance of our findings regarding calculated APP serves to provide rudimentary understanding of normal APP in the horse. True validation of APP as an assessment of visceral perfusion requires further studies to compare this calculated parameter with gold standard measurements of abdominal organ blood flow. Subcutaneous tissue O$_2$ has been shown to reflect oxygen metabolism of the small intestinal mucosa during hemorrhage and resuscitation in pigs and other reported indirect measurements of visceral perfusion include gastric tonometry. Given the unique circumstances of our data acquisition (i.e. normal horses under general anesthesia), another factor to consider is the applicability of these results to clinical cases. Measuring APP in conscious horses and/or horses undergoing abdominal surgery for colic would provide an optimal clinical circumstance
to aid in the development of a repeatable methodology for APP measurement and fully
assess the significance of this parameter.

Given that the forces of gravity, visceral shear deformation and visceral compression
change in response to a change in body position, it is important to consider the effect of
gut fill on all of these forces, and therefore on IAP. Different magnitudes of large
intestinal fill have been shown to affect IAP measurements in horses. The population of
horses used in this study was of variable size and weight; however strategies employed in
an attempt to standardize intestinal fill included a fasting protocol and administration of
ental mineral oil. The significant correlation between left flank IAP and body condition
score with horses in right lateral recumbency was unexpected. The direct effect of equine
body condition and magnitude of abdominal volume (i.e. gut fill, visceral distension and
abdominal fat) on IAP remains to be fully determined and warrants further investigation.

The effect of general anesthesia and skeletal muscle relaxants (guaifenesin
guaiacolate/diazepam) on abdominal compliance should be considered in this study
because muscle relaxation may lead to falsely decreased IAP in humans. Anesthesia was
required to manipulate horses into different recumbencies and could not be avoided in
this study. However, the anesthetic protocol we used was standardized according to body
weight in order to reduce variability of the response to anesthesia. An improved protocol
would utilise inhalant anesthetics and ventilatory support to emulate the conditions that
are most likely to be encountered by clinical cases with surgical colic. Moreover, the
effect of positive pressure ventilation may affect visceral perfusion indices and could also be documented. In light of this, the absolute values of IAP and APP obtained from this study may not be directly applicable to clinical cases of surgical colic where patients are frequently anesthetized and placed into dorsal recumbency, however the authors propose that the relative changes in IAP observed here with manipulation of body position are still clinically relevant in the conscious horse displaying signs of abdominal pain such as lying down and rolling and conditions associated with prolonged recumbency.

Standardized protocols for the measurement of IAP in the horse have not yet been developed. Differences between investigational approaches thus far have contributed to substantial variation in reported normal values. A validated methodology is required before research can continue in the clinical setting to evaluate the prevalence, treatment options, outcome and prognosis associated with IAH in horses. The results of this study may assist in the development of a standardized protocol for IAP determination in horses and reference for future studies. Moreover, the repeatability of measurements and simplicity of the technique lends itself to being used in future investigations assessing abdominal pressures in horses with abdominal disease.

In conclusion, this study demonstrates the effect of body position on direct intra-abdominal and haemodynamic pressures in healthy adult horses under intravenous general anesthesia without assisted ventilation. These effects should be considered in the development of standardized methodology to measure IAP and APP in both normal and
clinically affected horses with abdominal disease or conditions associated with prolonged recumbency (i.e. botulism).
3.4 Footnotes

c Hospira, Lake Forest, IL, USA

f Akorn Inc, Decatur, IL, USA

g Pfizer Animal Health, New York, New York, USA

h Maquet GmbH & Co. KG, Rastatt, Germany

i Prism, version 5.0, GraphPad Software Inc., San Diego, CA, USA

j Excel, Microsoft Corporation, Mountain View, CA, USA
TABLE 3.1: Effect of body position on direct intra-abdominal pressure (IAP), mean arterial blood pressure (MAP) and calculated abdominal perfusion pressure (APP) in mmHg for normal anesthetized horses (n=9)

<table>
<thead>
<tr>
<th></th>
<th>LLR</th>
<th>RLR</th>
<th>DR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>IAP</td>
<td>MAP</td>
<td>APP</td>
</tr>
<tr>
<td>Left Flank</td>
<td>-5.4 ± 3.3</td>
<td>95.0 ± 19.3</td>
<td>15.3* ± 4.6</td>
</tr>
<tr>
<td>Right Flank</td>
<td>-8.1 ± 2.1</td>
<td>82.5 ± 19.2</td>
<td>91.0 ± 18.8</td>
</tr>
<tr>
<td></td>
<td>(-9.7, -6.5)</td>
<td>(67.8, 97.3)</td>
<td>(76.2, 105.1)</td>
</tr>
<tr>
<td>Ventrum</td>
<td>11.3 ± 3.3</td>
<td>83.6 ± 14.9</td>
<td>72.0 ± 15.7</td>
</tr>
</tbody>
</table>

Values shown as mean +/- s.d (95% confidence interval). LLR: left lateral recumbency; RLR: right lateral recumbency; DR: dorsal recumbency. * denotes significant difference from pressure measurements obtained at the same site in differing recumbencies (P < 0.05)
**Figure 3.1:** Effect of body position on direct intra-abdominal pressure (IAP) from the left flank, right flank and ventrum in normal anesthetized horses (n=9). Mean values ± s.d are shown.

* denotes significant difference from measurements obtained at the same site in differing recumbencies (P < 0.05)
Figure 3.2: Effect of body position on calculated abdominal perfusion pressure (APP) from the left flank, right flank and ventrum in normal anesthetized horses (n=9). Mean values ± s.d are shown.

* denotes significant difference from measurements obtained at the same site in differing recumbencies (P < 0.05)
**Figure 3.3:** Effect of body position on mean arterial blood pressure (MAP) from the left flank, right flank and ventrum in normal anesthetized horses (n=9). Mean values ± s.d are shown.

* denotes significant difference from measurements obtained at the same site in differing recumbencies (P < 0.05)
References


