Original Study

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Comparison of direct and indirect methods of intra-abdominal pressure measurement in normal horses

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Abstract

Objectives – To develop a direct method for measuring intra-abdominal pressures in the standing horse, identify a reference interval for direct intra-abdominal pressures, compare these pressures to indirect intra-abdominal pressures measured from the bladder, and determine the optimal bladder infusion volume for indirect pressure measurement.
Design – Prospective, experimental study.
Setting – A university-based equine research facility.
Animals – Ten healthy adult horses, 5 males and 5 females.
Interventions – Direct intra-abdominal pressures were measured through an intraperitoneal cannula and zeroed at the height midway between the height of the tuber ishii and point of the shoulder. Indirect measurements of intra-abdominal pressure were performed by measuring intravesicular pressures through a transurethral catheter zeroed at the tuber ishii.
Measurements and Main Results – Direct pressure measurements obtained in the standing horse were subatmospheric (mean, $-1.80\,cm\,H_2O$; SD, $1.61\,cm\,H_2O$; 95% CI, -2.80 to -0.80) and were shown to decrease as the horse's weight increased (Pearson's $r=-0.67$, $P=0.04$), with no effect of head position ($P=0.15$). Mean baseline indirect pressure measurements (mean, $-8.63\,cm\,H_2O$; SD, $4.37\,cm\,H_2O$; 95% CI, -13.05 to -4.21) were significantly different from the pressures measured directly from the abdomen ($P<0.001$). Indirect pressure measurements were noted to increase with increasing volumes infused into the bladder, and were statistically different at a volume of 100 mL ($P=0.004$). There was low to moderate correlation between direct and indirect pressure measurements of intra-abdominal pressure over a range of fluid volumes infused into the bladder (Pearson's correlation range -0.38 to 0.58).
Conclusion – Pressures measured directly in the standing horse were subatmospheric, and increased as the horse's weight increased. Indirect pressures measured were altered by increasing volumes infused in the bladder. There was no significant correlation between the 2 methods of intra-abdominal pressure measurement.

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Keywords: bladder pressure, equine, intraperitoneal pressure, intravesicular pressure

Introduction

A pathological increase in pressure in the abdomen is described as intra-abdominal hypertension in humans, and is defined by sustained or repeated measures of intra-abdominal pressure >12 mm Hg.[1] With increased intra-abdominal pressure, venous return and cardiac output decrease, and tissue perfusion is reduced.[1,2] Intra-abdominal hypertension is an independent risk factor for multiple organ dysfunction, and organ failure resulting from intra-abdominal hypertension is known as abdominal compartment syndrome.[1,3]

Three causes of intra-abdominal hypertension in human medicine include decreased body wall compliance (eg, tight abdominal closures), increased intra-abdominal contents (eg, due to ileus, ascites, or hemoabdomen), as well as intra-abdominal hypertension secondary to large volume resuscitation resulting in capillary leak syndrome,

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reperfusion injury, and cytokine release.[2,4,5] Similar risk factors for intra-abdominal hypertension are present in equine patients, and recognition of intra-abdominal hypertension in this species would allow for development of therapies to prevent multiorgan dysfunction from compartment syndrome.

Intra-abdominal pressures can be obtained directly, through an intraperitoneal catheter, or through indirect methods, using catheters introduced into one of a number of intra-abdominal organs that transfer pressure through their walls.[6] The indirect method most commonly implemented in human patients involves infusing a small volume of fluid into the bladder through a transurethral catheter to obtain a solid fluid column to the bladder, followed by connection of this continuous fluid column to a pressure transducer or water manometer to obtain the pressure.[1,6,7] This indirect method using intravesicular pressures has been investigated as technique for intra-abdominal pressure measurement in veterinary patients,[8,9] as well as in canine and porcine models of human intra-abdominal hypertension.[10–12]

The relevance of work performed in other species, and its application to the horse, is difficult to assess based on anatomical differences that may alter transmission of pressures in the peritoneal cavity. In the equine patient, external variables such as head position, body size, abdominal compartmentalization, urethral length, temperament, and muscle tone all may have an effect on intra-abdominal pressure measurements. Recent research models measuring intra-abdominal pressures in horses have used both a direct and indirect method.[13,14] However, a standard technique for the horse has not been defined, and many of the variables that may affect the measurements obtained, including the effects of the abdominal viscera and the height of catheter placement, still require investigation.

The purpose of this study was to describe a method for direct intra-abdominal pressure measurement, and to obtain measurements using this technique in normal, standing horses. Our objectives were to (1) assess the effect of variables including head position and body weight on direct pressure measurements and (2) compare this direct method to an indirect method of pressure measurement using a transurethral catheter. Given that the volume infused into the bladder to measure indirect pressures in humans affects the pressures obtained,[12,15–19] the final objective was (3) to determine the optimal volume for indirect intra-abdominal pressure measurement to further improve this technique. The hypothesis was that measurements obtained by both methods would be repeatable within each horse and between horses, and that significant correlation between the techniques would allow either method to be used for measurement of intra-abdominal pressure in the horse.

Materials and Methods

Horses

All procedures were approved by Auburn University's Institutional Animal Care and Use Committee. Ten healthy adult horses, 5 geldings and 5 mares, weighing an average of 486 kg (range, 362–537 kg) were used for this investigation. Breeds represented included 3 Thoroughbreds, 2 Quarter Horses, 2 mixed breeds, 1 Arabian, 1 Paint, and 1 Tennessee Walking Horse. Ages ranged from 2 to 22 years. Each horse was fasted for 24 hours before initiation of the procedures, with water being withheld the last 3 hours. Fasting was instituted to reduce the effects of acute gastric fill on the pressure measurements.

Instrumentation

On the day of the procedures, the horses were weighed, restrained in stocks, and sedated with detomidine hydrochloride[a] (0.01 mg/kg, IV). For direct intra-abdominal pressure measurement, a modified abdominocentesis procedure was performed. The height of the midpoint of the tuber ishii and the point of the shoulder (cranial eminance of the greater tubercle of the humerus) were measured and recorded. A point midway between these measurements was calculated as the height for placement of the peritoneal cannula (Figure 1). The final

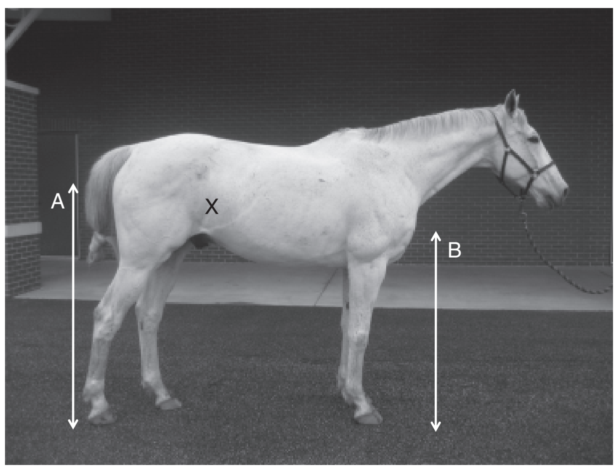

Figure 1: Method for determination of the site for placement of the cannula for direct intra-abdominal pressure measurement. The height of the center of the tuber ishii (A) and the cranial eminence of the greater tubercle (B) were determined using a line perpendicular to the ground with the horse standing square. The site (X) of entry into the abdomen in the right flank was the point midway between A and B.

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site was chosen at that height, approximately 12 cm caudal to the last rib in the right flank, and the area was clipped and aseptically prepared. Lidocaine[b] (0.1 mg/kg) was injected into the subcutaneous tissue and muscle at the selected site, and a stab incision was made through the skin using a number 15 scalpel blade. An 8-cm metal teat cannula was then bluntly introduced into the abdomen (Figure 2). Before placement, a 15-cm extension set[c] with an injection port near the hub was attached to the teat cannula and clamped to prevent introduction of air into the abdomen when the cannula was introduced. Sterile, water-based lubricant[d] was also applied after cannula introduction at the site of entry to reduce the risk of air entering the abdomen. For direct measurement of intra-abdominal pressure, a 2-Ga needle attached to the tubing from a water manometer[e] was introduced into the proximal injection port of the extension set, into the cannula lumen (Figure 2). A fluid column was established from the water manometer using balanced electrolyte solution,[f] and the 3-way stopcock was opened on the water manometer to measure the intra-abdominal pressures. The manometer was zeroed at the height measured for introduction of the cannula.

For indirect intra-abdominal pressure measurement, the open-system technique used by Kron was applied,[10] with a modification to allow for introduction of the priming volume after connection to the water manometer (Figure 3). The vulvae in the mares and the urethral processes in the geldings were cleaned and prepared. A catheter was placed in the bladder of each horse, using a stallion catheter[g] for the males, and a 24-Fr Foley catheter for the females, and the urinary catheters were connected to the water manometer by pressure tubing[h] and a 3-way stopcock (Figure 2). Balanced electrolyte solution,[f] at body temperature (37°C),

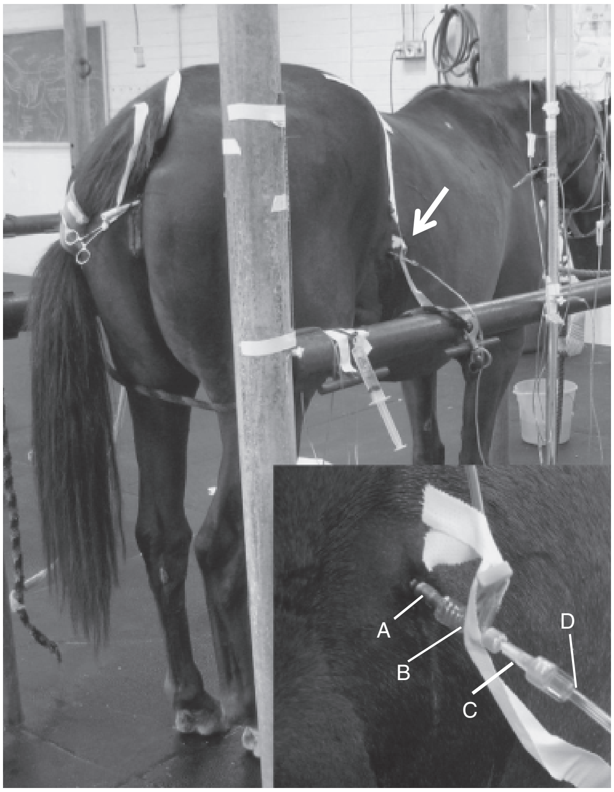

Figure 2: Horse instrumented for direct and indirect intra-abdominal pressure measurements. A Foley catheter is placed in the bladder, and clamped at the vulva to prevent air entry into the bladder (the manometer tubing for indirect pressure measurement is not attached in this picture). The arrow denotes the site of placement of the cannula for direct intra-abdominal pressure measurement. Inset shows detail: the 8-cm metal cannula (A) connected by an extension set (B) and 20-Ga needle (C) to the manometer tubing (D). The manometer was zeroed at the site of cannula entry into the flank for direct pressure measurement, and the tuber ishii for indirect pressure measurement.

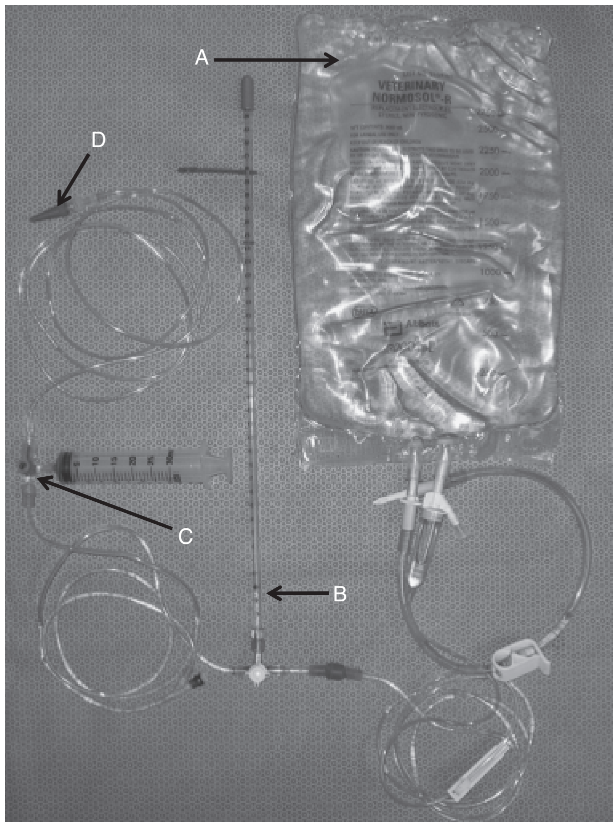

Figure 3: Modified Kron instrumentation for indirect intra-abdominal pressure measurement. A fluid reservoir (A) is connected to the water manometer (B) by an IV infusion set. The water manometer is connected to a 3-way stopcock and syringe (C) by pressure tubing. The syringe allows for a measured volume to be removed from the reservoir and infused into the bladder. The stopcock is attached to either a Foley or stallion urinary catheter by additional pressure tubing and a tubing adaptor (D).

was introduced using a 30-mL syringe attached to this stopcock. The fluid reservoir was linked by a fluid administration set to the 3-way stopcock attached to the manometer. For pressure measurement, the bladder was emptied of urine, and then the manometer tubing was attached. Entrainment of air into the system was prevented by clamping the urinary catheter before connection to the manometer. The desired amount of fluid plus an amount to fill dead space present in the urinary catheter (17 mL) was infused into the bladder. The stopcocks were then opened to the water manometer to obtain a pressure reading with the manometer zeroed at the tuber ishii.

Intra-abdominal pressure measurement

After instrumentation, the measurement of intra-abdominal pressures began approximately 30 minutes after sedation was administered. To assess baseline direct intra-abdominal pressure, the effect of body weight, and the effect of varying horse's head position, pressures were measured with the head elevated above, at, and below the withers. The measurements were repeated 3 times at each head height. For comparison of direct and indirect intra-abdominal pressures, measurements were obtained simultaneously for 4 separate volumes of fluid (0, 50, 100, and 200 mL), which were introduced into the bladder in random order. For each set of measurements at each volume, the bladder was first evacuated, and the desired volume was infused slowly into the bladder. Measurements were obtained after the bladder had equilibrated for 1 minute, based on human studies,[15–17] to reduce the effect of detrusor muscle contraction. The abdominal catheter was flushed at the time of fluid instillation into the bladder, and was also allowed to equilibrate for 1 minute. A total of 9 measurements were obtained for each intravesicular volume over 5 minutes. According to previous work, each measurement was obtained when intra-abdominal pressure was the lowest and when abdominal contractions were absent,[1,20] noted in these horses to be at the end of the inspiratory phase.

Data analysis

The averaged direct intra-abdominal pressure obtained from the abdomen was calculated for each horse with the head in a neutral position to give a baseline pressure with no external effects. The correlation of body weight to mean baseline intra-abdominal pressure was determined through a Pearson's product moment correlation coefficient and regression analysis. All direct intra-abdominal pressure measurements were normally distributed, therefore, a single factor, repeated measures ANOVA was performed to determine the effect of the head position on pressure. Post-hoc analysis using a Newman-Keuls multiple comparison post-test was used to determine significance, when indicated. The simultaneous indirect and direct intra-abdominal pressure measurements were normally distributed, and were evaluated using a 3-way ANOVA, followed by post-hoc analysis of least squares mean to assess the effects of the instillation volume. If statistical significance was met, it was confirmed using a Bonferroni's correction of the P value. Correlation of the 2 methods of pressure measurement was assessed using a Pearson's correlation and regression analysis. All correlations were further assessed with analysis of difference in fits and Cook's distance parameters to assess extreme values for undue influence. Where indicated, results are reported as mean (standard deviation), with a 95% confidence interval (CI). Statistical significance was set at $P < 0.05$.

Statistical analysis

All statistical analyses were performed by commercially available statistical software packages.[i,j,k]

Results

The averaged direct intra-abdominal pressure measured from standing, normal horses with the head in a neutral position was -1.80 cm H_2O (1.61 cm H_2O; 95% CI, -2.80 to -0.80), ranging from -5.0 to 0.3 cm H_2O (median -1.65 cm H_2O). Serial measurement of direct intra-abdominal pressure was performed in each horse, which obtained consistent readings (variance 0.00–0.85, average SD 0.22). A significant relationship was found between horse's weight and direct intra-abdominal pressure measurements, which were negatively correlated (Pearson's $r = -0.67$, $r^2 = 44.5\%$, SE = 1.28, $P = 0.04$) (Figure 4). Perfect correlation would be evident if Pearson's r approached 1 or -1. The slope of the regression line (-0.02) indicates a decrease in direct intra-abdominal pressures of 2 cm H_2O for every 100 kg increase in body weight. Head position (up, down, or neutral) had no effect on pressure, based on a single factor, repeated measures ANOVA ($P = 0.15$). Of the 3 positions, the neutral position had the least variation in pressure. A Newman-Keuls multiple comparison post-test confirmed the significant lack of difference between the means ($P > 0.05$) for all comparisons of head position.

The averaged indirect intra-abdominal pressure of -8.63 cm H_2O (4.37 cm H_2O; 95% CI, -13.05 to -4.21) measured with 0 mL of fluid infused into the bladder was more negative than the direct pressure and ranged from -1.98 to -14.06 cm H_2O (median -7.84 cm H_2O) (Table 1). Averaged direct intra-abdominal pressures measured simultaneously was -0.11 cm H_2O

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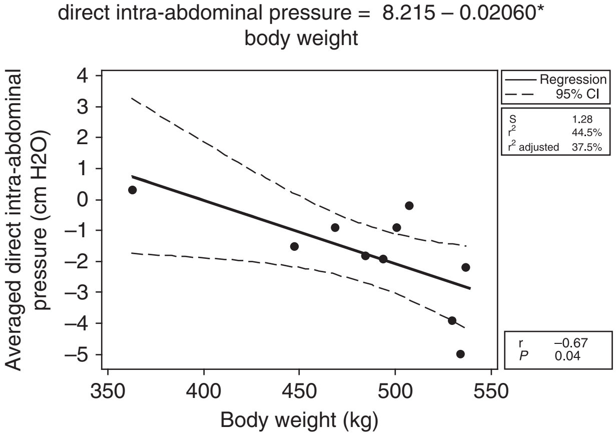

Figure 4: Correlation between body weight and the averaged direct intra-abdominal pressure for each horse. Direct pressures are measured using an intraperitoneal cannula. A significant negative effect of body weight is noted ($P = 0.04$).

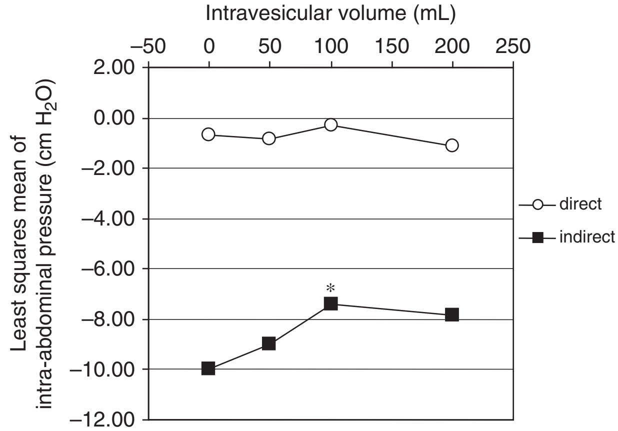

Figure 5: Comparison of the least squares means of the direct and indirect intra-abdominal pressure measurements as bladder infusion volume increases from 0 to 200 mL. Increasing bladder infusion volumes showed an effect on indirect pressures measured. Using Bonferroni's correction, a significant effect (denoted by *) of the infusion volume on indirect pressure was noted when 100 mL of fluid was infused in the bladder ($P = 0.004$) when compared with baseline.

(1.36 cm H_2O; 95% CI, -0.92 to 0.7). Measurements of direct and indirect intra-abdominal pressures were repeatable within each horse for all volumes infused into the bladder, however, the variance of indirect pressures between horses was 3–10 times the variance of direct pressure measurement.

Indirect measurements of intra-abdominal pressure were not obtained by the manometer in 4 horses (2 males, 2 females), noted by a lack of respiratory variation or oscillations in the fluid column with abdominal ballottement, for the bladder instillation volume of 0 mL. The indirect and the corresponding direct intra-abdominal pressure measurements for this volume in these horses could not be compared. Once fluid was infused into the bladder at higher volumes (≥ 50 mL), there were no additional problems noted with indirect pressure measurement using the manometer.

The effect of variations in intravesicular fluid volumes on indirect and direct measurement of intra-abdominal pressure was assessed by a 3-factor ANOVA and post-hoc analysis of least squares mean, comparing the horse, volume infused, and method of pressure measurement (Figure 5). While direct measurement of intra-abdominal pressure was not altered with increasing volumes of fluid infused into the bladder as compared with the baseline of 0 mL ($P > 0.58$ for all comparisons), indirect pressures increased from baseline as the volume infused in the bladder increased. Comparisons of the indirect intra-abdominal pressure at each instillation volume noted a statistically significant increase in indirect intra-abdominal pressures when 100 mL of fluid was infused in the bladder when compared with pressures measured when 0 mL was infused ($P = 0.004$). The difference between pressures measured with 100 mL and 0 mL instillation volumes was also significant when a Bonferroni's correction factor for multiple comparisons was applied ($P = 0.008$).

The direct intra-abdominal pressures were significantly different from the indirect pressures for all blad-

Table 1: Summary of indirect and direct intra-abdominal pressure measurements averaged between all horses by bladder infusion volume, with variation assessed by standard deviation and variance

Bladder instillation volume (mL)	Mean pressure (cm H_2O)		Standard deviation (cm H_2O)		Variance (cm H_2O)		95% Confidence interval	
	Indirect	Direct	Indirect	Direct	Indirect	Direct	Indirect	Direct
0	−8.63	−0.11	4.37	1.36	19.07	1.84	± 4.42	± 0.81
50	−7.85	−0.83	3.70	1.89	13.68	3.59	± 2.29	± 1.17
100	−7.43	−0.29	4.74	2.12	22.45	4.44	± 2.94	± 1.31
200	−7.81	−1.11	4.71	2.25	22.15	5.07	± 2.92	± 1.40

Table 2: Correlation and results for the regression analysis for indirect and direct intra-abdominal pressure measurements by bladder infusion volume

Bladder instillation volume (mL)	Pearson's correlation (*r*)	*P* value	r^2 (%)	Standard error
0	0.39	0.45	15.0	4.5
50	0.38	0.31	14.7	3.58
100	0.58	0.08	33.6	4.09
200	0.51	0.14	25.5	4.31

der volume comparisons, based on the 3-factor ANOVA and post-hoc analysis of least squares mean ($P<0.001$). The regression analyses were graphed for each correlation, and a suspected outlier (50 mL instillation volume, direct pressure $-5.47\,\text{cm}\,H_2O$, indirect pressure $-8.19\,\text{cm}\,H_2O$) was noted. Based on a significant Cook's distance measure of 1.85 (>1 is suspicious), and a difference in fits of 1.85 (significant influence for this comparison ≥ 1.309), Pearson's correlation and regression analysis were reassessed without this point. Pearson's *r* value improved from 0.12 to 0.38, and the r^2 value increased from 1.5% to 14.7%. This point was determined to be an outlier and was removed from the final analysis. No additional points were deleted. Pearson's correlations show a low to moderate positive correlation between the pressures measured by the intravesicular catheter and those measured directly in the abdomen, with values for Pearson's *r* ranging from 0.38 to 0.58 (Table 2 and Figure 6). None of the correlations reached statistical significance.

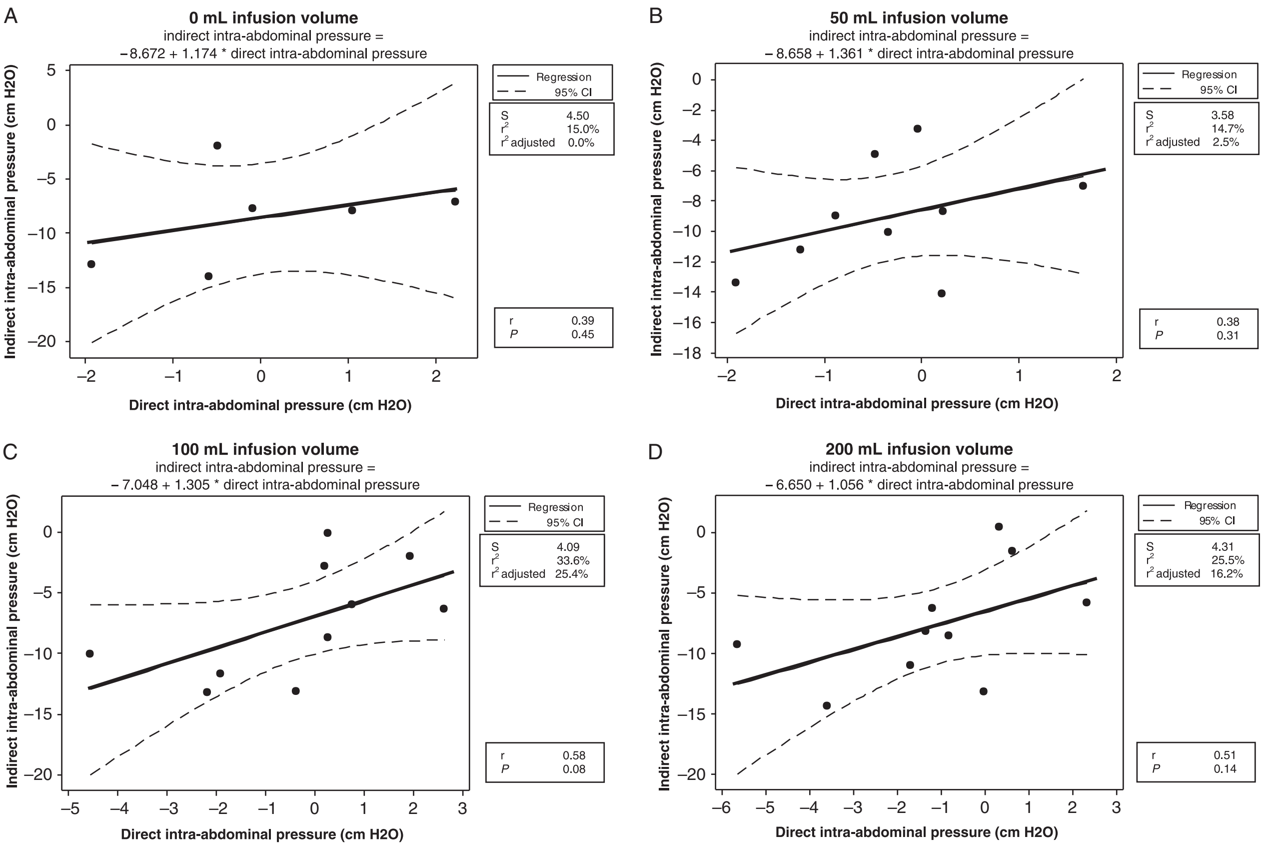

Figure 6: Correlations of the averaged direct and indirect intra-abdominal pressures for each horse for each volume of fluid infused in the bladder (panels A–D). A suspected outlier (direct intra-abdominal pressure of $-5.47\,\text{cm}\,H_2O$ and indirect pressure of $-8.19\,\text{cm}\,H_2O$) was noted when 50 mL of fluid was infused into the bladder. A Cook's distance measure and calculation of difference of fit supported deletion of this value from the correlation. Low to moderate correlation was noted for the comparisons, but statistical significance ($P<0.05$) was not met.

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Discussion

In this study, the intra-abdominal pressures obtained directly with an intraperitoneal cannula and indirectly using an intravesicular catheter were subatmospheric. These pressures were consistent and repeatable within each horse, but showed increased variation between horses for the indirect method. As the weight of the horse increased, the direct intra-abdominal pressures decreased significantly. Although the position of the head did not have a statistical effect on pressure, variation in pressure measurement was lowest with the head in a neutral position. The fluid volume infused into the bladder influenced the indirect pressures obtained, indicated by an increase in the pressures measured as the volume infused increased. At an infusion volume of 100 mL, the difference was statistically significant. Correlation between the techniques was not statistically significant, indicating that the 2 techniques cannot be used interchangeably to measure normal intra-abdominal pressure, and that individual reference intervals must be developed for both techniques.

The cannula site for direct pressure measurement was selected based on 3 factors, since a standard site is not defined for horses. First, the site was extrapolated from the mid-axillary line, the recommended reference point for indirect pressure measurement in humans.[1] This site was easily accessible in the flank, and used 2 boney landmarks to allow for consistent selection of an entry point. Second, this site was chosen to allow for more accurate measurement of intra-abdominal hypertension. Previous work has shown that the mass of the abdominal contents above the site of measurement influences the intra-abdominal pressure measured.[2,6,20,21] Because the majority of gastrointestinal viscera lies beneath the cannula, the site selected should reduce error due to normal variations in abdominal fill, but still allow space above the cannula to measure any abnormal increase in intra-abdominal pressure in future studies. Finally, the catheter site was selected to allow for a more relevant comparison between direct and indirect intra-abdominal pressure measurement by intravesicular and intragastric catheters. Based on the unknown effects of the abdominal viscera on the pressures measured at the various positions of the catheters in the abdomen, the site was selected to approximate a similar height in the abdomen for all 3 catheters in an effort to reduce this effect.

To allow for a direct comparison with previous reports, indirect intra-abdominal pressure measurements in this study were zeroed at the tuber ishii. Assuming similar external variables, the pressures obtained in this study appear to show agreement with previous data obtained from standing horses.[13,14] In these reports, indirect pressures range from subatmospheric to slightly positive when zeroed at the pubis (95% CI -7.9 to 2.3 cm H_2O),[13] and up to 7 cm H_2O when zeroed at the tuber ishii.[14] These studies used a 100-mL bladder infusion volume to obtain pressures, and at that volume we obtained a mean of -7.43 cm H_2O (4.74 cm H_2O; 95% CI, -10.37 to -4.49). Our more negative range of pressures could be attributed to subtle variations in determination 0 point, due to the size and shape of the tuber ishii used as reference. In addition, the study that zeroed to the pubis would also have produced values slightly more positive than studies referenced to the tuber ishii, due to its more ventral reference point relative to the abdominal contents.

In our study, direct intra-abdominal pressures were subatmospheric, which is expected to allow for normal venous return and perfusion of the abdominal organs.[1,2,22] However, direct pressures measured previously through a ventral midline cannula in horses were extremely positive (95% CI 17.9–43.1 cm H_2O).[13] The most likely explanation for the higher intra-abdominal pressures described previously is the increased weight and volume of viscera above the cannula when pressures were measured on ventral midline. Higher direct pressures are noted in other species as pressures are measured more ventrally related to the known effects of gravity, the mass and deformability of organs, and compressive external forces.[6,20] It is unknown if these forces may inhibit the ability to detect alterations in normal intra-abdominal pressure in the horse. Future studies would be indicated to further compare these effects on direct intra-abdominal pressure at different sites of cannula placement and at increased intra-abdominal pressures.

The effect of body weight on direct intra-abdominal pressure was evaluated due to the significant positive effect of body mass index on pressure measurement in humans.[23–26] In horses, body weight correlates well with body mass index, allowing weight to substitute for body mass index for this comparison.[27] In this study, direct pressures measured were negatively correlated to body weight. An explanation for this finding could relate to either variations in body condition, or a relative increase in abdominal dimensions compared with body size as body weight decreased. Future studies using this direct technique may require assessment of abdominal girth and body condition scores to further assess the correlation. Although a decrease of 2 cm H_2O for each 100 kg increase in weight may not be clinically relevant in adult horses, it may significantly alter pressures measured in smaller equids.

The direct intra-abdominal pressures measured in our study were not significantly affected by the head height. It is known that indirect blood pressure measurement can vary with head position; raising horse's head can falsely increase blood pressure, and conversely, the pressure decreases if the head is lowered.[28] This may be relevant when applying goal-directed therapy endpoints because abdominal perfusion pressure, calculated as the mean arterial blood pressure minus the intra-abdominal pressure, has been shown to be a better resuscitation endpoint and predictor of outcome for critical human patients than intra-abdominal pressure, mean arterial pressure, pH, base deficit, lactate, or hourly urine output.[29] Although head position did not affect intra-abdominal pressure in our study, consistent head position (ideally in the neutral position) is likely necessary for accurate calculation of abdominal perfusion pressure.

Previous assessments of indirect intra-abdominal pressure measured with an intravesicular catheter in the horse have not evaluated the effect of infused fluid volume on bladder pressures. Our results indicate that indirect pressures were increased with increasing bladder infusion volumes. We speculate that this may be due to increased detrusor tone as has been reported in the human literature.[12,15–19] Current recommendations suggest that bias can be reduced by infusing a minimal amount of fluid, <25 mL in humans, to establish a column of fluid for a pressure reading.[1,15,18,19,30] The results of this study show no effect on pressures with infusion volumes of 50 mL or less, and more consistent readings obtained with volumes >0 mL. Therefore the 50-mL infusion volume appears to allow for the most dependable indirect pressure measurement in the horses in our study.

When indirect intra-abdominal pressures were compared with direct pressures across the range of bladder volumes in this study, the correlations were only low to moderate for all volumes infused. These correlations improved slightly as volume increased, but were not significant. Human studies that examined the correlation of direct and indirect intra-abdominal pressures across a range of volumes showed much higher correlation coefficients for all volumes, with Pearson's r ranging from 0.78 to 0.97.[16,30] Anatomical differences, including the position of the bladder (retroperitoneal) in the human versus the horse (intraperitoneal), make direct comparisons between studies difficult.[12] However, it would be reasonable to assume that the correlation must be better if methods of measurement are to be compared or used interchangeably. The lack of correlation in this study may be related to the large variation in indirect intra-abdominal pressures noted between horses, which could affect the establishment of a standard for documentation of intra-abdominal hypertension by this indirect method. Further investigation will be required to determine if these findings hold true in a larger population and across a range of intra-abdominal pressures.

Critique of our methods of direct and indirect intra-abdominal pressure measurement could be based on use of a water manometer, the under- and overdamping inherent in manometer tubing, or from error introduced by air bubbles often present in these systems.[6] In addition, variation between measurements may have resulted from detrusor muscle tone directly increasing bladder pressures due to temperature of the infused fluid or filling rate, among others.[17,19] Contraction or relaxation of the abdominal wall due to movement or level of sedation may also have altered the pressures obtained, and the vertical heights of the catheters for each method were not identical, which may have allowed the weight of the viscera to affect the measurements. It is difficult to assess each issue separately, and each confounding factor could affect either method of intra-abdominal pressure measurement in a different way.

Indirect intra-abdominal pressure measurement with an intravesicular catheter has been reported to be the gold standard in humans.[1] However, numerous authors have called this method into question based on variability in technique, inherent bladder tension, reference level, body position, and indirectness.[6,12,30,31] Based on the results of this study and our techniques, we have shown that indirect intra-abdominal pressures were repeatable within each horse, but not between horses, and that indirect pressures did not significantly correlate to direct pressure measurements. Because of the large variation in measurement of indirect pressures between horses, validation of this technique may be difficult. Advantages of this technique include cost effectiveness and simplicity of measurement, which would make measurement of indirect intra-abdominal pressures an effective screening tool for trends in pressure. Drawbacks to this method include possible iatrogenic urinary tract infection, and problems caused by active urination by the horse, which tended to dislodge the catheters in our subjects, and could make repeated measurement difficult.

Potentially serious complications of direct intra-abdominal pressure measurement, using the technique described in this study, include enterocentesis, peritonitis, pneumoperitoneum, and local subcutaneous infection or abscess formation. The risks of these complications could increase in horses with increased intra-abdominal pressures or visceral distention, as well as the risk of cannula occlusion by the viscera. However, this method is comparable in risk to a teat-cannula abdominocentesis, commonly performed in horses with abdominal disease. Clinical use of this procedure may be contraindicated in any horse in which

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cannula abdominocentesis was deferred, or in horses where long-term intra-abdominal pressure monitoring is required. Refinement of this method for direct pressure measurement would allow for evaluation of additional, less invasive, indirect methods of intra-abdominal pressure measurement in the research setting. Therefore, validation of this technique at higher intra-abdominal pressures is warranted.

Acknowledgements

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Footnotes

[a] Detomidine hydrochloride, Pfizer Animal Health, Exton, PA.
[b] Lidocaine 2%, Hospira Inc, Lake Forest, IL.
[c] Macrobore extension set no. 19328-48, Hospira Inc.
[d] Surgilube, E. Fougera and Co, Melville, NY.
[e] CVP manometer, Mila International Inc, Erlanger, KY.
[f] Veterinary Normasol R, Abbott Laboratories, North Chicago, IL.
[g] Stallion urinary catheter, Jorgensen Laboratories Inc, Loveland, CO.
[h] Pressure monitoring extension tubing, Mila International Inc.
[i] SAS Analytics Pro, SAS Institute Inc, Cary, NC.
[j] GraphPad Prism 5 for Windows, GraphPad Software Inc, La Jolla, CA.
[k] Minitab 15, Minitab Inc, State College, PA.

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