

Evaluation Of Intra-Abdominal Pressure In Horses That Exhibit Cribbing Behavior

by

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Abstract

Cribbing behavior in horses is associated with an increased incidence of small intestinal strangulation through the epiploic foramen. The suggested mechanism for this association is through changes in intra-abdominal pressure (IAP); however, the effect of cribbing behavior on IAP has not been previously researched. This study used 16 healthy horses to investigate the effect of cribbing on IAP.

Eight healthy cribbing horses (cribbing cohort) and 8 healthy non-cribbing horses (non-cribbing cohort) were selected and a microsensor catheter was introduced into the peritoneal cavity through the right paralumbar fossa, using local anesthesia, for measurement of IAP. These pressures were recorded in one minute intervals for 2 hours, while the horses were standing tied in a stall.

Upon data analysis, baseline IAPs were not significantly different between cribbing and non-cribbing cohorts ($P=0.08$). However, IAPs in the cribbing cohort were significantly increased when compared to the non-cribbing cohort, during the period of active cribbing behavior ($P=0.002$). The frequency of cribbing was not associated with increased IAP ($P=0.3$). IAPs in the cribbing cohort remained significantly elevated compared to the non-cribbing cohort, even for the 30 minutes measurement taken after the behavior had ceased ($P=0.0002$).

We concluded that cribbing is significantly associated with increased IAP in the horse, both during and after the behavior.

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List of Abbreviations

ACS	Abdominal Compartment Syndrome
APP	Abdominal Perfusion Pressure
ARDS	Acute Respiratory Distress Syndrome
CIVP	Common Iliac Venous Pressure
CNS	Central Nervous System
CO	Cardiac Output
CoPP	Coronary Perfusion Pressure
CPP	Cerebral Perfusion Pressure
CVP	Central Venous Pressure
CVVH	Continuous Veno-Venous Hemofiltration
FG	Filtration Gradient
GFP	Glomerular Filtration Pressure
IAH	Intra-Abdominal Hypertension
IAP	Intra-Abdominal Pressure
ICP	Intra-Cranial Pressure
IGP	Intra-Gastric Pressure
IRP	Intra-Rectal Pressure
ITP	Intra-Thoracic Pressure
IUPC	Intra-Uterine Pressure Catheter
IVCP	Inferior Vena Cava Pressure
IVP	Intra-Vesical Pressure
MAP	Mean Arterial Pressure
MOF	Multi-Organ Failure
PAOP	Pulmonary Artery Occlusion Pressure
PEEP	Positive End-Expiratory Pressure
PTP	Proximal Tubular Pressure
RPP	Renal Perfusion Pressure
SVCP	Superior Vena Cava Pressure
SVR	Systemic Vascular Resistance
WSACS	World Society on Abdominal Compartment Syndrome

I. INTRODUCTION AND LITERATURE REVIEW

a. Cribbing Behavior In Horses

Definitions

Stereotypies are invariant, repetitive behaviors, with no apparent function, performed at a higher than normal rate (Broom and Kennedy 1993, Dantzer 1986). Several stereotypic behaviors have been described in animals other than horses, including pacing and licking in captive giraffes (Bashaw et al. 2001), rumination in captive lowland gorillas (Lukas 1999), bar-biting and sham chewing in sows (Rushen 1984) and tongue rolling in cows (Wiepkema et al. 1987). Stereotypic behaviors in horses can be oral or locomotor in nature (Dodman et al. 2005). Locomotor stereotypies include weaving, a lateral rocking movement of the head, neck and forelimbs, pawing, repetitively striking the ground with a forefoot, and head bobbing, a repetitive up and down movement of the head (Kiley-Worthington 1983, Mills et al. 2005). Oral stereotypies include cribbing, wind sucking, and wood chewing, which involves the use of incisors to remove pieces of wood, which are not swallowed (Dodman et al. 2005, Mills et al. 2005).

Cribbing, crib-biting, wind-sucking and aerophagia are terms used synonymously (Hayes 1968, McGreevy et al. 1995a). Cribbing is an oral stereotypic behavior performed by horses involving the placement of the upper incisors on a firm surface, which is often preceded by licking of the surface (McGreevy et al. 1995a). The horse then flexes the ventral neck muscles and rocks backwards, causing the larynx to retract caudally. Air then passes through the pharynx and into the cranial esophagus, causing a characteristic grunting noise (Lebelt et al. 1998, McGreevy et al. 1995a). Wind-sucking is a behavior defined in a similar manner as cribbing, except the wind-sucking horse does not place its incisors on a fixed surface (Hayes 1968). What happens to the air that passes into the cranial esophagus during cribbing and windsucking is controversial, with many believing these behaviors have a component of aerophagia, or swallowing of air (Hayes 1968, Houpt 1986, Dodman et al. 1987). However, radiographic studies performed by McGreevy et al. (1995a) showed that the majority of air returns to the pharynx before being expelled, and little air passes on into the stomach.

Prevalence

Cribbing has been observed in domestic and captive equines, but does not appear to be significantly prevalent in wild horses. Dodman et al. (2005) has reported on the prevalence of stereotypic behaviors, including cribbing, in formerly feral Mustangs. Data collected on 243 Mustangs, found only six (2.4%) displayed some form of stereotypic behavior and three (1.2%) were known to crib (Dodman et al. 2005). On the other hand, in domestic horses, cribbing has a reported incidence of 2.1-13.3%, depending on breed, location, use and management (Albright et al. 2009, Bachmann et al. 2003a, Luescher et al. 1998, McGreevy et al. 1995a, Mills et al. 2005,

Vecchiotti and Galanti 1986, Wickens and Heleski 2010). Affected horses may spend anywhere from 10-65% of their day cribbing (Bachmann et al. 2003a, Nicol et al. 2002).

Risk factors

Numerous management factors such as decreased turn out, decreased amounts of forage, increased amounts of concentrates and increased social isolation have been implicated in development of cribbing behavior. A survey of owners found that 40% of farms allowing stereotypic horses on property kept these horses isolated from other animals (McBride and Long 2001). However, social isolation has been reported to induce a stress response in horses (Alexander et al. 1988, Bagshaw et al. 1994, Lansade et al. 2008) and stereotypic behaviors seem to occur with greater frequency under stressful conditions (Mason 1991). Horses and other animals allowed social contact with conspecifics have been shown to have a lower prevalence of abnormal behavior (Redbo 1990, McGreevy et al. 1995b, Bachmann et al. 2003b). While increased time on pasture may reduce frequency of cribbing (McGreevy et al. 1995b), it has not been shown to completely extinguish performance of the behavior. This further supports the theory that the behavior is liberated from the original eliciting stimulus as it develops.

Diets high in concentrates and low in forage are also related to this vice. A prospective study found Thoroughbred foals were four times more likely to develop cribbing behavior if fed concentrates at weaning (Waters et al. 2002). Parker et al. (2008) determined that natural weaning, which occurs at an older age and at the discretion of the mare, resulted in a decreased risk of developing stereotypic behaviors. Weaned foals kept on grass pasture were less likely to develop abnormal behavior than those kept in stalls (Parker et al. 2008). Furthermore, multiple

studies have found that as turn out time increases, performance of stereotypic behaviors, including cribbing, decreases (McGreevy et al. 1995b, Wickens and Heleski 2010). Social contact with other horses has been shown to reduce the probability of cribbing behavior (Bachmann et al. 2003b, Wickens and Heleski 2010) while isolation often results in increased risk of developing abnormal behaviors associated with social deprivation (Mills et al. 2005). Visser et al. (2008) found that 22% of young horses housed in isolation displayed cribbing behavior compared to no stereotypic behaviors in horses that were paired.

Heritability of stereotyped behaviors, including cribbing, is highly debated, especially since the behavior seems to occur more commonly in some breeds compared to others. Twenty five percent of horse owners believed stereotyped behaviors were inherited (McBride and Long 2001). Indeed, eight of 14 cribbing horses had one or more relatives that also displayed the behavior (Vecchiotti and Galanti 1986). However, it is difficult to distinguish whether these findings are the result of genetic influence or a reflection of management strategies.

Whether cribbing behavior can be transmitted to horses observing the behavior is also debatable. About half of horse owners, and other individuals associated with horses, believed that it could be learned by observation (McBride and Long 2001), to the point that many felt that affected animals should be isolated. Despite this belief, there is no evidence suggesting that horses are capable of learning to do a task by watching a more experienced individual (Baer et al. 1983). In a study from Clegg et al. (2008) cribbing behavior could not be elicited in unaffected horses by housing them in contact with affected horses.

Prevention

Strategies to prevent or deter horses from cribbing have been researched with variable results. Bucket muzzles can be used but they obviously interfere with prehension of food (McGreevy and Nicol 1998a). Acupuncture may be useful for decreasing cribbing and aerophagia, but its mechanism of action in this specific scenario is unclear, and the results are not consistent (Kuussaari 1983). Taste deterrents painted on cribbing substrates, shock collars, electric fencing, and metal inserts in the oral cavity can be impractical and success rates have been inconsistent (Magner 1903, McGreevy and Nicol 1998a, Owen 1982). The list of taste deterrents for horses is exhaustive and ranges from sheepskin (Magner 1903) to asafoetida (Leeney 1929) and creosote (Miller and Robertson 1959). The use of proprietary electric fencing inside stables is a common deterrent to crib-biting. It is arranged on all ledges in the same way that taste deterrents are applied (Haupt and McDonnell 1993). Meanwhile, filing of the incisor teeth, placement of metal inserts between them, (Magner 1903) or insertion of implants that impinge on the palate (Owen 1982) have been described as means of making the grasping of fixed objects unpleasant. Commercially available electronic dog training collars can be adapted to fit the equine neck and can be remotely controlled so that the horse does not associate punishment with human presence (Haupt and McDonnell 1993). It is reported that by applying an electric shock after the horse has grasped but before it has engulfed air, extinction of grasping may be achieved, rather than simple avoidance (Baker and Kear-Colwell 1975).

Dodman et al. (1987) reported the successful one-time parenteral administration of opioid antagonists, including naloxone, nalmefene and diprenorphine, to prevent horses from cribbing for anywhere from 20 minutes to four hours. The mechanism of action of these drugs in relation to cribbing behavior is unclear; they may act by sedating the animal thus making the behavior less rewarding, or by eliminating the frustration caused by the surrounding environment

(McGreevy and Nicol 1998a). However, the sedation displayed by the animals under influence of these medications may be undesirable, and horses resumed cribbing when the drug was discontinued or wore off. Continuous administration of injectable drugs is not a practical preventative strategy for most owners due to time and cost constraints.

Three surgical procedures are described to treat cribbing behavior: the Forssell's procedure, the modified Forssell's procedure, and the bilateral neurectomy of the ventral branch of the spinal accessory nerve (Houpt 1986, Baker and Kear-Colwell 1974, Forssell 1926, Hamm 1977, Firth 1980). The original procedure described by Forssell in 1920 consists of surgically removing portions of the sternomandibularis, sternothyrohyoideus and omohyoideus muscles that are involved in the cribbing action (Baker and Kear Colwell 1974, Forssell 1926). The procedure has been modified to improve its cosmetic outcome by decreasing the extent of tissue resected. The technique for bilateral neurectomy of the ventral branches of the spinal accessory nerves (11th cranial nerves) was initially described by Hamm (1977) and subsequently modified (Bruere 1966) to remove the innervation to the sternomandibularis muscles, which are the major muscles used by the horse to flex its neck. Another surgical method to prevent cribbing is permanent buccal fistulation, which prevents the horse from keeping the mouth airtight (Karlander et al. 1965). However, the mouth is open when cribbing, so both the rationale and efficacy of this procedure have been questioned (McGreevy and Nicol 1998a).

To date, the surgical treatment of choice for cribbing is a combination of a modified Forssell's procedure and a bilateral neurectomy (Houpt 1986). The success claimed for myectomy diverges between authors, with Forsell (1926) quoting success rates of 100-60% and, more recently (Hermans 1973), a 53% 'cure' rate being reported. Similar discrepancies arise for neurectomy. Monin (1982) and Fraufelder (1981) cite success rates of 60%, while Firth (1980)

and Owen et al. (1980) cite complete failure. It has been suggested that confusion in terminology and differing criteria for success, follow-up periods and post-operative management may have contributed to these divergences (Owen 1982). Of the surgical cases that show partial rather than complete resolution, grasping is reported to be more persistent than grunting. This supports the findings of McGreevy et al. (1995a) which revealed the involvement of the musculature of the ventral neck in the air-engulfing process that accompanies the characteristic grunt.

The most common method of managing cribbing behavior in horses is the use of a cribbing collar or strap. This device is used to punish and prevent neck flexion (Hayes 1968). In general, the collar consists of a leather strap with or without a hinged, metal curve to allow room for the trachea. Many modifications of the basic design exist, including metal spikes and leather spurs that are meant to increase discomfort when the neck is flexed (Owen 1982), and shock collars. The collar is placed around the neck at the throatlatch and is tightened to the point where neck flexion cannot be performed. Many animals will adapt to the constriction and then resume cribbing, causing the collar to be further tightened, which eventually could lead to trauma (Hatchen 1995). Use of a cribbing collar has been shown to induce a stress response (McBride and Cuddelford 2001). Also, while the cribbing collar may initially reduce performance of the behavior, horses have been shown in one study to crib at higher than normal frequencies once the device is removed (McGreevy and Nicol 1998b).

Consequences

There are a number of negative side effects of cribbing behavior. Regarding their environment, horses displaying cribbing behavior usually cause significant damage to equine

facilities by continuously latching on surfaces with their incisors. Cribbing can lead to loose fence posts and broken boards and doors, as well as damage to feed and water buckets, hay rings and gates. Not only is cribbing an annoyance for horse owners, it is also can result in medical problems for affected horses. The incisors are invariably eroded prematurely due the repeated stress placed on them (Fraser 1992), which could also lead to fractures or avulsions of these teeth. Horses affected by cribbing behavior may also be underweight (Hayes 1968). McGreevy et al. (2001) determined that cribbing horses displayed a trend for weight loss compared to horses that did not perform the behavior. Difficulty maintaining weight could be attributed to the propensity of cribbing horses to spend less time eating and resting compared to non-cribbing horses (McGreevy et al. 2001). The musculature of the neck can also become hypertrophic in habitual cribbers (Dodman et al. 1987). This feature could make the animal esthetically unacceptable to potential buyers and could potentially even affect the animal's ability to be safely and pleasantly ridden by increasing the animal's pull on the bit.

Regarding gastrointestinal disorders, reports have linked cribbing to a higher incidence of large colon tympany (Dodman et al. 1987, Hillyer et al. 2002) and simple large colon displacements (Hillyer et al. 2002). Caretaker's preconceptions of any association between this vice and colic may have resulted in reporting bias for this variable. However, Hillyer et al. (2002) designed a study that effectively minimized this bias and still found a strong association between cribbing and large colon tympany and displacement. McGreevy (1996) recognized an association between cribbing and colic, although previous work suggests it may not be a result of direct passage of air into the stomach (McGreevy et al. 1995a). Later research by the same group showed a prolongation of intestinal transit time in cribbing horses (McGreevy et al. 2001) and

this may provide a mechanism for the increased risk of large colon tympany and displacements associated with this behavior (Hillyer et al. 2002).

There is also evidence that cribbing behavior may be associated with foregut acidosis and irritation. Nicol (1999) hypothesized cribbing serves to increase saliva flow and protect against gastric irritation. Indeed, cribbing horses seem to produce less saliva overall compared to non-cribbing horses, and decreased saliva production was observed when cribbing was prevented (Moeller et al. 2008). Sixty percent of cribbing foals suffer from gastric ulceration, compared with only 20% of non-cribbing foals (Nicol et al. 2002). Interestingly, addition of anti-acid medications to the foals' diets resulted in decreased cribbing behavior as well as improved the health of the gastric mucosa, suggesting that cribbing and colic may be the result of altered gastrointestinal physiology, rather than the cause. Cribbing behavior is suggested to manifest in response to anything that results in visceral pain, which would include gastric ulceration (Mills et al. 2005). More recently, a study from Wickens et al. (2013) found no difference in number or severity of gastric ulcers, prevalence of hyperkeratosis, or baseline gastric pH between cribbing and non-cribbing adult horses, indicating that cribbing behavior per se would not directly cause gastric damage; however, consumption of concentrate feed resulted in greater serum gastrin concentration in cribbing horses compared to non-cribbing horses.

Two separate studies (Archer et al. 2004, 2008) have solidly proven an association between cribbing behavior and epiploic foramen entrapment in horses. Epiploic foramen entrapment (EFE) is one of the most common causes of small intestinal strangulation in this species. While EFE represents a relatively small proportion of colic cases occurring within the general population, it accounts for 5–23% of all strangulating lesions of the small intestine, it is

the second most prevalent type of small intestinal strangulating lesion in some hospital populations, and it represents 2–8% of horses with colic that undergo surgery (Freeman 2006).

Horses of greater height at the withers were identified to be at a higher risk for development of EFE (Archer et al. 2008). The relationship between height and altered likelihood of EFE may be due to anatomical differences in the relative dimensions of the epiploic foramen making entrapment more likely to occur in larger horses, but this is unproven. Age was not shown to alter the likelihood of EFE in some studies (Archer et al. 2004, 2008, Freeman and Schaeffer 2001), in contrast with older literature (Wheat 1972). In fact, horses of all ages can be affected, including foals less than 9 months old and horses 11 months to 3 years (Freeman 2006). In some of the larger studies, 47% to 71% of horses were younger than 11 years of age, and none of the affected horses was older than 20 years (Vachon and Fischer 1995, Scheidemann 1989, Schmid 1998, Engelbert et al. 1993, Freeman and Schaeffer 2001). Some studies found Thoroughbred and Thoroughbred-crosses to be at higher risk (Vachon and Fischer 1995, Vasey 1988, Archer et al. 2004), and geldings or stallions constituted the vast majority of cases in two studies (Vachon and Fischer 1995, Scheidemann 1989). Increased stabling in the 28 days prior to the colic event was significantly associated with increased likelihood of EFE in one study (Archer et al. 2008). Increased stabling may be a marker for a number of other changes such as reduced access to pasture, increased quantity of supplementary forage and reduction in exercise. Evidence of a seasonal pattern with more cases of EFE occurring in January than in any other month was consistent across several studies (Archer et al. 2004, 2006, 2008). Sudden increases in stabling may coincide with particular seasonal weather patterns, therefore seasonality and stabling may be two reflections of the same practice management (Archer 2008).

The proposed pathogenic factor for development of EFE was a decrease in intra-abdominal pressure (IAP), which would cause expansion of the epiploic foramen, and increase the risk for entrance of the small intestine. In human medicine, a similar condition of intestinal strangulation is described as herniation through the foramen of Winslow (Ghahremani 2009). This form of strangulation in humans is very rare, but the interesting fact about it is that its onset is often preceded by an event that results in a significant increase in IAP, such as parturition, straining, or sneezing (Erskine 1967, Forbes and Stephen 2006, Meyers 1994). In horses, the effect of cribbing behavior on IAP has not been directly assessed. During previous studies conducted by the authors that investigated IAP in horses, it was noted that IAP increased during coughing, urination and defecation (Munsterman, unpublished data); therefore it is likely that cribbing causes an increase in IAP. The goal of this study was to measure the IAP of horses before, during and after the cribbing behavior. We hypothesized that IAP of horses at the time of cribbing would be significantly higher compared to resting IAP and to horses that do not crib.

b. Intra-Abdominal Pressure In Human Medicine

Historical Background

As summarized by Schein, the effects of elevated IAP have been known since 1863, when Marey of Paris highlighted that “the effects that respiration produces on the thorax are the inverse of those present in the abdomen” (Schein 2006). It was not until 1911 that Emerson showed in dogs that elevated IAP increases systemic vascular resistance (SVR) and can cause death from cardiac failure even before the development of asphyxia. The term abdominal compartment syndrome (ACS) was first used by Fietsam et al. (1989) to describe the pathophysiologic alterations resulting from intra-abdominal hypertension (IAH) secondary to aortic aneurysm surgery: “In four patients that received more than 25 L of fluid resuscitation increased IAP developed after aneurysm repair. It was manifested by increased ventilatory pressure, increased central venous pressure, and decreased urinary output. This set of findings constitutes an ACS caused by massive interstitial and retroperitoneal swelling [...]. Opening the abdominal incision was associated with dramatic improvements [...]”. Hence the first definition of ACS was finally coined (Malbrain et al. 2008).

Definitions

The World Society on Abdominal Compartment Syndrome (WSACS – www.wsacs.org) was founded in 2004 to serve as a peer-reviewed forum and educational resource for all healthcare providers and industry members who have an interest in human IAH and ACS. The first consensus definitions report of the WSACS was recently published (Malbrain et al. 2006). In the consensus, IAP is defined as the steady-state pressure concealed within the abdominal cavity. Abdominal Perfusion Pressure (APP) is the difference between Mean Arterial Pressure (MAP) and IAP. Normal IAP is approximately 5-7 mmHg (6.8-9.5 cmH₂O) in critically ill human adults. IAH is defined by a sustained or repeated pathologic elevation of IAP above 12 mmHg (>16.3 cmH₂O), and is graded as grade I (12-15 mmHg, 16.3-20.4 cmH₂O), grade II (16-20 mmHg, 20.5-27.2 cmH₂O), grade III (21-25 mmHg, 27.3-34 cmH₂O) and grade IV (>25 mmHg, >34 cmH₂O). When new organ or dysfunction occurs concurrently to an IAP >20 mmHg (>27.2 cmH₂O), ACS is defined. ACS can be primary or secondary. Primary ACS is associated with injury or disease in the abdomino-pelvic region, whereas secondary ACS does not originate from conditions affecting the abdomino-pelvic region directly (Malbrain et al. 2006).

Analogous to the widely accepted and clinically utilized concept of cerebral perfusion pressure (CPP), which is calculated as mean arterial pressure (MAP) minus intracranial pressure (ICP), abdominal perfusion pressure (APP), calculated as MAP minus IAP, has been proposed as a more accurate predictor of visceral perfusion and a potential endpoint for resuscitation (Cheatham et al. 2000, Malbrain 2002, Deeren et al. 2005, Cheatham and Malbrain 2006a). With respect to both arterial inflow (MAP) and restrictions to venous outflow (IAP), APP is statistically superior to either parameter alone in predicting patient survival from IAH and ACS

(Cheatham and Malbrain 2006b). A target APP of at least 60 mmHg (81.6 cmH₂O) has been demonstrated to correlate with improved survival from IAH and ACS (Malbrain et al 2008).

Etiology

ACS can be diagnosed when there is increased IAP with evidence of end-organ dysfunction. Although multiple causes of acute cardiopulmonary, renal, hepatosplanchnic or neurologic deterioration exist in the ICU, it is particularly important that IAP is recognized as an independent risk factor for organ function deterioration. Many conditions have been reported in association with IAH/ACS and can be classified into four categories (Burch et al. 1996, Ivatury et al. 2001): factors that diminish abdominal wall compliance, factors related to increased intra-abdominal contents, factors related to abdominal collections of fluid, air or blood, and factors related to capillary leakage and fluid resuscitation (See Table 1).

Diagnosis

The abdominal circumference is not a reliable parameter to assess IAP, and clinical IAP estimation is also inaccurate, with a sensitivity and a positive predictive value of 40-60% (Kirkpatrick et al. 2000, Sugrue et al. 2002). Radiologic investigations with plain radiography of the chest or abdomen, abdominal ultrasound or CT scans are also not sensitive to increased IAP (Malbrain et al. 2008). Direct or indirect measurement of IAP is the only effective method to assess it (Malbrain et al. 2008).

The abdomen and its contents can be considered as relatively non-compressive and fluid in character, therefore they are thought to behave in accordance with Pascal's law that states that pressure exerted anywhere in a confined incompressible fluid is transmitted equally in all directions throughout the fluid. The IAP measured at one point may therefore be assumed to represent the IAP throughout the abdomen (Malbrain 2004a, Malbrain and Jones 2006). IAP increases with inspiration (diaphragmatic contraction) and decreases with expiration (diaphragmatic relaxation) normally ranging from 0 to 10 mmHg (0-13.6 cmH₂O) (Sanchez et al. 2001). However, certain physiologic conditions such as morbid obesity (Sugerman et al. 1997, Sugerman 2001), ovarian tumors, cirrhosis or pregnancy may be associated with chronic IAP elevations of 10-15 mmHg (13.6-20.4 cmH₂O), to which patients can adapt without significant pathophysiology (Malbrain et al. 2008). In contrast, children commonly show lower IAP values (median 4 mmHg, 5.4 cmH₂O) (Davis et al. 2005).

The clinical importance of IAP must therefore be assessed in view of the baseline steady-state IAP for the individual patient (Malbrain et al. 2008). IAP can be directly measured with an intraperitoneal catheter attached to a pressure transducer. During CO₂-insufflation in laparoscopic surgery IAP is measured directly via the Verres needle. Different indirect methods for estimating IAP are used clinically because direct measurements are considered to be too invasive (Malbrain 2004b, De Potter et al. 2005). These techniques include rectal, uteral, gastric, inferior vena caval and urinary bladder pressure measurement.

1. Bladder

1.1 Original Open Single Measurement Technique

This bladder technique, first described by Kron et al. (1984), has traditionally been used as the method of choice for measuring IAP. Each measurement involves disconnecting the patient's Foley catheter from the urine collection bag and sterilely instilling 50-100 ml of saline in the bladder. For each individual IAP measurement a 16 g needle is then used to connect a manometer or pressure transducer. The symphysis pubis is used as a reference line. This technique has many disadvantages. First and foremost, it is time consuming. Second, each measurement disrupts a closed sterile system, elevating the risk for contamination and urinary tract infections. Third, if the same pressure transducer is used for IAP and Central Venous Pressure (CVP), with zero-reference at the midaxillary line, putting the patient upright with concomitant rise in the transducer may lead to underestimation of IAP, while putting the patient in the Trendelenburg position can lead to overestimation. Fourth, the fact that recalibration needs to be done before every measurement augments the risk for errors.

Finally, a fluid-filled system can produce artifacts that further distort the IAP pressure waveform. Failure to recognize these recording system artifacts can lead to interpretation errors (Darovic et al. 1995). Any fluid-filled system is prone to changes in body-position and over- or underdamping due to the presence of air-bubbles, tubing that is too compliant or too long, etc. A rapid flush test should, therefore, always be performed before an IAP reading in order to obtain an idea of the dynamic response properties and to minimize these distortions and artifacts (Iberti et al. 1987). Confirmation of correct measurement can be done by inspection of respiratory variations and by gentle oscillations applied to the abdomen that should be immediately transmitted and seen on the monitor with a quick return to baseline. In case of a questionable signal, the flush test should be repeated.

Other disadvantages of this technique are that it is an intermittent technique that interferes with urine output without the possibility of obtaining a continuous trend, it places the patient at increased risk of urinary tract infection or sepsis, and it subjects healthcare providers to the risk of needle stick injuries and exposure to blood and body fluids (Kron et al. 1984). In conclusion, the Kron technique has at the present time no clinical implications.

1.2 Closed System Single Measurement Technique

Iberti and co-workers reported the use of a closed system drain and transurethral bladder pressure monitoring method (Iberti et al. 1987, 1989). Using a sterile technique, the method infuses an average of 250 ml of normal saline through the urinary catheter to purge catheter tubing and bladder. The bladder catheter is clamped and a 20-gauge needle is inserted through the culture aspiration port for each IAP measurement. The transducer is zeroed at the symphysis, and mean IAP is read after a 2-min equilibration period. This method has the same disadvantages related to the hydrostatic fluid column as the Kron technique, and because it is not needle-free it also subjects health care workers to needlestick injuries (Sugrue et al. 2002; Castillo et al. 1998). The advantages compared with the Kron technique are that it is simpler, less time-consuming, and there are fewer manipulations, thus a lesser risk of infections. In conclusion, the Iberti technique has at the present time limited clinical implications (e.g. screening for IAH).

1.3 Closed System Repeated Measurement Technique

Cheatham and Safcsak reported a revision of Kron's original technique (Cheatham and Safcsak 1998). In this method, a standard intravenous infusion set is connected to a 1,000 ml

reservoir bag of normal saline, two stopcocks, a 60-ml Luer-lock syringe and a disposable pressure transducer. An 18-gauge plastic intravenous infusion catheter is inserted into the culture aspiration port of the Foley catheter and the needle is removed. The infusion catheter is attached to the pressure tubing and the system flushed with saline (Fig.1). Measurements of IAP are then obtained.

This technique has the same inconveniencies related to any fluid-filled system as described with the Kron and Iberti techniques. It can pose problems after a couple of days because the culture aspiration port membrane can become leaky or the catheter may kink, leading to false IAP measurement. The fact that the infusion catheter needs to be replaced after a couple of days could increase the infection risk and needle-stick injuries. However, this technique has minimal side effects and complications, e.g. a decreased risk for urinary tract infection (Sagraves et al. 1997), it is safer, less invasive, takes less than 1 minute, it allows repeated measurements and is more cost-effective (Cheatham and Safcsak 1998). This technique is ideal for screening and monitoring, but because of leakage it cannot be used for longer than 48 hours.

1.4 Revised Closed System Repeated Measurement Technique

The technique of Cheatham and Safcsak (1998) was modified as follows. A ramp with three stopcocks is inserted in the drainage tubing connected to a Foley catheter. A standard infusion set is connected to a bag of 1,000 ml of normal saline and attached to the first stopcock. A 60-ml syringe is connected to the second stopcock and the third stopcock is connected to a pressure transducer via rigid pressure tubing (Fig.2). The system is flushed with normal saline

and the pressure transducer is zeroed at the symphysis pubis (or the midaxillary line when the patient is in complete supine position). It has the same inconveniencies related to a fluid-filled system as described with the Kron, Iberti or Cheatham techniques. This technique has the same advantages as the Cheatham technique, with a required nursing time of less than 2 min per measurement, a minimized risk of urinary tract infection and sepsis since it is a closed, sterile system, the possibility of repeated measurements and reduced cost. Since it is a needle-free system, it does not interfere with the culture aspiration port and the risk of needle stick injuries is absent. This technique can be used for screening or for monitoring for a longer period of time (2–3 weeks).

In an anuric patient, continuous IAP recordings are possible via the bladder using a closed system connected to the Foley catheter after the culture aspiration port, or directly to the Foley catheter using a conical connection piece connected to a standard pressure transducer via pressure tubing. After initial calibration of the system with 50 ml of saline and zeroing at the symphysis pubis, the transducer is taped at the symphysis or thigh and a continuous IAP reading can be obtained.

In conclusion, if one wants to use Intra-Vesical Pressure (IVP) as estimate for IAP, the Cheatham or revised technique is preferred over the Kron or Iberti technique. The revised methods for IAP measurement via the bladder maintain the patient's Foley catheter as a closed system, limiting the risk of infection. Since these are needle-free systems they also avoid the risks of needle-stick injury and overcome the problems of leakage and catheter kinks in the method described by Cheatham. They are more cost-effective, and facilitate repeated measurements of IAP.

1.5 Classic Technique

A quick estimate of the IAP can also be obtained in a patient without a pressure transducer by using his own urine as the transducing medium, first described by nurse Harrahill (Malbrain 2001, 2002; Harrahill 1998). To perform this measurement, one clamps the Foley catheter just above the urine collection bag. The tubing is then held at a position of 30–40 cm above the symphysis pubis and the clamp is released. The IAP is indicated by the height (in cm) of the urine column from the pubic bone. The meniscus should show respiratory variations. This rapid estimation of IAP can only be done in case of sufficient urine output. In an oliguric patient, 50 ml of saline can be injected to prime the system. This method has all the inconveniences associated with a fluid-filled system, as described previously. However, since it is needle-free, it poses no risks for injuries. It allows repeated measurements, is very inexpensive, and fast with minimal manipulation. Commercial kits are available for this technique (Fig.3).

1.6 U-tube Technique

In an animal study, Lee and co-workers compared direct insufflated abdominal pressure with indirect bladder, gastric and inferior vena cava pressures (Lee et al. 2002). IVP was measured by both the standard and U-tube technique, using the patient's own urine. With the U-tube technique, the catheter tubing was raised approximately 60 cm above the animal to form a fluid filled manometer, and IVP was measured as the height of the meniscus of urine from the pubic symphysis. The authors found a good correlation between the U-tube pressure and other direct and indirect techniques. It has the same advantages and inconveniences as the classic

“Harrahill” technique. The major advantage of this technique is that the volume re-instilled into the bladder is more stable (but still not well defined). This method can be used as a quick screening method.

1.7 Foley Manometer Technique

A prototype Foley catheter device (Holtech Medical, Copenhagen, Denmark) was tested for IAP measurement using the patients’ own urine as pressure transmitting medium (Malbrain et al. 2002). A 50 ml container fitted with a bio-filter for venting is inserted between the Foley catheter and the drainage bag. The container fills with urine during drainage; when the container is elevated, the 50 ml of urine flows back into the patient’s bladder, and IAP can be read from the position of the meniscus in the clear manometer tube between the container and the Foley catheter.

A good correlation was found between the IAP obtained via the Foley manometer and the gold standard in 119 paired measurements ($R^2=0.71$, $P<0.0001$). It has the same inconveniences and advantages as the other manometry techniques. It allows repeated measurements, is very cost-effective, and fast, with minimal manipulation. The advantage with the Foley manometer is that the volume re-instilled into the bladder is standardized at 50 ml; therefore, it is preferred over the other manometry techniques. A major drawback is the possibility of occasional obstruction of the bio-filter, leading to overestimation of IAP in some cases, and the presence of air-bubbles in the manometer tube, producing multiple menisci leading to misinterpretation of IAP. Further refinement and multicentric validation needs to be done before this method is used in a clinical setting.

In conclusion, the manometry techniques give a rapid and cost-effective idea of the magnitude of IAP and may be as accurate as other direct and indirect techniques. They can easily be performed every other hour together with and without interfering with urine output measurements. Moreover, the risk of infection and needle stick injury is absent. Since they need to be validated in a multicenter setting, they are currently not ready for general clinical use.

2. Stomach

2.1 Classic Intermittent Technique

The IAP can also be measured by means of a nasogastric or gastrostomy tube. This method can be used when the patient has no Foley catheter in place, or when accurate bladder pressures are not possible due to the absence of free movement of the bladder wall. In case of bladder trauma, peritoneal adhesions, pelvic hematomas or fractures, abdominal packing, or a neurogenic bladder, IVP may overestimate IAP, and an alternative method of measurement should be used (Collee et al. 1993). The same inconveniences associated with every fluid-filled system apply to measurements from the stomach. Another disadvantage is that the migrating motor complex and nasogastric feeding interfere with gastric pressures. Furthermore, all air and fluid needs to be aspirated from the stomach before measuring IAP, which is difficult to verify and becomes very difficult to confirm in patients with ileus. The advantages are that it is cheap,

does not interfere with urine output, and the risks of infection and needlestick injuries are absent. This cost-effective technique is ideal for screening.

2.2 Semi-Continuous Technique

Sugrue and co-workers assessed the accuracy of measuring simultaneous IVP and IAP via the balloon of a gastric tonometer during laparoscopic cholecystectomy (Sugrue et al. 1994). The tonometric balloon on the tube is usually employed for tonometry, a technique of indirectly measuring intramural pH. The balloon was inserted orally, and its intragastric position was confirmed by aspiration of gastric juice, auscultation of air insufflation into the stomach, and confirmation of a rise in IAP following external epigastric pressure. A pressure volume curve of the gastric tonometer balloon at 37 °C confirmed that instillation of up to 3 ml of air allowed the balloon to act as a pressure transducer. Particular attention was paid to make sure that the stomach was in a period of quiescent motor activity. They found a good correlation between the intravesical and the intragastric method. These results were validated and a good correlation was found between the classic gastric method, the tonometer method and IVP in a subsequent study (Debaveye et al. 2000).

Measurement via the tonometer balloon limits the risks and has major advantages over the standard intravesical method: no infection risk and no interference with estimation of urine output. Since it is air-filled, it has none of the disadvantages associated with fluid-filled systems (zero-reference points, over- or underdamping or body position). A possible disadvantage is the effect on interpretation of IAP values by the migrating motor complex. Recording the “diastolic” value of IAP at end-expiration can solve this problem. Other problems are that a 5-ml glass

syringe is needed to fill the balloon, and that no data are available on effects of enteral feedings on these IAP measurements. This technique could be used for experimental purposes and in cases where clinicians are interested in simultaneous CO₂ gap and IAP monitoring.

2.3 Revised Semi-Continuous Technique

In this method, an esophageal balloon catheter is inserted into the stomach for measurement of intra-gastric pressures. When the balloon is in the stomach, the whole of the respiratory IAP pressure wave will be positive and will increase upon inspiration in cases of a functional diaphragm. If the balloon is too high in the thorax, the pressure will flip from positive to negative on inspiration, indicating the balloon is measuring esophageal or pleural pressure instead. A standard three-way stopcock is connected to a pressure transducer. All air is evacuated from the balloon with a glass syringe and 1–2 ml of air reintroduced to the balloon. The balloon is connected via a “dry” system to the transducer; however, the transducer itself is not classically connected to a pressurized bag and not flushed with normal saline to avoid air/fluid interactions. The transducer is zeroed to the atmosphere and IAP is read at end expiration.

A disadvantage is that the air in the balloon is reabsorbed after a couple of hours, so that “recalibration” of the balloon is necessary with a 2–5 ml glass syringe for continuous measurement. Inaccurate measurements may occur if the nurse waits too long for recalibration or if the re-instilled volume is not exactly the same as the previous one. Advantages are it is less time-consuming, and it has all the advantages of an air-filled system. By using this technique, the cost of IAP is further reduced depending on the catheter used. Moreover, a semi-continuous measurement of IAP as a trend over time is possible. This technique is ideal for monitoring for

an extended period of time; however, when using multiple tubes the risk of sinusitis or infection needs to be evaluated.

2.4 Continuous Fully Automated Technique

For this continuous technique, the IAP catheter is introduced like a nasogastric tube, and it is equipped with an air pouch at the tip. The catheter has one lumen that connects the air-pouch with the IAP monitor and one lumen that takes the guide wire for introduction. The pressure transducer, the electronic hardware, and the device for filling the air-pouch are integrated in the IAP-monitor. Once every hour, the IAP monitor opens the pressure transducer to atmospheric pressure for automatic zero adjustment. The air-pouch is then filled with a volume of 0.1 ml required for accurate pressure transmission. Initial validation in ICU patients and laparoscopic surgery showed good correlation with the standard IVP method (Malbrain 2003). Schachtrupp and co-authors used the same technique to directly measure IAP in a porcine model and found a good correlation between the air pouch system and direct insufflator pressure (Schachtrupp et al. 2003).

This technique has no major disadvantage except that validation in humans is still in its infant stage. The advantages are similar to those related to other gastric and air-filled methods. In summary, it is simple, fast, accurate, reproducible, and fully automated, so that a real continuous 24 hour trend can be obtained. This technique is not suited for screening, but is best for continuous, fully automated monitoring for extended periods of time. Since it is less prone to errors and more cost-effective if in place for a longer period of time, this technique has potential in becoming the future standard for multicenter research purposes.

In summary, the revised methods via the stomach have the advantage of being free from interference caused by inaccurate transducer positions, since the creation of a conductive fluid column is not needed as air is used as the transmitting medium. The continuous fully automated technique also gives a continuous tracing of IAP together with APP, analogous to measurement of intracranial pressure and cerebral perfusion pressure, allowing both parameters to be monitored as a trend over time. The APP is calculated by subtracting IAP from the mean arterial blood pressure. Clinical data showed the importance of APP as a superior marker for IAH, allowing for improved treatment of patients with IAH and ACS, and reducing end-organ failure and associated morbidity and mortality (Malbrain 2002; Cheatham et al. 2000).

3. Rectum

Rectal pressures are used routinely as an estimate for IAP during urodynamic studies. Transmural detrusor muscle pressure is calculated as IVP minus IAP (Lacey et al. 1987; Shafik et al 1997). Rectal pressures can be obtained by means of an open rectal catheter with a continuous slow irrigation (1 ml/min), but special fluid-filled balloon catheters are used more routinely, although they are more expensive. The major problem with the open catheter is that residual feces can block the catheter-tip opening leading to overestimation of IAP. Other disadvantages of this technique are that it is more difficult, requires more manipulation, is intermittent, and cannot be used in patients with lower gastro-intestinal bleeding or profound diarrhea. There is also a great reluctance among nurses to use it. Since it is fluid-filled, it has all the problems associated with a hydrostatic fluid column, but since it is needle-free it decreases patient and healthcare worker infections or injuries. The fluid-filled balloon catheters are more

expensive and could theoretically stay in place for a longer period of time, but they may interfere with gastro-intestinal transit and can cause erosions and even necrosis of the anal sphincter and rectal ampulla. Finally these techniques have not been validated in the ICU setting. This technique has no clinical implications in the human ICU setting.

4. Uterus

This technique is performed with the same catheters as for the rectal route. Uterine pressures are used routinely by gynecologists during pregnancy and labor. Classically, a standard so-called “intra-uterine pressure catheter” (IUPC) is used for this purpose (Dowdle 1997). A special fluid-filled balloon catheter (as for rectal pressure) can be used; however electronic catheters are becoming more available (Fig.4). The major disadvantages of this technique are the same as for rectal pressures: i.e., it is more difficult, requires more manipulation, is intermittent, and cannot be used on patients with gynecological bleeding or infection. In its manometric, fluid-filled version, it has all the problems associated with a hydrostatic fluid column. Finally, this technique has not been validated in ICU patient populations. This technique has no clinical implications in the human ICU setting, and is limited to females.

5. Inferior Vena Cava

The inferior vena cava pressure (IVCP) has been suggested as an estimation for IAP in humans. It uses the same techniques as described previously but the methods are applied to an inferior vena cava catheter. A central venous line is inserted into the inferior vena cava via the

left or right femoral vein. The intra-abdominal position of the catheter is confirmed by portable lower abdominal radiographs, and confirmation of a rise in IAP following external abdominal pressure. A three-way stopcock is connected to the distal lumen, one end is connected to a pressure transducer via arterial tubing, and the other end is connected to a pressurized infusion bag of 1,000 ml saline. The transducer is zeroed at the midaxillary line with the patient in the supine position and IAP is read end-expiratory as with CVP.

The major disadvantage of this technique is the risk of possible catheter-related bloodstream infections and septic shock. The initial placement is more time-consuming. It also has the problems inherent to fluid-filled systems and poses potential injury to the patient and healthcare workers. The major advantages are that a continuous trend can be obtained, it does not interfere with urine output, and it could be used in bladder-trauma patients. Finally this technique has not been validated in human ICU patient populations.

In a rabbit study comparing different methods of indirect IAP measurement, Lacey and coworkers found a good correlation between bladder and inferior vena cava pressure with direct intraperitoneal IAP measurement, but not with gastric, femoral or rectal pressure (Lacey et al. 1987). Lee et al. (2002) also found a good correlation in 30 patients during laparoscopy. A study conducted in humans comparing superior vena cava pressure (SVCP) with common iliac venous pressure (CIVP) in various conditions of IAP and PEEP showed that the difference between CIVP and SVCP was not affected by the IAP, which implies that CIVP does not reflect IAP correctly (Yol et al. 1998). The most likely explanation is the differing anatomy between the humans and an experimental model used to induce increased IAP in canines. In humans both CIVP and SVCP increase as IAP increases (Yol et al. 1998). Joynt et al. (1996) also found a

good correlation between SVCP and IVCP regardless of IAH. This technique has limited implications in the ICU setting.

6. Microchip Transducer-Tipped Catheters

Different types of catheters tipped with microchip transducers are now available on the market (Fig.4). They can either be placed via the rectal, uterine, vesical or gastric route. These catheters have two types of construction: a 360 degree membrane pressure sensor in the organ (rectum, uterus, bladder, stomach) connected to an external transducer in a reusable cable, or a fiber-optic in vivo pressure transducer in the tip of the catheter itself. These catheters provide true zero in-situ calibration. By disconnecting and checking for zero on the monitor, clinicians can instantly validate and check the zero status of the monitor and the transducer (Dowdle 1997).

Schachtrupp and co-workers found a good correlation between IAP obtained by a piezoresistive pressure device and direct insufflator pressure ($R^2=0.92$), with a difference of 1.6 ± 4.8 mmHg (2.2 ± 6.5 cmH₂O); however, the limits of agreement were large (8 to 11.2 mmHg, 10.9 to 15.2 cmH₂O) (Schachtrupp et al. 2003). This might have been due to an unknown measurement drift due to the fact that the device cannot be zeroed to the environment when placed intra-abdominally. The major disadvantages of this technique is that it is very expensive; these catheters are said to be re-usable a couple of times after cleaning with soap and water and gas sterilization, but no data on ICU patients is available. They are mostly used during urodynamic studies or in females in labor for a limited period of time (hours); none have been tested in ICU patients for longer periods of time (days to weeks). The major advantages are that a

continuous trend can be obtained, it is less time consuming, and it does not interfere with urine output.

In summary, only gastric and bladder pressures are used clinically in humans. Over the years, bladder pressure has advanced as the gold-standard indirect method and commercial measurement kits have become available including the Foley Manometer (Holtech Medical, Kopenhagen, Denmark) and AbViser- valve (Wolfe Tory Medical, Salt Lake City, UT, USA). The bladder technique has achieved widespread adoption due to its simplicity and minimal cost (Malbrain 2004a, Malbrain and Jones 2006). However, considerable variation is noted between the different techniques used, and clinical data suggest that minimal volumes (10-25 ml) should be instilled in the bladder for priming to achieve consistent readings. (De Waele 2006, Malbrain and Deeren 2006, Ball and Kirkpatrick 2006).

Pathophysiologic Implications

IAH affects multiple organ systems in a graded fashion. In order to fully understand the clinical presentation and management of IAH disorders, the pathophysiology of each organ system must be considered separately (Saggi et al. 2001, Malbrain 2004b, Malbrain et al. 2005).

1. Neurologic Function

Acute IAH causes increased ICP due to augmentation of pleural pressure. Cranial perfusion pressure (CPP) decreases due to functional obstruction of cerebral venous outflow caused by increased intrathoracic pressure (ITP), which in turn is due to cephalad displacement

of the diaphragm in combination with the reduction of systemic blood pressure by decreased preload and cardiac output (CO). Cerebral blood flow and jugular bulb saturation also decrease. The effects of IAP on the central nervous system (CNS) have not been extensively studied to date and remain a challenging area for laboratory and clinical investigators (Malbrain et al. 2008, Deeren et al. 2005, Citerio and Berra 2006, Citerio et al. 2001, Bloomfield et al. 1999, Bloomfield et al. 1995, Bloomfield et al. 1996, Bloomfield et al. 1997, Saggi et al. 1999).

2. Cardiovascular Function

Pleural pressure and ITP also increase due to cephalad movement of the diaphragm. This results in difficult assessment of preload because traditional filling pressures are erroneously increased. When IAP rises above 10 mmHg (13.6 cmH₂O), CO drops because of increased afterload, as well as decreased preload and left ventricular compliance. Systemic vascular resistance (SVR) increases due to mechanical compression of vascular beds, and preload is reduced by decreased stroke volume and venous return (Kashtan et al. 1981, Ridings et al. 1995, Richardson and Trinkle 1976, Malbrain and Cheatham 2004). Mean arterial blood pressure may initially rise due to shunting of blood away from the abdominal cavity, but thereafter normalizes or decreases (Cheatham and Malbrain 2006a, Cheatham and Malbrain 2006b).

3. Pulmonary Function

Interactions between the abdominal and thoracic compartments pose a specific challenge to ICU physicians (Mertens zur Borg et al. 2006a). Both compartments are linked via the

diaphragm and on average a 50% (range: 25-80%) transmission of IAP to the ITP has been noted in previous animal and human studies (Malbrain and Cheatham 2004). Patients with primary ACS often develop secondary acute respiratory distress syndrome (ARDS) and require a different ventilatory strategy as well as more specific treatment than patients with primary ARDS (Ranieri et al. 1997, Gattinoni et al. 1998). The major problem lies in a reduction of functional residual capacity, which, together with alterations caused by secondary ARDS, leads to so-called “baby-lungs”. The “baby-lungs” concept originated from a series of CT examinations carried in patients with primary or secondary ARDS, which showed that the normally aerated tissue has the dimensions of the lung of a 5- to 6- year old child (Gattinoni and Pesenti 2012). Also, the compression of the pulmonary parenchyma, which appears to begin with an IAP of 16-30 mmHg (21.8-40.8 cmH₂O), results in alveolar atelectasis, decreased oxygen transport across the pulmonary capillary membrane, reduced pulmonary capillary blood flow, decreased CO₂ excretion and increased alveolar dead space, which in turn lead to hypoxia and hypercarbia. Both peak inspiratory and mean airway pressures are also significantly increased and may result in pulmonary edema (Cheatham 2009).

4. Hepatic Function

The liver appears to be particularly susceptible to injury in the presence of elevated IAP. Animal and human studies have shown impairment of hepatic cell function and liver perfusion even with an only moderately elevated IAP of 10 mmHg (13.6 cmH₂O) (Diebel et al. 1992a, Wendon et al. 2006). Furthermore, acute liver failure, decompensated chronic liver disease and

liver transplantation are frequently complicated by IAH and ACS (Biancofiore et al. 2004, Biancofiore et al. 2003a and b).

5. Renal Function

IAH has been associated with renal impairment for over 150 years (Schein 2006), but a clinically recognized relationship was only recently found (Biancofiore et al 2003b, Sugrue et al. 2006). An increasing number of large clinical studies have found that IAH is independently associated with renal impairment and increased mortality (Sugrue et al. 1995, Sugrue et al. 1999). The etiology of these changes is not well established but may be multifactorial and include reduced renal perfusion, reduced CO, increased SVR and altered expression of humeral and neurogenic factors. Elevated IAP significantly decreases renal artery blood flow and compresses the renal vein, leading to renal dysfunction and failure (Kirkpatrick et al. 2007). Oliguria develops at an IAP of 15 mmHg (20.4 cmH₂O) and anuria at 30 mmHg (40.8 cmH₂O) in the presence of normovolemia, and at lower levels of IAP in patients with hypovolemia or sepsis (Bradley et al. 1955, Harman et al.1982).

Renal perfusion pressure (RPP) and renal filtration gradient (FG) have been proposed as key factors in the development of IAP-induced renal failure and are defined as $RPP = MAP - IAP$ and $FG = GFP - PTP = (MAP - IAP) - IAP = MAP - 2 \times IAP$, where GFP is the glomerular filtration pressure and PTP the proximal tubular pressure. Thus, changes in IAP affect renal function and urine production more than changes in MAP. It is therefore not surprising that decreased renal function as evidenced by oliguria is one of the first visible signs of IAH (Malbrain et al. 2008).

6. Gastrointestinal Function

Intra-abdominal hypertension has profound effects on splanchnic organs, causing diminished perfusion, and mucosal acidosis, setting the stage for multi-organ failure (MOF) (Ivatury et al. 2006). The pathologic changes are more pronounced after sequential insults of ischemia-reperfusion and IAH. Intra-abdominal hypertension and ACS may serve as the second insult in the two-hit phenomenon of multiple-organ dysfunction syndrome (Diebel et al. 1997, Diebel et al 1992b). Clinical studies have demonstrated a temporal relationship between ACS and subsequent MOF (Ivatury and Diebel 2006, Balogh and Moore 2006, Raeburn and Moore 2006).

In animals, ACS provokes cytokine release and neutrophil migration, resulting in remote organ failure. In humans, ACS results in splanchnic hypoperfusion that may occur in the absence of hypotension or decreased CO. This ischemic and reperfusion injury to the gastrointestinal tract serves as the second insult in a two-hit model of MOF where the lymph flow conducts gut-derived pro-inflammatory cytokines to remote organs.

7. Abdominal Wall and Endocrine Function

Increased IAP has been shown to reduce abdominal wall blood flow by direct compressive effects leading to local ischemia and edema (Diebel et al. 1992c), which in turn can decrease abdominal wall compliance and exacerbate IAH (Mutoh et al. 1992). Abdominal wall

muscle and fascial ischemia may contribute to infectious and non-infectious wound complications (e.g., dehiscence, herniation, necrotizing fasciitis) often seen in patients with IAH.

Clinical Management

The management of patients with IAH is based on three principles (Mayberry 2006, Parr and Olvera 2006): specific procedures to reduce IAP and the consequences of ACS, general support (intensive care) of the critically ill patient, and optimization after surgical decompression in an attempt to counteract some of the specific adverse effects associated with decompression.

1. Medical Treatment

Before surgical decompression is considered, less invasive medical treatment options should be exhausted. Different medical treatment procedures have been suggested to decrease IAP (Malbrain 2002) and are based on five different mechanisms: improvement of abdominal wall compliance, evacuation of intraluminal contents, evacuation of abdominal fluid, correction of capillary leak and positive fluid balance, and specific treatments to reduce abdominal pressure.

1.1 Improvement of Abdominal Wall Compliance

A number of pharmacological, physical and surgical approaches can be used to manage abdominal wall compliance. Drugs that are used to decrease IAP include sedatives and curarizing

agents. Sedation can help to control IAH by increasing abdominal wall compliance. Fentanyl, however, may acutely increase IAP by stimulation of active phasic expiratory activity (Drummond and Duncan 2002) so opioids should be used judiciously in sedation protocols for these patients. Curarization decreases IAP, however its use is almost exclusive to the operating theater (Deeren et al. 2005, De Waele et al. 2003, Macalino et al. 2002, Kimball and Mone 2005, Kimball et al. 1985).

Regarding mechanical strategies, body positioning has an important effect on IAP. It appears that supine position results in a decrease in IAP and prone positioning results in its increase, most likely as a consequence of restriction of abdominal movements (Hering et al. 2001, 2002, Michelet et al. 2005). In situations where prone positioning is necessary for other reasons, for example to improve arterial oxygenation in patients presenting with ARDS, the use of skin pressure decreasing interfaces such as air mattresses can help keep the increase in IAP to a minimum (Michelet et al. 2005).

As far as surgical approaches to treatment of IAH and ACS, a percutaneous procedure for increasing abdominal capacity/compliance and decreasing IAP based on the principles of abdominal wall component separation was validated in a porcine ACS model (Voss et al. 2003). Briefly, bilateral subcutaneous tunnels were made above the plane of the abdominal musculature, and dissection of the external oblique insertion and development of the plane between external and internal oblique muscles was performed. The fascia overlying internal oblique was left intact. This procedure resulted in an increase in the abdominal capacity of more than 1 L, a mean pressure drop of 31.6%, and a 61% improvement in intestinal perfusion (Voss et al. 2003). In burn patients, a similar procedure also had beneficial effects (Latenser et al. 2002).

1.2 Evacuation of Intra-Luminal Contents

Ileus is common in most critically ill patients. Non-invasive evacuation of abdominal contents should be attempted by gastric tube placement and suctioning, rectal catheters, enemas and possibly endoscopic decompression (Bauer et al. 1985, Cheatham et al. 1995, Moss and Friedman 1977, Savassi-Rocha et al. 1992). These procedures can be performed in conjunction with administration of gastro- and or colonoprokinetics such as erythromycin, metoclopramide and neostigmine or prostigmine (Ponec et al. 1999, Wilmer et al. 1997, Madl and Druml 2003, Malbrain 2000a, Gorecki et al. 2000, van der Spoel et al. 2001).

1.3 Evacuation of Abdominal Fluid Collections

Drainage of tense ascites may result in decreased IAP (Luca et al. 1994, Cabrera et al. 2001, Reckard et al. 2005). In patients with liver cirrhosis and esophageal varices, paracentesis helps to decrease variceal wall tension and the risk of rupture and bleeding. (Escorsell et al. 2002). Paracentesis is also the treatment of choice for burn patients with secondary ACS (Latenser et al. 2002, Gotlieb et al. 1998, Navarro-Rodriguez et al. 2003). For hematomas, blood collections and local abscesses, CT-guided fine needle aspiration has been described in the setting of IAH and ACS (Malbrain and De Laet 2009).

1.4 Correction of Capillary Leakage, Blood Pressure Management and Positive Fluid Balance

In the initial phase, fluid loss should be compensated to prevent splanchnic hypoperfusion (Friedlander et al.1998, Gargiulo et al. 1998, Simon et al. 1997). Low-dose infusion of dobutamine, but not dopamine, also corrects the impairment of intestinal mucosal perfusion by moderate increases in intra-abdominal pressure (Agusti et al. 2000). Abdominal compartment syndrome patients retain large volumes of sodium and water that exacerbates tissue edema and third spacing due to capillary leakage, thereby resulting in a vicious cycle of ongoing IAH. In the early stages, diuretic therapy in combination with albumin can mobilize the edema, but only if the patient is hemodynamically stable. In some cases, it is preferable to give colloids or albumin instead of crystalloids (O'Mara et al. 2005, SAFE 2004). In burn patients, co-administration of ascorbic acid results in reduced fluid requirements (Matsuda et al. 1991, Tanaka et al. 2000). Many patients, however, will develop anuria as renal blood flow is reduced. In these cases, renal replacement therapy with fluid removal by intermittent dialysis or continuous veno-venous hemofiltration (CVVH) should not be delayed (Oda et al. 2005, Kula et al. 2004, Vachharajani et al. 2003).

1.5 Specific Treatments

The application of continuous negative abdominal pressure using an externally applied, continuous, negative abdominal pressure device has shown to decrease IAP and increase end-expiratory lung volumes in animals and humans (Bloomfield et al. 1999, Saggi et al. 1999, Valenza et al. 2005, Valenza et al. 2003, Valenza and Gattinoni 2006). In a manner similar to the targeting of CPP ($CPP=MAP-ICP$) or coronary perfusion pressure (CoPP) ($CoPP = \text{diastolic blood pressure} - \text{pulmonary artery occlusion pressure}$), it may be appropriate to target APP,

where $APP=MAP-IAP$, to a level that reduces the risk of worsened splanchnic perfusion and subsequent organ dysfunction (Cheatham et al. 2000, Malbrain 2002, Malbrain and Cheatham 2004).

2. Surgical Decompression

Although surgical decompression remains the only definitive management tool for ACS, the timing of this procedure still remains controversial. During the intervention, specific anesthetic challenges need to be addressed, and after decompression the patient is at risk for ischemia-reperfusion injury, venous stasis and fatal pulmonary embolism (Mertens zur Borg et al. 2006b). Maintenance of adequate preload and APP is the key to success (Cheatham et al. 2000, Cheatham and Malbrain 2006a, Simon et al. 1997). Open abdomen treatment (or laparostomy) was initially intended for patients with diffuse intra-abdominal infections and often was used in combination with a planned re-laparotomy approach. Due to the increased awareness of the deleterious effects of IAH, open abdomen treatment, either prophylactic or therapeutic, is more common in the ICU (Balogh and Moore 2006, Balogh et al. 2006).

c. Intra-Abdominal Pressures in Equine Medicine

Potential Relevance

As previously mentioned, three causes of IAH in human medicine include decreased body wall compliance (e.g., tight abdominal closures), increased intra-abdominal contents (e.g., due to ileus, ascites, or hemoabdomen), as well as IAH secondary to large volume resuscitation resulting in capillary leak syndrome, reperfusion injury, and cytokine release (Pelosi et al. 2002, Ivatury et al. 1997, Malbrain et al. 2008). Similar risk factors for IAH are present in equine patients (Munsterman and Hanson 2009), and recognition of IAH in this species would allow for development of therapies to prevent multiorgan dysfunction from ACS (Munsterman and Hanson 2009).

Current Literature

Although animal models for IAH and ACS have been developed using pigs, dogs, cats, ruminants, rabbits, chimpanzees and guinea pigs (Bailey and Shapiro 2000, Rosenthal et al. 1997, Rosenthal et al. 1998, Gudmundsson et al. 2001, Schachtrupp et al. 2002, Harman et al. 1982, Davis et al. 1965, Beckett et al. 1967, Dougherty et al. 1955, Yagci et al. 2005, Doty et al. 2002), clinical reports in veterinary medicine are sparse. In companion animals, IAH has been associated with ovariohysterectomy, gastric dilatation and volvulus, pyometra, hemoperitoneum,

ascites, diaphragmatic hernia, bile peritonitis, and babesiosis (Conzemius et al. 1995, Drellich 2000, Joubert et al. 2007). In large animal species, cardiopulmonary sequelae of pathologic IAH in ruminant bloat and iatrogenic IAH secondary to CO₂ insufflation during laparoscopy in horses have been investigated (Donaldson et al. 1998, Latimer et al. 2003, Cruz et al. 2004). More recent research in horses established reference values for indirect IAP in standing, sedated and recumbent, anesthetized horses (Southwood and Wilkins 2005), which measured <10 cmH₂O (<7.4mmHg) in anesthetized, recumbent horses; and <7 cmH₂O (<5mmHg) in standing sedated horses using a bladder catheterization technique and a water manometer (Wilkins 2005, Southwood and Wilkins 2005). Munsterman and Hanson (2009) developed a direct method for measuring intra-abdominal pressures in the standing horse, established reference values for pressures using this technique in horses off feed, and investigated several indirect measurement techniques in this species. The same group of investigators researched the effect of abdominal bandages and gastric fill on IAP (Barrett et al. 2013a,b), and validated the use of a microsensor catheter as a more practical tool for direct IAP measurement in this species (Barrett et al. 2013c). Reference values for direct (invasive) measurement techniques as established by Munsterman and Hanson (2009, 2011) were subatmospheric (range -5.0 to 0.3 cm H₂O, mean ± SD -1.80 ± 1.61 cm H₂O in the 2009 study; range -6.6 to 3.1 cm H₂O, mean ± SD, -1.59 ± 2.09 cmH₂O in the 2011 study).

Diagnosis

Similarly to human medicine, IAP in horses 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 (Malbrain 2004a). The indirect method using intravesicular pressures has been investigated as technique for intra-abdominal pressure measurement in veterinary patients (Joubert et al. 2007, Wilkins 2005, Munsterman and Hanson 2009) as well as in canine and porcine models of human intra-abdominal hypertension (Kron et al. 1984, Iberti et al. 1987, Gudmundsson et al. 2002). Research models measuring intra-abdominal pressures in horses have used both a direct and indirect method (Dechant et al. 2008, Southwood and Wilkins 2005).

1. Bladder

1.1 Water Manometry

Munsterman and Hanson (2009) have shown that indirect IAP measured using a transvesical technique were repeatable within each horse, but not between horses, and that indirect pressures did not significantly correlate to direct pressure measurements (Munsterman and Hanson 2011, Barrett et al. 2013a, Barrett et al. 2013b). This study was also the first in evaluating the effect of infused fluid volume on bladder pressures in horses. The results indicated that indirect pressures were increased with increasing bladder infusion volumes, probably due to increased detrusor tone as reported in the human literature (Gudmundsson et al. 2002, DeLaet et al. 2008, Souminen et al. 2006, Chiumello et al. 2007, Malbrain and Deeren 2006, De Waele et al. 2006). Current recommendations suggest that bias can be reduced by infusing a minimal amount of fluid, 25mL in humans, to establish a column of fluid for a pressure reading (Malbrain et al. 2006, DeLaet et al. 2008, Malbrain and Deeren 2006, De Waele et al. 2006, Fusco et al.

2001). The results of the study from Munsterman and Hanson (2009) show no effect on pressures with infusion volumes of 50mL 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 that study.

When indirect IAP were compared with direct pressures across the range of bladder volumes in that 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 IAP across a range of volumes showed much higher correlation coefficients for all volumes, with Pearson's r values ranging from 0.78 to 0.97 (Souminen et al. 2006, Fusco et al. 2001). Anatomical differences, including the position of the bladder (retroperitoneal) in the human versus the horse (intraperitoneal), make direct comparisons between studies difficult (Gudmundsson et al. 2002, Munsterman and Hanson 2009).

1.2 Air Filled System

An alternative air-filled system (Canola et al. 2009) has been used for intravesical measurement resulting in inconsistent findings; correlation between values of intravesical pressure and IAP was lacking. The authors speculated on several possible reasons for this lack of correlation; the bladder may have been over-distended (3 ml/kg fluid was used in each horse), the compliance of the bladder wall may not be consistent amongst individuals which may have reflected in transvesical pressure measurements, and circulating catecholamines due to stress of

catheter placement and manipulation may have had an effect on the detrusor muscle and therefore on bladder pressures (Canola et al. 2009).

2. Stomach

Equine intragastric pressure (IGP) was first measured in studies on exercise physiology, by means of a balloon catheter (Slocombe et al. 1991), a microchip-tipped transducer (Ainsworth et al. 1996), and a specially made barostatic intragastric bag (Lorenzo-Figueras and Merritt 2002). This bag measures changes in pressure by recording the amount of air that must be injected or removed to maintain a preset pressure, and it has been used in place of the tonometry balloon for gastric pressure measurement in exercising horses (Lorenzo-Figueras and Merritt 2002); however, direct comparison to intraperitoneal pressures or any other method of indirect pressure measurement has not been performed.

Munsterman and Hanson (2009) tested IGP in horses and their correlation with directly measured intra-abdominal pressures. Indeed, the stomach acts in a manner similar to the bladder, allowing transduction of intra-abdominal pressures to the fluid column established within a nasogastric tube (Munsterman and Hanson 2011). To allow for a comparison, simultaneous direct intraperitoneal pressure measurement was performed. For indirect IAP measurement using gastric pressures, a U-tube manometry technique was used based on a previously published method (Lee et al. 2002). A standard equine nasogastric tube (12mm internal diameter, 295cm long) was placed in the stomach to the level of the 11th rib space, with the distance measured before placement of the tube. Air was removed from the stomach, and the tube was kinked and then capped to reduce the entrance of room air. For gastric pressure measurement, a solid fluid

column was established with the residual fluid in the stomach by infusion of a specific volume of water using a funnel. Gastric pressures were measured by holding the nasogastric tube vertical to act as a manometer, and the pressure determined using a centimeter ruler, zeroed at the point of the shoulder (Munsterman and Hanson 2011).

This method uses the tubing itself as the manometer and has been validated in pigs and in humans as a noninvasive method for IAP measurement (Collee et al. 1993, Lee et al. 2002). By raising the tubing vertically, a U is formed, allowing the water pressure to be measured as the height of the column of fluid above a given reference. The point of the shoulder was chosen in this specific study as a repeatable reference point to approximate the level of the stomach in the horse (Munsterman and Hanson 2011).

For comparison of the intraperitoneal and gastric pressures measurement techniques, pressures were recorded using both methods simultaneously after infusion of 5 different volumes of fluid (0, 400, 1,000, 2,000, 3,000mL) into the stomach. Multiple volumes were selected to determine the effect, if any, on gastric pressure, as well as to determine the optimum volume to consistently obtain a manometry reading. Although the authors were able to obtain gastric pressure measurements in all of the horses, the intra- and inter-individual variation was significantly greater for gastric pressure measurements at all infusion volumes when compared with intraperitoneal pressures. Comparison between the two methods of pressure measurement demonstrated a conclusive lack of correlation (Lin's concordance correlation coefficient, -0.003; $P = 0.75$), indicating that gastric pressures should not be used in place of intraperitoneal pressures for IAP measurement.

The authors suggested the most likely cause of the inaccuracies of the pressures recorded to be the fluid manometry method itself (Malbrain 2004a). The residual volume in the stomach was unknown, which raises questions as to the accuracy and reproducibility between measurements based on a specific volume infused. Furthermore, it is impossible to know exactly where the tubing is placed in a horse's stomach, and any air pocket in the stomach or tubing could attenuate the pressures transferred through the fluid column (Malbrain 2004a). The U-tube method, as described, requires complete drainage of the stomach and removal of any residual air in the organ before measurement to avoid this complication (Collee et al. 1993, Lee et al. 2002), but this is difficult to perform or confirm in horses (Munsterman and Hanson 2011).

To avoid the pitfalls of the manometry system, the use of a gastric tonometry balloon in human medicine has been shown to increase accuracy, and also allow for the measurement of gastric pH as an independent measure of perfusion (Turnbull et al. 2007, Sugrue et al. 1994). The balloon is filled with a specific volume of air, and pressure changes are recorded by measuring compression of the balloon. This air-filled system negates the problems with the manometry technique in terms of the variability of an arbitrary reference point, or over- and underdamping of the system by air bubbles (Munsterman and Hanson 2011). Gastric tonometry has been described in foals (Sanchez et al. 2008, Valverde et al. 2006), and the use of gastric and esophageal balloon manometers has been attempted subsequently; however the correlation with directly measured IAP was poor (Canola et al. 2011a).

3. Rectum

Intra-rectal pressures (IRP) in horses have been tested as part of an exercise physiology study using a balloon catheter (Slocombe et al. 1991). That study found lack of correlation between IRP, IGP and IAP and also inconsistent readings for each catheter. The authors speculated that there may be real differences in regional pressures throughout the abdomen attributable to elastic, resistive and inertial effects of different regions of the visceral mass. However, this explanation contradicts Pascal's law that states that pressure exerted anywhere in a confined incompressible fluid is transmitted equally in all directions throughout the fluid such that the pressure variations remain the same (Bloomfield 2006). Alternatively some data in Slocombe's study may be spurious due to the fact that the catheters may not have been surrounded by a fluid medium at all times during measurements (Slocombe et al. 1991).

4. Direct Techniques

4.1 Teat Cannula and Water Manometer

Munsterman and Hanson (2011) were the first to describe a standardized and repeatable technique for direct measurement of IAP in horses. A teat cannula was placed intra-peritoneal using a modified abdominocentesis technique. The height of the midpoint of the tuber ischii and the point of the shoulder (cranial eminence 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. The final site was chosen at that height, approximately 12 cm caudal to the last rib in the right flank. After proper clipping, aseptic preparation and local anesthesia, an 8-cm metal teat cannula was introduced into the abdomen.

An extension set with an injection port near the hub was attached to the teat cannula. A water manometer system was connected to the extension set and a fluid column was established from the water manometer using sterile electrolyte solution. The manometer was zeroed at the height measured for introduction of the cannula. The averaged direct IAP measured from standing, normal horses with the head in a neutral position was -1.80 cmH₂O (1.61 cmH₂O; 95% CI, -2.80 to -0.80), ranging from -5.0 to 0.3 cmH₂O (median -1.65 cmH₂O) in that study. Serial measurement of direct IAP was performed in each horse, which obtained consistent readings (variance 0.00–0.85, average SD 0.22) (Munsterman and Hanson 2009). This study is the first in reporting a standardized technique for direct IAP measurements in the horse.

The cannula site for direct pressure measurement was selected based on 2 factors. First, the site was extrapolated from the mid-axillary line, the recommended reference point for indirect pressure measurement in humans (Malbrain et al. 2006). Second, this site was easily accessible in the flank, and used 2 boney landmarks to allow for consistent selection of an entry point. Previous work had shown that the mass of the abdominal contents above the site of measurement influences the IAP measured (Pelosi et al. 2002, Malbrain 2004a, Loring et al. 1994, Bumaschny and Rodriguez, 2000). Because the majority of gastrointestinal viscera lie beneath the cannula, the authors postulated that their site selected should reduce error due to normal variations in abdominal fill, but still allow space above the cannula to measure any 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 IAP 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 (Munsterman and Hanson 2009).

Direct IAP obtained in the study were subatmospheric, which is expected to allow for normal venous return and perfusion of the abdominal organs (Malbrain et al. 2006, Pelosi et al. 2002, Masey et al. 1985). Interestingly, direct pressures measured previously through a ventral midline cannula in horses were extremely positive (95% CI 17.9–43.1cmH₂O) (Dechant et al. 2008) probably due to 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, which has been related to the known effects of gravity, the mass and deformability of organs, and to compressive external forces (Malbrain 2004a, Loring et al. 1994).

In humans, body mass index significantly increases IAP (Lambert et al. 2005, Sanchez et al. 2001, Malbrain et al. 2004b, Malbrain 2000b), but interestingly the opposite is true for horses (Munsterman and Hanson 2009). 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 (Munsterman and Hanson 2009). When both studies from Munsterman and Hanson are analyzed (2009 and 2011), intra- and inter-individual variance for directly measured IAP were similar in both reports, indicating that the use of this method appears to provide reliable results in normal horses. Both studies noted a lack of correlation between the indirect measurements using bladder or gastric pressures and intraperitoneal pressures. In addition, there was significantly greater inter-individual variation for the indirect measurement of intra-abdominal pressures regardless of technique (Munsterman and Hanson 2011). The authors concluded that both methods of indirect intra-abdominal pressure measurement are highly

variable between horses, which will make statistical comparison between horses and between studies 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 cannula abdominocentesis was deferred, or in horses where long-term intra-abdominal pressure monitoring is required.

Differences between investigational approaches and reference points for placement of the cannula have contributed to there being substantial variation in reported normal values. Some obtained subatmospheric values ranging from -11.6 ± 2.0 mmHg (-11.6 ± 2.7 cmH₂O) (Canola et al. 2009) and -10.16 ± 2.2 mmHg (-14.4 ± 2.3 cmH₂O) (Canola et al. 2011b) to -1.32 ± 4.5 mmHg (-1.8 ± 6.1 cmH₂O) (Munsterman and Hanson 2009) and -1.17 ± 1.53 mmHg (-1.6 ± 2 cmH₂O) (Munsterman and Hanson 2011) while others have reported positive IAP values, ranging from 2.72 ± 1.0 mmHg (3.7 ± 1.4 cmH₂O) (Slocombe et al. 1991) to 32.5 ± 11.5 mmHg (44.2 ± 15.6 cmH₂O) (Dechant et al. 2008). In the first case series describing IAH in 2 clinical equine cases, IAP values measured directly by abdominal puncture ranged from 21–26 mmHg (28.5–35.3 cmH₂O) (Brosnahan et al. 2009).

Direct IAP measurement in man has also been shown to be prone to errors caused by flow of ingesta, resulting in rapid increases in abdominal pressure during IAP investigation

previously to abdominal inflation. Furthermore, the needle opening can be blocked by tissue leading to over- or underestimation of IAP (Malbrain 2004a). Many diverse factors are known to influence IAP, including body position, body weight, obesity, mechanical ventilation under general anesthesia, intestinal motility and intestinal content, and anesthesia-induced muscle relaxation (Malbrain 2004a, Southwood and Wilkins 2005, Dechant et al. 2008, Cheatham 2009, de Keulenaer et al. 2009, Munsterman and Hanson 2009, Gallagher 2010). Based on a critical review of the current literature, it is possible to conclude that at this point standard reference intervals for diagnosis of intra-abdominal hypertension may only be possible based on direct intraperitoneal pressure measurement (Munsterman and Hanson 2011).

4.2 Microchip Transducer-Tipped Catheters

Electronic catheters were used for IGP measurement in horses in the study by Ainsworth et al. (1996). More recently, Barrett et al (2013c) validated the use of a solid-state microsensor catheter (Fig.5) for direct measurement of IAP using a technique modified by Munsterman and Hanson (2011). The method used a solid microsensor (Fig. 5) placed at the same height as the cannula at a location 14 cm caudal to the last rib, on the right side of the horse. Prior to placement within the abdomen, the microsensor is zeroed within a fluid medium as directed by the manufacturer. An open-ended metal cecal cannula (Fig.6) was placed intraperitoneally at this location in the same fashion as the first metal cannula. The obturator was removed, and the microsensor was fed through the cannula into the abdomen. After the microsensor is fed 12 cm into the abdomen, the cannula is removed from the body wall, leaving only the microsensor in place within the abdomen. The microsensor is then connected to an electronic display.

Advantages of the microsensor are that the malleable cord allows for continuous direct IAP measurements without repeatedly cannulating the abdomen and without the need for restraint in stocks. Additionally, the unit is simple to use and allows for digital recording of any measured data (Barrett et al. 2013c).

Clinical Applications

Clinical signs displayed by horses affected by IAH are not well recognized and will most likely depend on the nature of the underlying causative disease (Wilkins 2005). From a general perspective, abnormal physical examination findings may include lethargy, reduced or absent appetite, tachycardia, tachypnea, abdominal distention, oliguria, ventral subcutaneous edema, and limb edema (especially affecting the pelvic limbs). Signs of decreased cardiac output such as cool distal extremities have also been reported (Brosnahan et al. 2009). Abnormalities regarding the pattern of urination such as dysuria and pollakiuria have been described in both equine (Brosnahan et al. 2009) and human patients (Sugrue 2005); these may be the clinical manifestation of renal dysfunction occurring as a result of IAH, due to increased renal vascular resistance, decreased cardiac output and glomerular filtration rate. Cardiac anomalies may be further demonstrated by echocardiography, which may show decreased right ventricular end-diastolic volume, consistent with decreased venous return and thoracic tamponade (Brosnahan et al. 2009). Finally, ultrasonographic examination of the abdomen may demonstrate an increased quantity of peritoneal fluid (Wilkins 2005, Brosnahan et al. 2009).

A number of conditions frequently reported in equine medicine may alter IAP in this species, namely gastric fill, abdominal bandages and abdominal palpation per rectum. Clinically,

the volume of contents within the equine stomach may be increased in two scenarios. The first is pathologic, such as in intestinal ileus or small intestinal impaction with ingesta that causes the buildup of fluid within the stomach (Freeman 2006, Barrett et al. 2013a). The second is iatrogenic, through instillation of a volume of fluid (e.g., water, electrolyte solution, mineral oil, or feed slurry) into the stomach to treat dehydration, malnutrition, diarrhea, fecal impactions, or large colon displacements, among others (Monreal et al. 2010, Rainger and Dart 2006, Lopes et al. 2004, Lopes 2003, Barrett et al. 2013a).

Barrett et al. (2013a) elegantly demonstrated that gastric distension significantly increases intra-abdominal pressures in normal horses. In this study, the mean IAP prior to placement of the nasogastric tube was subatmospheric, consistent with the findings from Munsterman and Hanson (2009). Comparisons of IAP taken after infusion of fluid into the stomach noted statistically significant differences from baseline when 5 L, 10 L, 15 L and 20 L were administered, with IAP rising up to 9 cm H₂O from baseline values. Abdominal organ perfusion pressures, determined from the MAP minus the mean IAP, decreased as the gastric instillation volumes increased, but were not significantly different for any comparison made. Average baseline APP in these horses was 138 ± 30 cm H₂O and decreased to 131 ± 21 cm H₂O after instillation of a total of 20 L of water.

The rise in IAP seen in this study after the instillation of fluid into the stomach could produce an additive effect with pressure from preexisting abdominal disease leading to an increased risk of ACS in affected horses. The small increases in pressure seen in this study could escalate pressures to levels capable of compressing intra-abdominal vessels, leading to altered blood flow and reduced tissue perfusion. Additional work is required to assess the effect of increased gastric volumes in horses with concurrent disease, but the results of this study may

influence the use of enteral fluids in clinical cases. Nasogastric administration of between 8 and 10 L of balanced electrolyte solution every two hours has been suggested for the treatment of large colon impactions (Monreal et al. 2010), and volumes as high as 10 L every 30 min have been administered experimentally (Lopes 2003). Repeated administration of these large amounts of fluid as boluses within a short period of time could repeatedly increase pressures and may lead to sustained raised IAP with unknown clinical consequences. These results may suggest keeping the residual stomach volume to 5 L or less in refluxing horses to reduce adverse effects of gastric fill on IAP. Increased residual fluid volumes in the stomach may result from gastrointestinal disorders including intestinal impaction, postoperative ileus and enteritis.

Abdominal bandages are commonly used after a ventral midline celiotomy in horses, due to a reported decrease in the incidence of incisional infections (Smith et al. 2007). In addition, abdominal palpation per rectum is often performed in colic patients to monitor progression of the gastrointestinal disease (Hardy and Rakestraw 2012). These procedures may cause an abdominal press, due to the discomfort of the exam or bandage, and reduced abdominal compliance by mechanical pressure on the body wall by the bandage.

The same authors examined the effects of compressive abdominal bandages and abdominal palpation per rectum on IAP in horses (Barrett et al. 2013b). Placement of an abdominal support wrap resulted in a significant increase of IAP from baseline, whereas no significant effect was elicited by abdominal palpation per rectum. Tight abdominal wraps are known to reduce abdominal wall compliance in human patients and reduced compliance is a known contributing factor for IAH (Malbrain et al. 2008, Hunter and Damani 2004). The results of this study suggest that abdominal compression wraps can significantly increase the IAP measured in the normal horse. This complication of abdominal support wraps has not been

previously investigated in horses, and its clinical significance requires further investigation in horses with abdominal disease. While the relative magnitude of change in IAP was small, it is possible that this increase in pressure could provide an additive effect, increasing the risk of IAH in patients already experiencing increased IAP for other reasons (Barrett et al 2013b).

The clinical relevance of IAP in horses is an interesting prospect for future investigations in equine critical care. To date, changes in IAP have been considered in the pathogenesis of epiploic foramen entrapment in this species (Archer et al. 2008), and in turn the association between cribbing behavior and epiploic foramen entrapment has been proven by several retrospective studies (Archer et al. 2004, 2008). The objective of this research was to further investigate the association between cribbing behavior and IAP in horses, to offer a potential pathogenic explanation for development of epiploic foramen entrapment.

Previously, some authors suggested that cribbing behavior may decrease IAP, thereby causing expansion of the epiploic foramen and herniation of the small intestine through the foramen itself (Archer 2008). This study aimed to investigate the effect of cribbing behavior on IAP. The goal of the present study was to measure the IAP of horses before, during and after the cribbing behavior. The hypotheses of this study were that IAP of horses during cribbing would be significantly higher compared to resting IAP, and that IAP of cribbing horses would be higher than the IAP of horses that do not crib.

I. MATERIALS AND METHODS

This study was performed at Auburn University Large Animal Teaching Hospital, and all procedures were approved by the Auburn University Institutional Animal Care and Use Committee. The horses were selected based on the following inclusion criteria: no history of colic in the previous 6 months, no history of previous abdominal surgery, no ongoing pregnancy, body condition score $<6/9$ and $>4/9$ according to the system described by Henneke (1983, 1985), normal physical exam, normal trans-rectal palpation, and normal abdominal and thoracic ultrasonographic exam at the time of inclusion. A total of sixteen horses were used, 13 geldings and 3 mares. Breeds represented included Thoroughbred, Quarter Horse, Paint and a warmblood cross. Mean age was 13.8 years (median 14 years, range 10 to 18 years) and average weight was 519 kg (median 517 kg, range 422 to 585 kg). Mean height at withers was 163 cm (median 164 cm, range 148 to 170 cm). Eight of the selected horses (Group 1, cribbing cohort) were known to perform the stable vice of cribbing, based on history, observation of the stereotypical behavior, and dental wear. Of these, 7 were geldings and 1 was a mare. The other 8 were free of this vice (Group 2, non-cribbing cohort). Of these, 6 were geldings and 2 were mares.

a. Initial Examination (Day One)

For inclusion in the study, each horse was restrained in stocks and received a physical exam, external abdominal and thoracic ultrasound, and a trans-rectal palpation to confirm a lack of pregnancy, abdominal or thoracic disease. Body condition scores were recorded, as well as the body weight and height at the withers. Horses identified as cribbers were selected from an Auburn University herd specifically maintained and known to crib. Dental wear and history was evaluated on all horses to confirm or refute that the horses actively performed the vice. If the horses met the inclusion criteria, they were confined in a 12x12 foot stall. Food was withheld for 24 hours, and a muzzle was placed if necessary to prevent ingestion of shavings. Water was removed from the stall 3 hours prior to instrumentation. Visual checks every hour were performed during stall confinement.

b. Instrumentation (Day Two)

Each horse was restrained in the stocks and a peritoneal cannula was placed in a manner previously described for direct measurement of intra-abdominal pressures (Munsterman and Hanson 2009). Briefly, in the lower right flank at a level midway between the point of the shoulder and the tuber ischii, a 4x4 cm area of skin was clipped and aseptically prepared in a routine manner (chlorhexidine scrub and alcohol). The skin and subcutaneous tissues were anesthetized with 5 ml mepivacaine. A stab incision was made through the skin using a number 15 blade, allowing for placement of a 10 cm cannula through the body wall and peritoneum. Placement in the abdomen was confirmed by a loss of resistance to digital pressure on insertion, as well as the audible entrance of air into the abdomen. Sterile water-based lubricant was immediately placed around the cannula to prevent aspiration of air through the cannula at the insertion site. The stylet was removed from the cannula and a solid state, microsensor piezoelectric catheter (Codman, Raynham, Massachusetts) was placed through the cannula into the peritoneal cavity. The cannula was removed, leaving the catheter in place, and the insertion site bandaged with sterile gauze and elastic tape (Elastikon, Johnson and Johnson, New Brunswick, New Jersey). The Codman catheter is an electronic device and no cap or tubing is necessary.

c. Monitoring Phase (Day Two, Continued)

The horses were returned to their stalls and confined to one corner by loosely tying their heads. For measurement of the intra-abdominal pressures, the intraperitoneal catheter was attached to a commercial monitor with an electronic display (Codman, Raynham, Massachusetts). The monitor, as well as a digital video camera (Logitech HD 720 P Logitech, Newark, California), were placed on a cart by the horse's head, so the camera was able to continuously record both the readings of the monitor and the horse's behavior.

Baseline mean IAPs were obtained real time every minute over a 30 minute period (pre-cribbing period). After 30 minutes, a wooden board was positioned adjacent to the horse's head, to elicit cribbing behavior in horses of group 1 (Fig.7). In addition, the horses were teased with handfuls of hay to help instigate the behavior. Horses in group 2 were not provided boards, but were teased with hay in a similar manner. Placement of a wooden board in front of the horses not affected by cribbing behavior was not deemed biologically necessary to achieve significant data. All episodes of cribbing, defines as crib-bouts, were recorded and counted, as well as defecations and urinations, for the next 60 minutes, defined as the cribbing period, that was further divided into early cribbing (first 30 minutes) and late cribbing periods (second 30 minutes) for data analysis purposes. At 90 minutes, the wooden boards were removed from group 1 horses and

IAP monitored and recorded for an additional 30 minutes in all horses (post-cribbing period) (Fig.8). The intraperitoneal catheters were then removed and an analgesic cream (Surpass, Boehringer Ingelheim, St. Joseph, Missouri) was applied to the insertion site. The horses were turned loose in their stalls, provided feed and water, and monitored for an additional 48 hours for colic, altered vital parameters, and complications such as swelling, pain and heat at the sites of instrumentation.

d. Statistical Analysis

Intra-abdominal pressure was modeled using repeated measures analysis after evaluating residual plots for normality of data (PROC MIXED, SAS 9.2). Correlated data were accounted for using the following linear model: $Y = X\beta + Z\mu + e$ where Y was the vector of observations (intra-abdominal pressure), X was the treatment design matrix (cribbing and non-cribbing horses; pre-cribbing, early cribbing, late cribbing, and post-cribbing period; 1-30 minute observations), β was the vector of fixed treatment effects, Z was the random effects design matrix (horse), μ was the vector of random block effects, and e was the vector of experimental error. To account for the non-independence of observations within horses, 5 correlation structures were tested (compound symmetry, first order autoregressive, spatial power, unstructured, and variance component) and compound symmetry was used. Models were compared using Akaike's information criterion. "Horse" was included in the model as a random effect. The Kenward-Roger correction was used for all models. The P values of multiple comparisons were adjusted using the Tukey-Kramer method. P values ≤ 0.05 were considered significantly different.

III. RESULTS

During the study, no horse was noted to crib under hourly walk-by observations made during the 24 hours of stall confinement prior to the IAP measurements. Placement of intra-peritoneal catheters was well tolerated by all horses, without the need for sedation. Intra-abdominal pressures in the cribbing cohort ranged between -22 and 19 mmHg; in the non-cribbing cohort, IAP ranged between -25 and 5 mmHg. The cribbing cohort (group 1) had increased mean IAP as compared to the non-cribbing cohort horses (group 2) (see Fig.8 and Table 2). This increase in pressure was not statistically significant during the pre-cribbing period ($P = 0.0764$; non-cribbing = -9.24 ± 6.14 mmHg; cribbing = -1.52 ± 9.48 mmHg), but was significantly increased during the early cribbing period ($P = 0.0184$; non-cribbing = -10.1 ± 5.41 mmHg; cribbing = 0.838 ± 8.96) and the late cribbing period ($P = 0.0003$; non-cribbing = -9.79 ± 4.86 mmHg; cribbing = 5.53 ± 8.20 mmHg), and continued to remain significantly elevated after cribbing was discontinued ($P = 0.0002$; non-cribbing = -8.86 ± 5.83 mmHg; ; cribbing = 5.97 ± 7.15 mmHg). Compared to the cribbing cohort, IAPs of non-cribbing horses were relatively stable and maintained mean negative pressures over the course of the study (Fig.8, Table 2).

When only cribbing horses were evaluated, early cribbing period IAP were significantly increased compared to pre-cribbing period IAP ($P < 0.0001$; early cribbing = 0.838 ± 8.96

mmHg; pre-cribbing = -1.52 ± 9.48 mmHg); late cribbing period IAP (second 30 minutes of the cribbing period) were significantly increased compared to early cribbing period IAP (first 30 minutes of the cribbing period, $P < 0.0001$; late cribbing = 5.53 ± 8.20 mmHg; early cribbing = 0.838 ± 8.96 mmHg); but post-cribbing period IAP were not significantly different from late cribbing period IAP ($P = 0.617$; post-cribbing = 5.97 ± 7.15 mmHg ; late cribbing = 5.53 ± 8.20). The number of cribbing bouts was not associated with increased IAP ($P = 0.347$). During the total cribbing period (early and late cribbing periods combined), time was a significant predictor for increased IAP for the cribbing cohort ($P < 0.0001$), but not for the non-cribbing cohort ($P = 0.9976$).

None of the horses experienced peritoneal catheter insertion site infection. Minor complications included subcutaneous swelling at the peritoneal catheter site in 6 horses that resolved within 48 hours with local anti-inflammatory treatment, and one horse in the cribbing cohort (group 1) had an episode of mild colic 32 hours after the end of the measurements. Findings on physical exam, abdominal palpation per rectum and ultrasonographic exam of the abdomen were within normal limits and the horse recovered uneventfully after administration of 1 gallon mineral oil via nasogastric tube and 500 mg flunixin meglumine intravenously.

IV. DISCUSSION

During the course of this study, IAPs of the cribbing cohort remained relatively stable during the pre-cribbing period, steadily increased and, despite starting out with negative pressures, they obtained positive pressures during the cribbing period, and then leveled and remained elevated during the post-cribbing period. In contrast, IAPs of the non-cribbing cohort remained relatively stable and maintained negative pressures throughout the course of the study. The IAPs were significantly higher in cribbing horses during and after the cribbing episodes, compared to non-cribbing horses. This evidence supports our hypothesis that cribbing behavior is related to increased IAP, in contrast to a previous hypothesis that stated that cribbing behavior would actually decrease IAP (Archer et al. 2004).

It is unclear how cribbing increases IAP. When cribbing, horses can be observed to splint their abdomen, which may decrease abdominal wall compliance. In addition, aerophagia during cribbing may result in gastric and small intestinal distention (Hayes 1968, Houpt 1986, Dodman et al. 1987), although it is not proven that cribbing horses are truly aerophagic (McGreevy et al. 1995a). Both diminished abdominal wall compliance and intestinal distention have been advocated in human (Malbrain 2008) and equine medicine (Barrett et al. 2013a) as causes of alterations of IAP and could explain the positive correlation between cribbing and increased IAP noted in this study.

During the cribbing observation period, it was noted that the IAP increased significantly in the late cribbing period compared to the early cribbing period. This finding suggests that the increase in IAP is directly related to the amount of time the horse spends cribbing. However, the number of cribbing bouts did not seem to have an effect on IAP. Intra-abdominal pressure also remained significantly elevated in cribbing horses for 30 minutes after the cribbing behavior had ceased. This suggests a cumulative effect of cribbing on IAP that remains even after cribbing has ended. Based on this finding, it is possible that horses affected by cribbing behavior have chronically elevated IAP under conditions where they are allowed to crib ad libitum. The result of this could be explained by hypertrophy of the abdominal muscles which may occur in cribbers, or by air collected in the GI tract, although aerophagia in cribbers is questionable. One could argue that, if that was the case, IAP should be significantly different between the groups even during the pre-cribbing period, which is not what this study observed. However, the two groups were trending towards a difference even in the pre-cribbing period, as demonstrated by the $P = 0.0764$, which is close to the set value for significance. Alternatively, it may simply require longer than 30 minutes for pressures to return to normal values after the cribbing behavior has ceased. Further investigations that measure IAP over longer periods of time are needed to support or refute these hypotheses in horses allowed to crib ad libitum.

The pre-cribbing pressures were close to significantly different between the two cohorts ($P = 0.0764$): this finding may be explained by the possibility that those horses may have cribbed during the 24 hours prior to the instrumentation, although they were never observed to do so. Alternatively, the pressures in cribbing horses may take more than 24 hours to return to normal value even when the cribbing behavior has ceased.

In human medicine, a similar condition of intestinal strangulation called herniation through the foramen of Winslow has been occasionally reported, constituting about 8% of all internal hernias in people (Forbes and Stephen 2006). In general, the occurrence of internal abdominal herniations is relatively rare in people, with reports of 0.5% to 4.1% of cases of small bowel obstruction (Takeyama et al. 2005). Hernias through the foramen of Winslow most commonly involve the small bowel (60%–70% of all cases), but they also can contain the terminal ileum, cecum, and ascending colon (25%–30%). Rarely, hernias involving the transverse colon, the greater omentum, and the gallbladder have also been reported (Martin et al. 2006, Takeyama et al. 2005, Bruot et al. 2007, Inoue et al. 1996). Multiple anatomical and physiological abnormalities have been considered as predisposing factors (Forbes and Stephen 2006, Takeyama et al. 2005, Blachar and Federle 2002, Saida et al. 2000, Azar et al. 2010) including changes in IAP (Forbes and Stephen 2006) resulting from parturition, straining, or sneezing (Ghahremani 2009, Meyers 1994, Erskine 1967, Forbes and Stephen 2006, Martin et al. 2006). Published studies in veterinary medicine have inferred a similar pathogenesis for epiploic foramen entrapment in the horse (Archer et al. 2004), but up until now the relationship between IAP and cribbing in the horse was never established.

V. CONCLUSION

The present study, although novel, has two major pitfalls. The first is that IAP measurements were obtained on horses for 2 hours after a 24 hour starvation period. This was deemed necessary in order to have data as uniform as possible, by minimizing the possible effect of the weight of gastrointestinal contents on our measurements. However, this artificial situation may not reflect what happens in horses that are provided 24 hours access to hay or pasture, and in situations that would allow for normal cribbing behaviors in horses that crib. In a situation where cribbing is allowed free choice, it is possible that pressures may have been even higher, due to the residual effect of cribbing on IAP noted in this study. Further investigations in horses in a natural environment would be required for evaluation.

The second limitation of our study is that it provides evidence for only an association between cribbing behavior and increased IAP. This is a step forward in understanding the connection between cribbing and epiploic foramen entrapment, but does not establish a cause-to-effect relationship between cribbing and epiploic foramen entrapment through a change in IAP. A prospective, longitudinal study including a larger population of cribbing horses, evaluating IAP and observing the incidence of epiploic foramen entrapment in that same population would

be necessary to establish an association between these three factors (cribbing, pressures and epiploic foramen entrapment).

IAP and IAH is a rapidly developing field of research in equine critical care. Further research is needed to investigate the role played by IAH in the equine acute abdomen and to elucidate its potential involvement in postoperative complications. Finally, techniques to manage and decrease IAP in this species must be investigated. The clinical application of measuring methods and of management strategies will be the challenge for the next generation of investigators in equine critical care.

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Appendix: Figures and Tables

Fig. 1. Cheatham and Safcsak's revision of Kron's original technique (Cheatham and Safcsak 1998). A standard intravenous infusion set is connected to 1,000 ml of normal saline, two stopcocks, a 60-ml Luer-lock syringe and a disposable pressure transducer. An 18-gauge plastic intravenous infusion catheter is inserted into the culture aspiration port of the Foley catheter and the needle is removed. The infusion catheter is attached to the pressure tubing and the system flushed with saline.

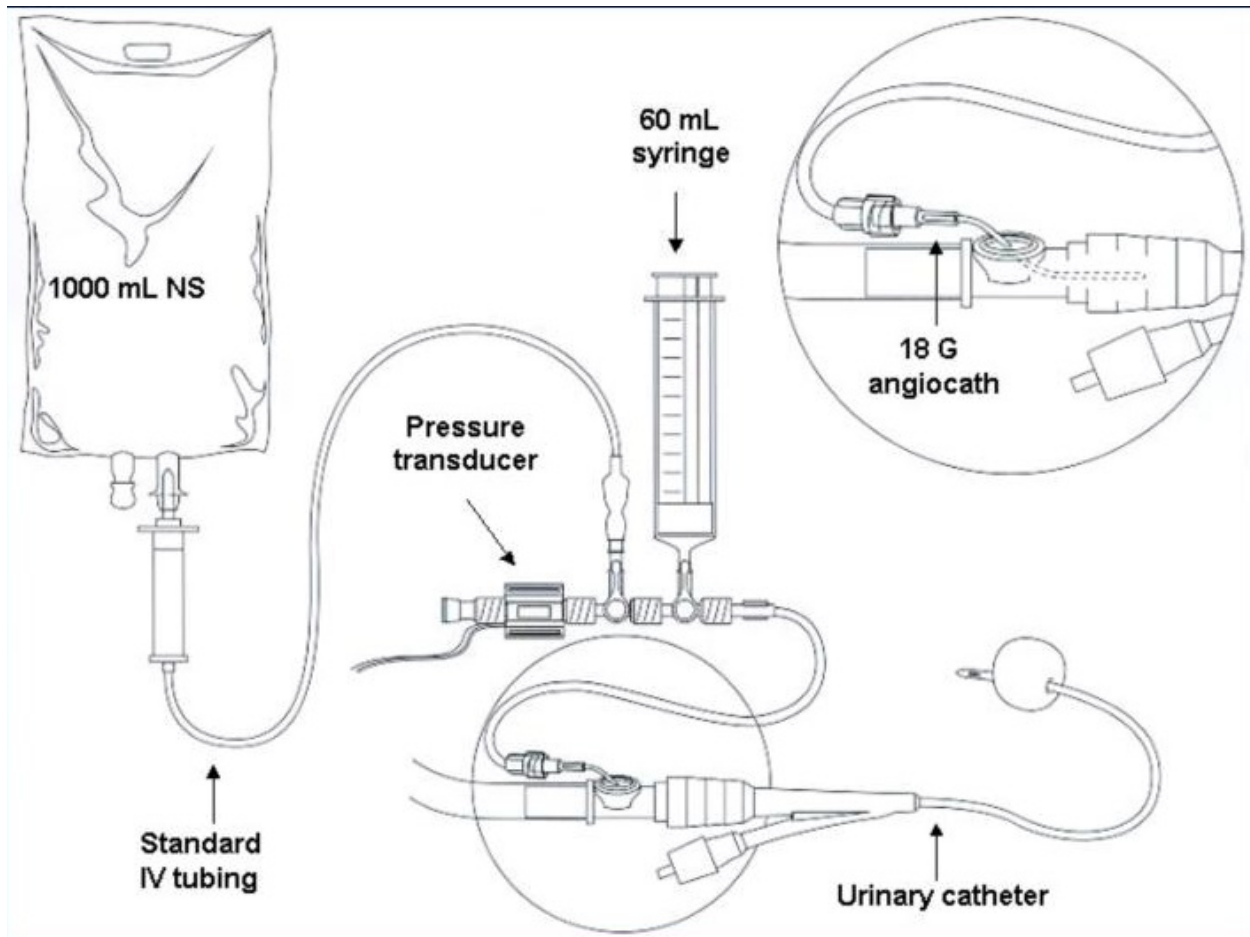


Fig.2. System described by Desie et al. (2002). A ramp with three stopcocks is inserted in the drainage tubing connected to a Foley catheter. A standard infusion set is connected to a bag of 1,000 ml of normal saline and attached to the first stopcock. A 60-ml syringe is connected to the second stopcock and the third stopcock is connected to a pressure transducer via rigid pressure tubing. The system is flushed with normal saline and the pressure transducer is zeroed at the symphysis pubis (or the midaxillary line when the patient is in complete supine position).

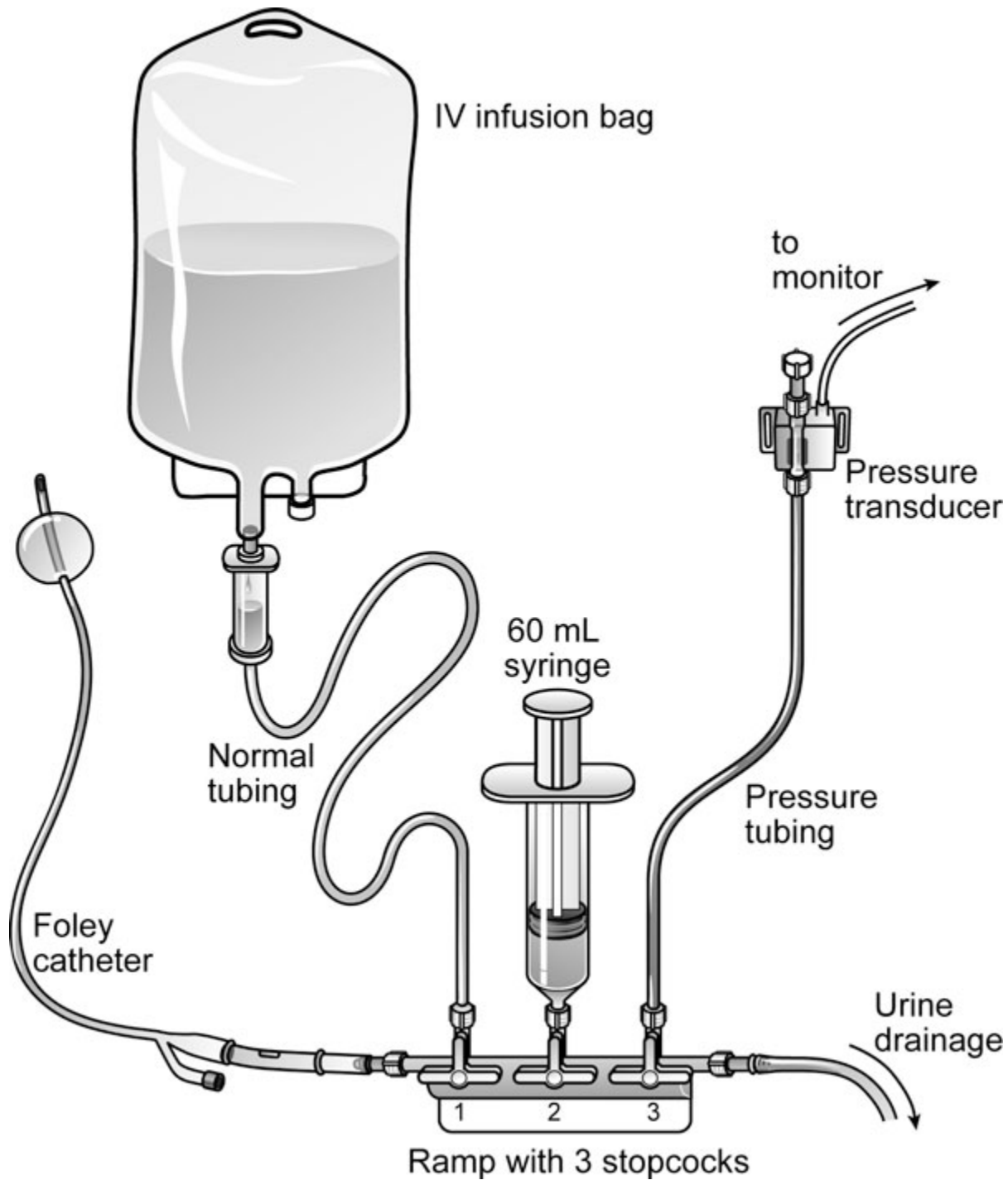


Fig.3. BARD® Intra-abdominal Pressure Monitoring Device (Bard Medical Division, Covington, Georgia)

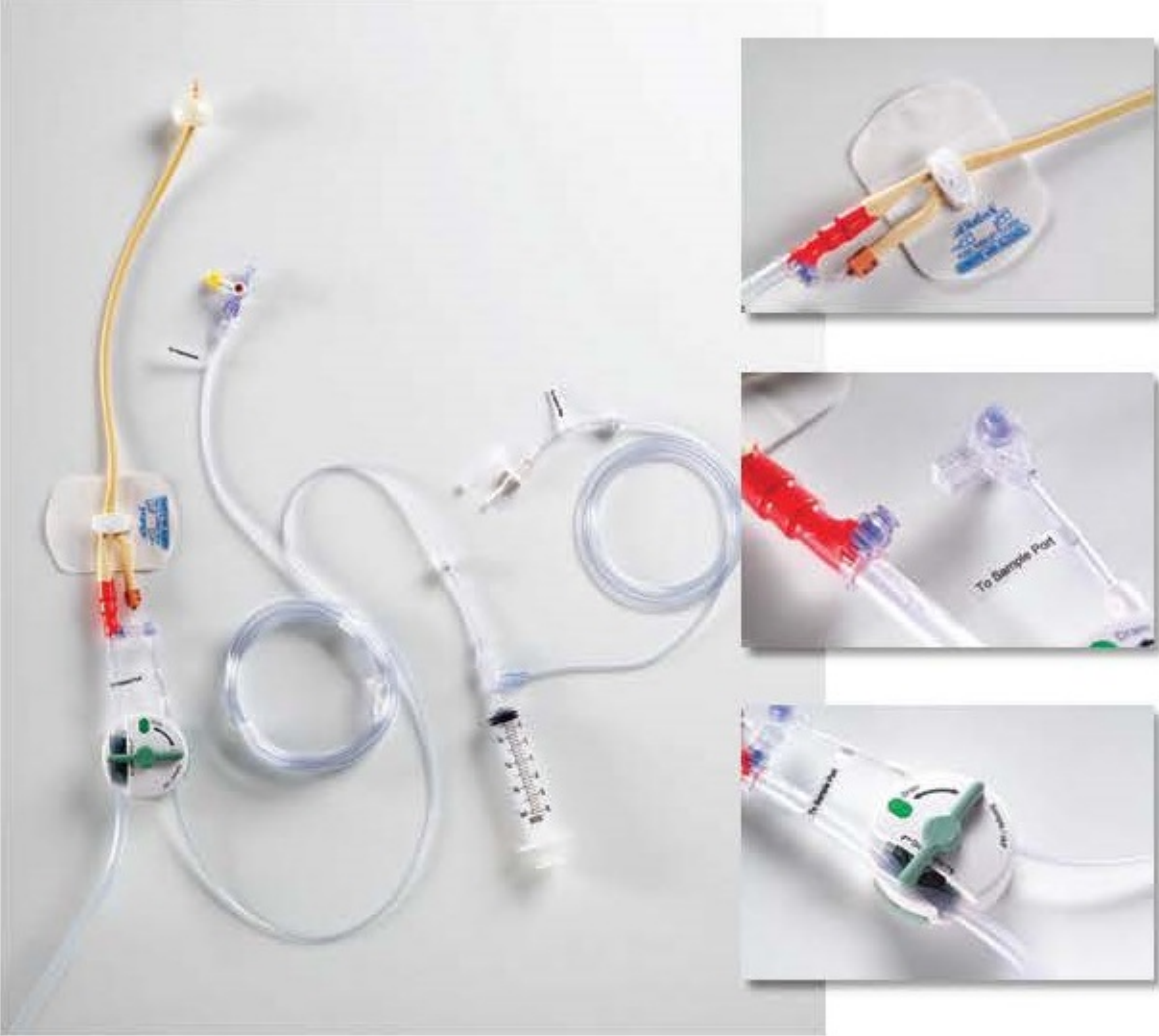


Fig.4. Intran® Plus transducer-tipped catheter for intrauterine pressure measurement in humans (Utah Medical Products, Midvale, Utah).



Fig.5. Piezoelectric sensor catheter for ICP pressure in human, validated as an IAP measuring tool by Barrett et al. (2013c) (Codman, Raynham, Massachusetts).

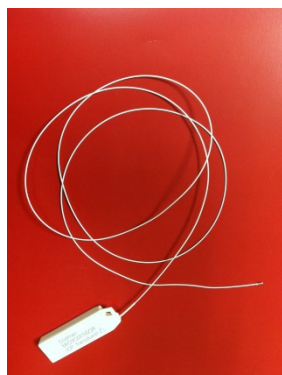


Fig.6. Open-ended metal cecal cannula.



Fig.7. Horse cribbing on the wooden board placed in front of it. Note the monitor recording IAP in real time.



Fig. 8. Mean intra-abdominal pressures (IAP) in cribbing horses (orange) compared to non-cribbing horses (blue) during the 2 hour study. X axis: minutes, Y axis: IAP (mmHg)

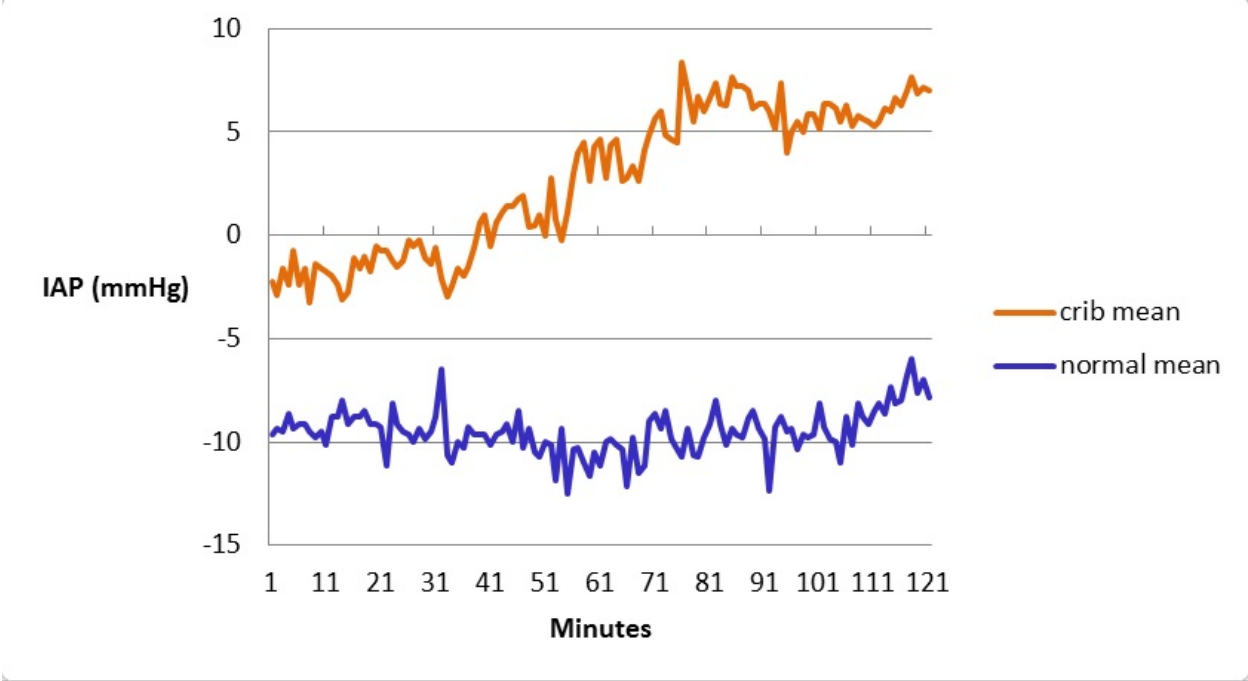


Table 1. Risk factors for the development of IAH and ACS.

<p>A- Related to diminished abdominal wall compliance</p> <ul style="list-style-type: none"> • Mechanical ventilation, especially fighting with the ventilator and the use of accessory muscles • Use of positive end-expiratory pressure (PEEP) or the presence of auto-PEEP • Basal pleuropneumonia • High body mass index • Pneumoperitoneum • Abdominal surgery, especially with tight abdominal closures • Abdominal bandages • Prone position • Abdominal wall hematomas • Correction of large hernias, gastroschisis or omphalocele • Burns with abdominal eschars
<p>B- Related to increased intra-abdominal contents</p> <ul style="list-style-type: none"> • Gastroparesis, gastric distention • Ileus • Volvulus • Colonic pseudo-obstruction • Abdominal tumor • Retroperitoneal/abdominal wall hematoma • Enteral feeding
<p>C- Related to abdominal collections of fluid, air or blood</p> <ul style="list-style-type: none"> • Liver dysfunction with ascites • Abdominal infection (pancreatitis, peritonitis, abscess etc.) • Hemoperitoneum • Pneumoperitoneum • Laparoscopy with excessive inflation pressures • Major trauma • Peritoneal dialysis
<p>D- Related to capillary leakage and fluid resuscitation</p> <ul style="list-style-type: none"> • Acidosis (pH < 7.2) • Hypothermia (core temperature < 33C) • Coagulopathy • Polytransfusion (> 10 units of packed red cells in 24 hours) • Sepsis, septicemia, septic shock • Massive fluid resuscitation • Major burns

(modified from Malbrain et al. 2008)

Table 2. Means \pm SDs for cribbing and non-cribbing horses by period; pre-cribbing period, 30 minute period before cribbing initiated; early cribbing period, initial 30 minute period of cribbing; late cribbing period, 2nd 30 minute period of cribbing; post-cribbing period, 30 minute period after cribbing was discontinued. All values are in mmHg.

		Period			
		Pre-cribbing	Early cribbing*	Late cribbing*	Post-cribbing*
Cohort	Cribbing horses	-1.52 \pm 9.48	0.838 \pm 8.96	5.53 \pm 8.20	5.97 \pm 7.15
	Non-cribbing horses	-9.24 \pm 6.14	-10.1 \pm 5.41	-9.79 \pm 4.86	-8.86 \pm 5.83

Periods marked with * indicate that cohorts were significantly different at $P < 0.05$ for that particular period.