INTRODUCTION
Determining intravascular blood volume in the critical ill patient can be extremely challenging. Appropriate early resuscitative fluid therapy improves survival but must be balanced against excessive fluid therapy and fluid overload. Fluid overload in critically ill human patients is associated with longer hospitalization, increased mechanical ventilation, acute kidney injury, abdominal compartment syndrome, organ dysfunction and increased mortality. Historically, aggressive fluid boluses and fluid challenges have been an integral part of early resuscitation in many patients with hypovolemia, hemorrhage, sepsis and other forms of shock. However, there is recent evidence in the human profession that critically ill ICU patients may benefit from avoidance of excessive fluid administration during resuscitation, and may benefit from removal of excess fluids once shock has resolved. A universal fluid protocol unfortunately does not exist, therefore patients must be assessed individually. The patient’s fluid needs should be determined based upon the underlying disease, pulmonary function, extent of lung injury/edema, intravascular volume status and cardiac function. Not knowing the volume status of critically ill dogs and cats makes administration of fluid therapy in the resuscitation phases of shock challenging.

Further complicating the issue is the fact numerous human studies have demonstrated that up to 50% of hemodynamically unstable children and adults in the ICU will not respond to a fluid challenge. This is probably true in veterinary patients as well. Therefore, although knowing a patient’s intravascular volume status is important, it does not necessarily predict which hemodynamically unstable patients will respond to fluid challenges and which subcategory of patients within a hypovolemic group are likely to respond to fluid challenges would allow fluid therapy to be tailored to individual patient needs. Patients unresponsive to fluid boluses (the flat portion of the Frank-Starling curve) are more likely to benefit from vasopressors and positive inotropes, while patients on the steep aspect of the Frank-Starling curve are likely to benefit from continued fluid boluses. This has led to investigators trying to identify “dynamic” indexes to assess fluid responses, as opposed to traditional “static” indexes that have historically assess pre-load to help guide fluid therapy.

PHYSICAL EXAM AND STATIC VARIABLES
Although practical and important in the assessment of any critically ill patient, human and veterinary studies have shown the assessment of hemodynamic status based on physical examination and routine non-invasive monitoring is not sensitive and is too nonspecific to predict intravascular volume status. Central venous pressure (CVP) and pulmonary artery occlusion pressure (PAOP) have traditionally been used to help guide fluid therapy in both human and veterinary patients, but recent studies have questioned the value of CVP and PAOP in predicting fluid responsiveness. These parameters are referred to as static indexes of cardiac preload, and mounting evidence suggests static indexes have limited value in guiding fluid resuscitation. Despite this, recent surveys suggest up to 90% of human clinicians continue to use static indexes to help guide decision regarding fluid therapy, including CVP. A recent review of the use of CVP in veterinary medicine (Hutchinson and Shaw 2016) details the potential value and controversies of CVP in cats and dogs: The authors conclude that “CVP monitoring of critically ill canine and feline patients should not have a primary role in patient monitoring until such time that additional studies supporting its use are performed”. Thoracic radiographs have also been used in...
veterinary and human medicine to compliment history and physical examination findings to estimate blood volume. Unfortunately, both the physical examination and chest radiography have limited value in the determination of a patient’s volume status.

Although multiple techniques are available to measure and estimate cardiac output, both invasively and non-invasively, the procedures tend to be somewhat time consuming and are not readily available in most veterinary clinical settings. Readers are referred elsewhere for a review of cardiac output measurement and its application in veterinary critical care (Marshal et al 2016).

**DYNAMIC VARIABLES**

Dynamic indexes (respiratory variations in systolic pressure, pulse pressure, and stroke volume in patients receiving positive pressure ventilation (PPV) being the most commonly studied) have been used to predict volume status and responsiveness to fluid therapy in children, adults and more recently, dogs. Dynamic variables tend to reflect variation in preload induced by PPV. During PPV there is a decrease in venous return and pulmonary artery blood flow during inspiration (vena cava blood flow is impeded during the inspiratory phase of PPV). Within 2-3 heart beats (pulmonary transit time) the decrease in venous return is apparent at the level of the left heart, which results in a decrease in left ventricular end diastolic volume and consequently stroke arterial blood pressure (particularly systolic) and plethysmographic waveform amplitude. The magnitude of the variation at all levels is greater in hypovolemic patients receiving PPV as these patients are functioning on the steep portion of the Frank-Starling curve of the heart. Dynamic variables can be quantified as a percentage difference between the maximal and minimal measured value of a single PPV breath. For example, the systolic pressure variation can be calculated as: \[ \text{SPV (\%)} = \frac{(\text{SAPmax} - \text{SAPmin})}{[(\text{SAPmax} + \text{SAPmin}) / 2]} \times 100. \] Other dynamic variables can be calculated with similar equations. In human patients, a pulse pressure variation < 12 - 13% indicates patients that are unlikely to respond to a fluid challenge as there is minimal effect of ventilation on venous return. In contrast, patients with a pulse pressure variation > 13% may be relatively hypovolemic and respond to a fluid bolus by increasing stroke volume. Several studies in dogs have demonstrated the value of dynamic variables in assessing responsiveness to blood loss and fluid therapy. A recent study in dogs demonstrated that pulse pressure variation can predict fluid responsiveness in isoflurane-anesthetized dogs, and that it can be used to guide fluid therapy with a cut-off value of 15% distinguishing responders from nonresponders, when mechanically ventilated with a tidal volume of 10 mL/kg and 3 cmH2O PEEP.

Unfortunately, dynamic variables are somewhat limiting in the fact they rely on patients receiving PPV and require an arterial catheter in most cases. Furthermore, although dynamic variable show promise in adult humans and dogs, a recent systematic review found these variables were not predictive of fluid responsiveness or volume status in children. Further studies are needed to further evaluate these indexes in critically ill veterinary patients.

**SONOGRAPHIC PARAMETERS**

The inferior vena cava (IVC) has also been investigated as a non-invasive means of predicting blood volume in humans. The venous capacitance system contains two thirds of the intravascular volume, with the caudal vena cava (CVC) being the largest capacitance vessel in animals. The thin wall and elastic nature of the CVC makes it a responsive and dynamic blood vessel. Similar to other dynamic variables that fluctuate with changes in the respiratory cycle, the high compliance of the caval wall allows its size and geometry to fluctuate in response to relative and absolute intravascular volume changes depending on both the respiratory and cardiac cycle. Spontaneous and PPV respirations results in a change in positive and negative pressures within the thorax. These pressure changes influence the vascular volume within the thorax and abdomen. With spontaneous respirations, negative pressure draws blood into the thoracic CVC from the abdominal CVC, causing the CVC to decrease in size within the abdomen while the positive pressure of expiration pushes blood from the thoracic CVC into the abdominal CVC.

Assessment of the IVC and IVC:aorta ratio has been criticized in human literature as being a static index, which implies similar limitations to the role of CVP in assessing volume status and fluid responsiveness. A dynamic measurement of the IVC has subsequently been investigated in human medicine and has shown promise predicting both volume status as well as responsiveness to fluid therapy. Initial dynamic indexes of the IVC were performed in patients undergoing PPV, but more recent studies have demonstrated the IVC index can be performed in critically ill spontaneously breathing human patients. The IVC collapsibility...
index (IVC-CI) is a dynamic index involves calculating the percentage change in the diameter of the vena cava during the respiratory cycle. For example, in spontaneously breathing patients the IVC-CI = end-expiratory diameter (max IVC diameter) – end-inspiratory diameter (min IVC diameter) / end-expiratory diameter. The measurement is based on the impedance of vena cava blood flow during the respiratory cycle. The interpretation is different between PPV ventilated patients and spontaneously breathing patients because of the impact of intrathoracic pressures on the impedance of blood flow in the vena cava. With PPV, the extra-thoracic vena cava diameter increases during inspiration, while the extra thoracic vena cava decreases in diameter during inspiration in spontaneously breathing patients. The CVC-CI values found in humans vary by study, but the (mean 26% mean values for IVC-CI reported in healthy, adult human studies are 47.3% +/-8.9%. Changes less than 20% are associated with hypervolemia while change greater than 60% are associated with hypovolemia.

There are also limited studies in dogs assessing echocardiographic changes in the heart in relation to blood volume status. In hypovolemic dogs “pseudohypertrophy” of the heart is noted, which correct following adequate resuscitation. Although worth noting, echocardiographic assessment of the hypovolemic heart has not been used in the veterinary clinical setting.

Finally, it is important to assess patients for conditions that will influence treatment decisions regarding fluid therapy. In this regard, the concept of “wet” vs. “dry” using lung ultrasound is helpful. Knowing if fluid is present in the lungs along with volume estimation/cardiac function provides a more global estimate of patient fluid status and response when determining a patient’s individual fluid needs. The “wet” vs “dry” lung is based on detecting the presence of absence of B lines (also called lung rockets), which are vertical white lines extending form the pleural line distally through the far field of the ultrasound image which move to and fro with respirations. The presence of one to three B line is considered normal in dogs and cats, however, the presence of multiple to coalescing B lines at a single site, particularly if they are present at more than one site over the thorax, is suggestive of interstitial alveolar syndrome. For example, the presence of numerous easily detectable B lines following trauma suggests pulmonary contusions while the presence of multiple B lines in a dog with cough and a heart murmur is more suggestive of cardiogenic pulmonary edema, particularly if evaluation of the heart supports cardiac disease. By recording the number and location of B lines within lung fields it is possible to gain a greater understanding of the degree of fluid in the lungs, which can be used to help guide fluid therapy decisions.

REFERENCES


