Dynamic behavior of venous collapsibility and central venous pressure during standardized crystalloid bolus: A prospective, observational, pilot study

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ABSTRACT

Introduction: Measurement of intravascular volume status is an ongoing challenge for physicians in the surgical intensive care unit (SICU). Most surrogates for volume status, including central venous pressure (CVP) and pulmonary artery wedge pressure, require invasive lines associated with a number of potential complications. Sonographic assessment of the collapsibility of the inferior vena cava (IVC) has been described as a noninvasive method for determining volume status. The purpose of this study was to analyze the dynamic response in IVC collapsibility index (IVC-CI) to changes in CVP in SICU patients receiving fluid boluses for volume resuscitation.

Materials and Methods: A prospective pilot study was conducted on a sample of SICU patients who met clinical indications for intravenous (IV) fluid bolus and who had preexisting central venous access. Boluses were standardized to crystalloid administration of either 500 mL over 30 min or 1,000 mL over 60 min, as clinically indicated. Concurrent measurements of venous CI (VCI) and CVP were conducted right before initiation of IV bolus (i.e. time 0) and then at 30 and 60 min (as applicable) after bolus initiation. Patient demographics, ventilatory parameters, and vital sign assessments were recorded, with descriptive outcomes reported due to the limited sample size.

Results: Twenty patients received a total of 24 IV fluid boluses. There were five recorded 500 mL boluses given over 30 min and 19 recorded 1,000 mL boluses given over 60 min. Mean (median) CVP measured at 0, 30, and 60 minutes post-bolus were 6.04 ± 3.32 (6.5), 9.00 ± 3.41 (8.0), and 11.1 ± 3.91 (12.0) mmHg, respectively. Mean (median) IVC-CI values at 0, 30, and 60 min were 44.4 ± 25.2 (36.5), 26.5 ± 22.8 (15.6), and 25.2 ± 21.2 (14.8), respectively.

Conclusions: Observable changes in both VCI and CVP are apparent during an infusion of a standardized fluid bolus. Dynamic changes in VCI as a measurement of responsiveness to fluid bolus are inversely related to changes seen in CVP. Moreover, an IV bolus tends to produce an early response in VCI, while the CVP response is more gradual. Given the noninvasive nature of the measurement technique, VCI shows promise as a method of dynamically measuring patient response to fluid resuscitation. Further studies with larger sample sizes are warranted.

Key Words: Central venous pressure, inferior vena cava collapsibility index, intravascular volume status assessment, intravenous fluid bolus, Point-of-care ultrasound
INTRODUCTION

Hemodynamic evaluation of the critically-ill patient continues to pose a significant challenge, with lack of a reliable and reproducible “gold standard” for intravascular volume assessment.[1,11] Moreover, traditionally employed invasive modalities are associated with significant potential complications.[2,3] Consequently, there is increasing interest in investigating venous collapsibility index (VCI) as a noninvasive, easily repeatable, and portable alternative to traditional invasive hemodynamic monitoring approaches.[4,5]

Although our knowledge of the characteristics of VCI in relation to CVP and other parameters affecting the dynamic behavior of the circulatory system is growing,[4-6] limited information exists regarding dynamic changes in VCI during intravenous (IV) fluid bolus administration. Most of the information available comes from studies involving observations of either venous collapsibility or vein diameters in patients with renal failure undergoing dialysis,[6,7] pediatric surgery, tricuspid regurgitation, heart failure,[8,9] and experimental anesthesia models.[10]

The objective of this study is to describe the simultaneous behavior of VCI and CVP during standardized IV bolus infusion in the surgical intensive care unit (SICU).

MATERIALS AND METHODS

After Institutional Review Board approval (The Ohio State University Protocol Number 2010H0247), a prospective, observational study was conducted on a convenience sample of consenting SICU patients who met clinical indications for IV fluid bolus and who had preexisting central venous access. Included in the study were patients between the ages of 18 and 89. Excluded were prisoners and patients <18 or ≥90 years of age. Two primary end-points were observed: (a) The behavior of the central venous pressure (CVP) during active IV bolus infusion; and (b) the simultaneous behavior of the VCI. Venous collapsibility was defined as the difference between the maximum and the minimum venous diameter [Figure 1] recorded on M-mode during the respiratory cycle.[4,11]

IV fluid boluses were standardized to crystalloid administration of either 500 mL over 30 minutes or 1,000 mL over 60 min. Concurrent measurements of VCI (taken at the inferior vena cava (IVC)[5] as previously outlined by our group) and CVP were conducted immediately prior to initiation of IV bolus (i.e. time 0) and then at 30 and 60 min (as applicable) after the bolus was started.

Data analysis

Patient demographics (age and gender), head-of-bed elevation (degrees), ventilatory parameters (presence of mechanical ventilation and positive-end expiratory pressure (PEEP)) and systolic blood pressure assessments were recorded. Due to the purely observational nature of this pilot study with use of convenience sampling, only descriptive outcomes are reported, including mean and median CVP/VCI values. In addition, data for the initial 30 min for the two groups were combined. Graphs were prepared using Microsoft Excel™ (Microsoft Corporation, Redmond, Washington, USA).

RESULTS

Twenty patients received a total of 24 IV fluid boluses. There were 12 men and eight women. Mean age was 58.4 ± 19.0 years (median 67.5, range 20–81). Mean Acute Physiology and Chronic Health Evaluation II (APACHE II) score for the study group was 13.0 ± 4.94 (median 12, range 5–21). Mean Simplified Acute Physiology Score (SAPS II) was 35.1 ± 12.4 (median 38, range 16–54). Ventilatory support was present during 17/24 (70.8%) bolus episodes, with median PEEP of 6.5 cmH₂O. Median head-of-bed elevation during standardized bolus administration was 25 degrees.

Overall, we recorded five episodes of a standardized 500 mL bolus given over 30 min and 19 episodes of a standardized 1,000 mL bolus given over 60 min. When comparing the dynamic response in both VCI and CVP, there was no observable difference between the 500 and the 1,000 mL bolus groups for either of the parameters. For CVP, the initial mean ± standard deviation values for the 500 and 1,000 mL groups were 6.00 ± 2.00 versus 6.05 ± 3.63, respectively. For the 30-min values, the CVP was 9.00 ± 2.55 versus 9.00 ± 3.67, respectively. For VCI, the initial values for the 500 and the 1000 mL groups were 39.9 ± 14.8 versus 45.5 ± 27.5, respectively. For the 30-min values, the VCI was 17.6 ± 12.3 versus 28.8 ± 24.6, respectively. For greater ease of presentation, both groups were combined for the composite analysis discussed below.
Venous collapsibility evaluation
Mean (median) VCI values at 0, 30, and 60 min were 44.4 ± 25.2 (36.5), 26.5 ± 22.8 (15.6), and 25.2 ± 21.2 (14.8), respectively. Graphical representation of the observed trend is depicted in Figure 2a.

CVP
Mean (median) CVP measured at 0, 30, and 60 min were 6.04 ± 3.32 (6.5), 9.00 ± 3.41 (8.0), and 11.1 ± 3.91 (12.0) mmHg, respectively. Graphical representation of the observed trend is depicted in Figure 2b.

Systolic blood pressure
For systolic blood pressure during IV bolus infusion, there is a nominal upward trend in the behavior or composite systolic pressure curve. Composite systolic blood pressure values for 0, 30, and 60 min were 114 ± 17.4, 120 ± 25.9, and 122 ± 27.7, respectively, as depicted in Figure 3.

DISCUSSION

Accurate estimation of intravascular volume status is an essential part of management of the critically ill. Invasive procedures may lead to a variety of complications and the VCI is being increasingly recognized as a potential noninvasive replacement or a source of adjunct information.[12,13] Nonetheless, there have been questions raised about its effectiveness. Initial evaluations of caval diameter for estimating fluid status were promising, but the static measurements obtained suffered from a number of shortcomings.[14,15] This led to the evolution of functional hemodynamic monitoring, including calculation of the VCI, which improved predictive accuracy of sonographic volume status assessment techniques by incorporating the fractional change in central venous diameters through the respiratory cycle in addition to simple measurement of maximal or minimal IVC diameter.[4,11,14‑18] Resnick et al., studied the use of venous collapsibility looking for early ultrasound evidence of blood loss in healthy volunteers donating blood.[19] They noted that their clinical findings were confounded by frequent measurement errors, as well as difficulty acquiring sonographic data in patients with small IVC diameters and high body mass indices.[19] However, their conclusions in healthy donors are at odds with Pasquero et al., who also studied healthy blood donors who were depleted of 400–450 mL of blood volume.[12] In the latter study, the mid-hepatic long-axis view correlated well with intravascular volume changes, with the VCI being able to detect early volume responses in regard to blood loss and volume repletion after donation.[12] Sonographic changes in the IVC also occur in patients with acute decompensated heart failure undergoing diuresis.[20] Venous collapsibility changes have also been shown to correlate with IV fluid resuscitation of intraoperative surgical patients and hypotensive emergency department patients.[21,22]

This pilot study provides important new information regarding the behavior of VCI during standardized IV fluid bolus, especially in the context of simultaneous CVP measurements. Our data further support the hypothesis that there is a dynamic relationship between fluid status administration and VCI behavior, as well as an approximate inverse relationship between VCI and CVP during fluid infusion. This is consistent with prior reports by Ferrada et al., who published studies demonstrating changes in VCI before and after IV fluid bolus and a positive correlation of IVC sonographic exam findings to clinical outcome in SICU and trauma patients.[23,24] It is important to note that the simultaneous responses of VCI and CVP, although characterized by the previously shown inverse relationship,[4,25] exhibit important differences. Namely, changes in venous collapsibility were characterized by a significant response during the first 30 min of infusion, with a less noticeable change during the subsequent 30 min. On the other hand, the composite response in CVP was more gradual and sustained throughout the entire 60-min interval. The gradual increase in CVP versus the more abrupt diameter changes observed in the vena cava were previously
described in an animal model by Lautt and Greenway in 1976. Their work demonstrated that the liver is an important buffer for changes in blood volume that occur over a short period of time. The more volume infused, the more important the liver becomes as a “volume buffer”. They also indicated that as the overall venous pressure rises above the level of 6 mmHg, the capacitance vessels of the liver demonstrate the ability to accommodate and store “additional amounts” of volume. In other words, the hepatic vascular system has the capacity to sequester greater amounts of volume as a compensatory mechanism.

Limitations of this pilot study include its small sample size, inability to make inferential comparisons due to limited statistical power, and lack of data following post-bolus changes in CVP or VCI. Anecdotally, the authors observed that, following the completion of the bolus, both CVP and VCI appeared to partially deflect back toward the pre-bolus baseline. This observation is likely a consequence of a number of factors, including the potential “third-spacing” of the infused IV fluid and ongoing physiologic fluid losses. Additionally, the volume of fluid infused in the study, while consistent with prior published literature on dynamic changes in VCI, was comparatively small to the needs of many critically-ill patients undergoing active resuscitation. Although the APACHE II and SAPS II scores indicated that our patient sample did not exhibit the highest acuity, this should not be perceived as a limitation for an observational pilot study in ICU patients.

While we have documented the various levels of PEEP, basic ventilator settings, and the angle of the head-of-bed elevation, it has to be noted that although changes in the above parameters can influence the CVP, they do not influence hepatic vascular pressure or vena cava behavior as much as one would intuitively anticipate. In fact, increasing PEEP from 5 to 10 cm of H$_2$O will increase CVP, hepatic pressures, and portal pressures by only about 1 mmHg and the effect of supine versus upright patient positioning has minimal effect on IVC metrics.

The lack of standardization of the above parameters in our patients may be initially considered a limitation to the study. However, reports of similar physiologic responses, regardless of the above differences, in fact suggest the opposite and indirectly help corroborate our current findings.

**CONCLUSIONS**

Observable changes in both VCI and CVP are apparent during an infusion of a standardized fluid bolus. Based on our data, the dynamic change in VCI as a measurement of responsiveness to fluid bolus is inversely related to changes seen in CVP. Moreover, an IV bolus tends to produce an early response in VCI, while the CVP response is more gradual. Given the relative simplicity of the measurement technique and its noninvasive nature, quantitative assessment of VCI shows promise as a method of dynamically measuring patient response to fluid resuscitation. Further prospective studies in larger populations are warranted to better evaluate the diagnostic value of VCI in intravascular volume assessment, and to determine which patients stand to benefit the most from this hemodynamic monitoring approach.

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