Accurate assessment of relative intravascular volume is critical to guide volume management of patients with acute or chronic kidney disorders, particularly those with complex comorbidities requiring hospitalization or intensive care. Inferior vena cava (IVC) diameter variability with respiration measured by ultrasound provides a dynamic noninvasive point-of-care estimate of relative intravascular volume. We present details of image acquisition, interpretation, and clinical scenarios to which IVC ultrasound can be applied. The variation in IVC diameter over the respiratory or ventilatory cycle is greater in patients who are volume responsive than those who are not volume responsive. When 2 recent prospective studies of spontaneously breathing patients (n = 214) are added to a prior meta-analysis of 181 patients, for a total of 7 studies of 395 spontaneously breathing patients, IVC collapsibility index (CI) had a pooled sensitivity of 71% and specificity of 81% for predicting volume responsiveness, which is similar to a pooled sensitivity of 75% and specificity of 82% for 9 studies of 284 mechanically ventilated patients. IVC maximum diameter <2.1 cm, that collapses >50% with or without a sniff is inconsistent with intravascular volume overload and suggests normal right atrial pressure (0-5 mmHg). Inferior vena cava collapsibility (IVC CI) > 20% with no sniff suggests increased right atrial pressure and is inconsistent with overt hypovolemia in spontaneously breathing or ventilated patients. These IVC CI cutoffs do not appear to vary greatly depending on whether patients are breathing spontaneously or are mechanically ventilated. Patients with lower IVC CI are more likely to tolerate ultrafiltration with hemodialysis or improve cardiac output with ultrafiltration. Our goal for IVC CI generally ranges from 20% to 50%, respecting potential biases to interpretation and overriding clinical considerations. IVC ultrasound may be limited by factors that affect IVC diameter or collapsibility, clinical interpretation, or optimal visualization, and must be interpreted in the context of the entire clinical situation.

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Keywords: Ultrasonography, Critical care, Ultrafiltration, Hemodialysis, Point-of-care systems

PROCEDURES AND TECHNICAL STEPS

Subcostal View
We begin by visualizing the heart using the subcostal approach in most supine patients, with a phased-array (cardiac) or curvilinear (abdominal) probe. The probe is then rotated vertically, with the orientation marker pointed cranially, and moved 1 to 2 cm to the right of the patient’s midline, while maintaining visualization of the right atrium (RA), to view the inferior vena cava (IVC) in its long axis (Fig 1A). One must fan the probe to intentionally view the aorta to the left of the midline in every patient to be sure it is not mistaken for the IVC, and to visualize the junction of the IVC with the RA (Supplementary Fig 1B, available at: http://doi.org/10.1053/j.ackd.2021.02.003). There are very few instances in which the IVC can be seen but not the aorta, while if only the aorta is visualized, the IVC may be totally collapsed.

The maximum and minimum diameters of the IVC with respiration/ventilation are most accurately measured 3 to 4 cm from the RA or approximately 1 cm distal to the hepatic vein inlet to the IVC (Fig 1A). In a large prospective study, inter-rater reliability was highest using the subcostal window long axis view in B-mode. We find the subcostal window to be particularly useful in patients who are morbidly obese or otherwise have large body habitus because the needed depth may be much greater from the mid-axillary line than from the subcostal view.

Midaxillary (Right Lateral Transabdominal Coronal Long Axis) View
With the patient supine and the orientation marker pointed cranially, the probe is moved laterally to the patient’s right in...
line with the sternal notch to over the lower ribs until your hand touches the bed (knuckles to the bed) (Fig 2A). The probe is then tilted anteriorly at an angle similar to the one used to visualize the kidney. It may be helpful to visualize aiming just anterior to the spine. The IVC crosses the diaphragm just inferior to the heart and traverses the liver. Traversing the abdomen, the aorta runs parallel to the IVC, farther from the probe (Fig 2B).

We find the midaxillary view to be particularly useful in patients with large anterior thoracic or abdominal surgical incisions, when the patient has anterior abdominal pain or distention, and in other instances when using the subcostal window is limited. In such difficult cases, the IVC may be visualized in the right midaxillary line and measured approximately 3 cm caudal to the RA (Fig 2).

**B-Mode vs M-Mode**

Measuring IVC maximum and minimum diameters using M mode has not been shown to be superior to choosing maximum and minimum diameters viewed frame by frame in B-Mode.\(^{15,16}\)

**Calculation of Collapsibility Index vs Distensibility Index**

The physiology of spontaneous breathing is different from that of mechanical ventilation. During spontaneous inspiration, negative intrathoracic pressure increases venous flow to the heart and reduces the IVC diameter.\(^{13}\) At end expiration, the intrathoracic pressure increases to zero, decreasing the venous return and maximizing the IVC diameter.\(^{13}\) This has been defined as collapsibility index (CI).\(^{13}\) \(\text{CI} = \frac{\text{IVC max-IVC min}}{\text{IVC max}}\).

With mechanical ventilation, the cycle is inverted. Positive intrathoracic pressure during inspiration reduces the venous flow to the heart and increases the IVC diameter. At end expiration, the intrathoracic pressure decreases to zero, increasing the venous flow to and minimizing IVC diameter.\(^{13,14}\) This has been defined as distensibility index (DI).\(^{14}\) \(\text{DI} = \frac{\text{IVC max-IVC min}}{\text{IVC min}}\).

Changes in IVC diameter do not appear to vary greatly depending on the mechanism by which intrathoracic pressure is changed.\(^{13}\) The convention to normalize by end-expiratory diameter, using CI for spontaneous breathing and DI for ventilated breathing in some publications, does not readily allow comparison of data between ventilated and spontaneously breathing encounters. CI and DI can be interconverted:\(\text{CI} = \text{DI}/(1 + \text{DI}); \text{DI} = \text{CI}/(1-\text{CI})\).

Some authors normalize by the mean IVC diameter, which we term variability index: \(\text{VI} = \frac{\text{IVC max-IVC min}}{\text{IVC mean}}; \text{CI} = 2 \times \text{VI}/(2 + \text{VI})\).

For consistency and convenience, we calculate CI for all of our patients, both ventilated and nonventilated. As many patients cannot perform voluntary maneuvers such as a sniff, which can accentuate IVC collapse,\(^{6,10}\) for consistency we do not routinely use a sniff. The IVC diameters are measured over several respiratory cycles with spontaneous respiration or mechanical ventilation.\(^{17}\)

**Accuracy of Predicting Volume Responsiveness in Patients Who Are Mechanically Ventilated Compared with Those Who Are Spontaneously Breathing**

A current meta-analysis\(^{18}\) indicates that the reliability of IVC diameter variation with respiration to predict volume responsiveness is greater in mechanically ventilated patients than those with spontaneous breathing. In this comparison, 284 patients in 9 studies with mechanical ventilation had a pooled sensitivity of 75% and specificity of 82%, whereas 181 spontaneously breathing patients reported in 5 studies had a pooled sensitivity of 56% and specificity of 78%. The quality of these studies varied, with heterogeneity with respect to patient population, sample size, definition of index test such as change in cardiac output or stroke volume and in one study, change in blood pressure to define volume responsiveness, and method for determining optimal cutoff values for the IVC index which may favor sensitivity or specificity.\(^{2,18,19}\) IVC CI cutoff values were not determined for equal sensitivity and specificity and varied widely among studies. Low sensitivity with spontaneous breathing was postulated to be due to shallow, nonstandardized breathing. However, if 2 large prospective studies of nonstandardized spontaneously breathing patients (\(n = 214\))\(^{20,21}\) reported since that meta-analysis\(^{18}\) are included, the pooled sensitivity is 71% and pooled specificity is 81%, which is similar to that of mechanically ventilated patients. The sensitivity and specificity of IVC ultrasound to predict volume responsiveness has been shown to be further improved by using deep standardized inspiration (pooled sensitivity 87%, pooled specificity 89%) in 146 spontaneously breathing patients from 2 prospective studies.\(^{20,22}\)

**Patient Positioning**

In contrast to jugular venous distention or measurement of collapsibility of more peripheral veins, which are highly
position dependent, similar values for IVC CI have been obtained with patients in the semisupine position from 0 to 45° head-of-bed elevation. Consequently, for assessment of IVC CI, time-consuming repositioning can often be avoided.

**CLINICAL UTILITY OF CARDIAC AND IVC ULTRASOUND**

Both cardiac and IVC ultrasound may be useful for the daily assessment of relative intravascular volume; need for and response to volume resuscitation or volume removal by diuresis, paracentesis, or ultrafiltration; and management of hyponatremia, hypernatremia, and intradialytic hypotension.

**Assessment of Relative Intravascular Volume**

The major clinical value of IVC ultrasound findings is to potentially eliminate either the possibility of overt relative intravascular hypervolemia or hypovolemia in a given patient. A patient with a small IVC maximum diameter or large IVC CI may be “euvolemic”, but is unlikely to have elevated cardiac filling pressures, and a patient with a large IVC maximum diameter and small IVC CI may be “euvolemic”, but is unlikely to have reduced cardiac filling pressures.

**Differentiate Types of Shock**

The RUSH (Rapid Ultrasound in SHock) protocol, which includes ultrasound assessment of the IVC diameter and its variation with respiration, is routinely used for the immediate assessment and management of shock and hypotension (Table 1). In a prospective study, the overall sensitivity of the RUSH examination for diagnosing the type of shock was 88% and specificity was 96%, compared with the final shock diagnosis. Ultrasound findings influenced management and were useful in guiding volume administration or restriction and vasopressor therapy, which resulted in improved 28-day patient survival, a reduction in stage 3 acute kidney injury (AKI), and more days alive and free of kidney support.

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**Figure 1.** (A) Subcostal IVC window. Subcostal landmarks, position of ultrasound probe for visualization of the inferior vena cava (IVC) (also see Fig 2A). The IVC is located to the right of midline and aorta (AO) as shown in the left panel. The corresponding ultrasound image of the IVC is shown in the right panel. It is recommended that the IVC be measured 3 to 4 cm from the right atrium (RA) or distal to the hepatic vein. The hepatic vein junction to the IVC and the IVC junction to right atrium are confirmatory landmarks. Reprinted with permission from Killu and colleagues. (Supplementary Fig 1B, available at: http://doi.org/10.1053/j.ackd.2021.02.003.):Video of the relationship of the IVC to the aorta viewed from the subcostal view while fanning the probe from left to right.

**Figure 2.** (A) Ultrasound probe positions. Adapted from Perera and colleagues with permission. Parasternal long- and short-axis views (phased-array). Subcostal cardiac view (phased-array or curvilinear probe). IVC long-axis view subcostal (phased-array or curvilinear). IVC long-axis view from mid-axillary line (phased-array or curvilinear). (B) Ultrasound images corresponding to IVC long-axis from midaxillary line. The IVC is to the right of patient’s midline and will be closer to the probe than the aorta.
Differentiate Types of AKI
Patients assessed to have intravascular hypovolemia are at high risk for decreased kidney perfusion, which may cause a rapidly reversible prerenal state vs acute tubular necrosis. Patients with severe intravascular volume overload may also have decreased kidney perfusion, especially with accompanying heart failure (cardiorenal), and may benefit from volume removal. Nonsteroidal anti-inflammatory drugs, calcineurin inhibitors, angiotensin-converting enzyme inhibitors, and angiotensin receptor blockers decrease kidney perfusion and can exacerbate any prerenal state. Patients who do not appear to have severely deranged relative intravascular volume status may be considered “euvolemic.” Such patients may have decreased kidney perfusion (prerenal) from hepatorenal syndrome, which may be reversible or lead to acute tubular necrosis. “Euvolemic” patients may also have primary postrenal (obstruction or retention) or intrarenal causes of AKI (as may patients with severely deranged intravascular volume status).

Assess Patients With Cirrhosis and AKI
IVC ultrasound can be useful to more accurately diagnose the cause of AKI in patients with cirrhosis assumed to have hepatorenal syndrome (HRS), which in turn can improve volume management and potentially improve outcomes. In an observational study of 53 cirrhotic patients with AKI assumed to have HRS-AKI and deemed to be adequately volume repleted, IVCmax and IVC CI were used to estimate relative intravascular volume, followed by volume management.32 Twenty-three percent had a ≥20% decrease in serum creatinine at 48 to 72 h following ultrasound-guided therapeutic volume management,32 making the diagnosis of HRS-AKI highly unlikely.

Guide Volume Management With Diuretics and Dialysis Prescription
Repeated evaluations of IVC CI with volume administration or removal can guide ongoing volume management and optimize therapy,17 which in turn may improve morbidity and mortality.33 IVC CI assessment may be useful to predict or avoid intradialytic hypotension.15,34 The goal for IVC CI is in the range of 20% to 50% respecting that there are many potential biases to interpretation and overriding clinical considerations which include, for example, acute respiratory distress syndrome, desire to extubate that may require volume removal, or preload dependent conditions that may require volume loading (Table 2).

COMPARISON OF TECHNIQUES TO ASSESS RELATIVE INTRAVASCULAR VOLUME AND RESPONSE TO VOLUME ADMINISTRATION OR REMOVAL
The only purpose of a volume challenge is to increase stroke volume or cardiac output by at least 10% to 15%, which has become the “gold standard” for assessing response to volume administration or removal.1,2 Passive leg raising is a reversible surrogate for volume administration with respect to changes in cardiac output to predict volume responsiveness.52,53 Passive leg raising is unsuitable in principle for predicting which patients may benefit from volume removal. Only 50% of hemodynamically unstable critically ill patients respond to volume expansion with a significant increase in stroke volume or cardiac output.1,2,54,55 There is a need for readily available techniques to help differentiate patients who will benefit from volume expansion from those who may benefit from inotropic or vasopressor support but not volume therapy or those who may benefit from volume removal using diuretics or ultrafiltration.57

Comparison of “Dynamic” to “Static” Parameters to Predict Responsiveness to Volume Administration or Removal
In contrast to “static” measures of cardiac preload such as mean values for central venous pressure, right atrial pressure (RAP), or pulmonary artery occlusion pressure, which have low sensitivity and specificity to predict volume responsiveness,54,56,58 IVC CI is a “dynamic” parameter, in that it reflects the interaction between the respiratory and cardiac cycles,18 similar to dynamic respiratory variation of central venous pressure59 or RAP60 as long as no obstruction or restriction of the vena cava is present (Fig 3). One study of dynamic RAP in 33 patients, using threshold of RAP respiratory variation ≥1 mmHg to predict volume responsiveness, had sensitivity of 91% and specificity of 92% to predict an increase of cardiac output >250 mL/min after volume administration.58 These dynamic parameters are technologically refined versions of jugular venous waveform,
in contrast to arterial parameters such as pulse pressure variation or stroke volume variation, which are refined versions of “pulsus paradoxus”. The variations in dynamic parameters are greater in volume responsive than volume nonresponsive patients. Change in cardiac output in response to a volume intervention is used as the \textit{“gold standard”} by which to judge other dynamic and static parameters.\textsuperscript{1,2}

\section*{CLINICAL INTERPRETATION OF IVC ULTRASOUND FINDINGS}

Following is a summary of the 2010 Guidelines for the echocardiographic assessment of the right heart in adults,\textsuperscript{9,26} which is a widely adopted method for interpreting measurement of IVC diameters to estimate relative intravascular volume status.

- IVC diameter <2.1 cm, that collapses >50\% with a sniff suggests normal mean RAP 0 to 5 mm Hg.
- IVC diameter >2.1 cm that collapses <50\% with a sniff suggests elevated mean RAP 10 to 20 mm Hg.
- Intermediate cases may be assigned an intermediate mean RAP 5 to 10 mm Hg.
- If there is minimal IVC collapse with a sniff (<35\%), mean RA pressure may be upgraded to 15 mm Hg.
- In patients who are unable to perform a sniff, IVC that collapses <20\% with quiet inspiration suggest elevated mean RA pressure.

\begin{table}[h]
\centering
\begin{tabular}{|l|c|c|l|}
\hline
\textbf{Table 2. Conditions Biasing Inferior Vena Cava Ultrasound Findings} & \textbf{IVC CI} & \textbf{IVC max} & \textbf{Comments} \\
\hline
\textbf{Underestimate Intravascular Volume}\textsuperscript{35} & & & \\
Increased tidal volume (ventilated) & Increased\textsuperscript{20} & No change? & \\
Increased inspiratory effort moving probe “in & out” of field (diaphragmatic breathing)\textsuperscript{9} & Increased & No change & Mid-axillary views\textsuperscript{36} Cross-sectional view\textsuperscript{8} \\
Increased inspiratory effort/ deep breathing (sniff)\textsuperscript{9,26,37} & Increased\textsuperscript{18,20} & No change & Large IVC max with no collapse indicates not hypovolemic. \\
Valsalva maneuver\textsuperscript{16} & Increased & Decreased & Large IVC max with no collapse indicates not hypovolemic. \\
Intra-abdominal hypertension\textsuperscript{9,26,38} & Decreased? (No data)\textsuperscript{32} & Decreased\textsuperscript{38,40} & Large IVC max with no collapse indicates not hypovolemic. \\
Off-center scan (cylinder tangent effect)\textsuperscript{51} & Minimal changes & Decreased & Attempt to maximize IVC diameter. Cross-sectional view\textsuperscript{9} \\
Hemodialysis (extracorporeal blood, steal from heart) & Increased? & Decreased? & \\
\hline
\textbf{Overestimate Intravascular Volume}\textsuperscript{35} & & & \\
Cardiac tamponade & Decreased & Increased & Preload dependent \textsuperscript{42} Preload dependent \textsuperscript{42} \\
Severe valvular stenosis & Decreased & Increased\textsuperscript{42} & Preload dependent \textsuperscript{42} \\
Massive pulmonary embolism\textsuperscript{9} & Decreased? & Increased & Preload dependent \textsuperscript{42} \\
Right ventricular myocardial infarction\textsuperscript{43} & Decreased & Increased & Decreased venous return to left ventricle \\
Severe tricuspid regurgitation & Decreased\textsuperscript{44,45} & Increased\textsuperscript{45} & Preload dependent \textsuperscript{42} IVC CI varies with relative intravascular volume with severe TR.\textsuperscript{46} \\
High PEEP\textsuperscript{47} & Minimal change\textsuperscript{48,49} & Increased\textsuperscript{48,49} & No difference between PEEP 0 and PEEP 5 cmH\textsubscript{2}O\textsuperscript{47} Different with PEEP 15\textsuperscript{45} \\
Decreased tidal volume & Decreased\textsuperscript{18,20} & No change? & \\
Decreased inspiratory effort/shallow breathing\textsuperscript{9,51} & Decreased\textsuperscript{18,20} & No change? & Highly collapsible IVC indicates not hypervolemic. \\
\hline
\end{tabular}
\end{table}

Abbreviations: CI, collapsibility index; IVC, inferior vena cava; IVCmax, IVC maximum diameter; PEEP, positive end-expiratory pressure; TR, tricuspid regurgitation.

Adapted from Kaptein and Kaptein\textsuperscript{5} with permission.
Hypovolemia vs. Not-hypovolemia
In a review of 4 publications with more than 50 extractable data points (total \( n = 298 \)) of patients who did not sniff, optimal sensitivity (80%) and specificity (79%) for predicting a mean RAP, \( 5 \) mmHg were obtained at a cutoff for IVC CI of \( \approx 47.3\% \) (approximately 50%).\(^{15,62-65} \) This essentially agrees with the 50% cutoff value for IVC CI in the echocardiography guidelines presented by Rudski and colleagues.\(^9,26 \) IVC CI is predictive of volume responsiveness with a pooled sensitivity of 75% and specificity of 82% in mechanically ventilated patients\(^18 \) and a pooled sensitivity of 71% and specificity of 81% in spontaneously breathing patients as described previously.\(^{18,20,21} \)

Hypervolemia vs Not-hypervolemia
We use as default the 2010 echocardiography guideline that states that in patients who are unable to adequately perform a sniff, an IVC that collapses \( \geq 20\% \) with quiet inspiration suggests elevated mean RAP.\(^{9,26} \) Our data, showing that the ability to remove \( \geq 0.5 \) L to \( \leq 2 \) L of ultrafiltrate during dialysis could best be predicted using an IVC collapsibility cutoff of 23% to 18.5% (approximately 20%), are consistent with this.\(^{15} \)

Nephrologists may more frequently need to consider whether patients may benefit from volume removal than volume administration because of baseline population characteristics. For example, in a convenience sample of 658 encounters with 267 ICU patients with nephrology consults, of which a subset who received dialysis was formally analyzed and published,\(^{15} \) we found that 47% of encounters had IVC CI \( \leq 20\% \), 18% had IVC CI > 50%, and 35% had IVC CI 20 to 50%. IVC collapsibility may also predict ability to remove volume by ultrafiltration or to increase cardiac output with net volume removal in patients with intravascular volume overload.\(^{15,34,66,67} \) Especially when at one extreme or the other, IVC ultrasound findings may influence the prediction of whether a patient would benefit from administration of volume, diuretics or ultrafiltration, or neither.

Change in Cardiac Output vs IVC CI and Change in Volume
Volume removal by ultrafiltration has been shown to increase cardiac output in patients with refractory congestive heart failure\(^68-70 \) and in volume overloaded patients with acute or chronic kidney failure.\(^71-73 \)

We reported how changes in cardiac output determined by thermodilution in 22 critically ill patients receiving kidney replacement therapy during 58 encounters related to relative intravascular volume assessed by IVC CI and to changes in net volume.\(^{34} \) In patient encounters with relative intravascular volume overload assessed by IVC CI < 20%, and net volume removal during continuous or intermittent dialysis, despite intradialytic hypotension in all cases, cardiac output increased > 10% in 36% of encounters, decreased \( \geq 10\% \) in 34% of encounters, and remained between \( -10\% \) and +10% in 30% of encounters.

LIMITATIONS OF IVC ULTRASOUND
Limitations to IVC ultrasound can be categorized as factors which affect the IVC diameter/collapsibility or its clinical interpretation\(^5,56 \) and those which limit optimal visualization.\(^74 \) The former can be addressed by a systematic understanding of the direction of potential biases, and interpretation of results in clinical context for a specific patient\(^5 \) (Table 2).

Factors That Affect IVC Diameter or Collapsibility
Overestimation of relative intravascular volume may occur in conditions that impede flow to the right heart, including valvular abnormalities, pulmonary hypertension, heart failure,\(^6 \) or poor respiratory excursions\(^37,51 \) (Table 2). Severe tricuspid regurgitation decreases IVC CI\(^44,45 \) and may increase IVCmax.\(^35 \) Rheumatic valvular
heart disease increases IVCmax. IVC CI may vary with relative intravascular volume with severe TR and still may be useful if IVC CI increases with volume removal. In such circumstances, if the IVC is highly collapsible or totally collapsed, relative intravascular hypovolemia is likely present, and volume resuscitation may be indicated.

Underestimation of intravascular volume may occur with intra-abdominal hypertension; therefore, a distended IVC in this circumstance likely indicates intravascular hypervolemia.

Interpretation of vena cava physiology may be hindered by conditions that restrict the physiologic variability of the IVC such as venous thrombosis, masses causing external compression, or large extracorporeal membrane oxygenation catheters. The central venous anatomy is significantly altered in patients after liver transplant, and there are several possible surgical approaches. This has yet to be systematically investigated. Interpretation of the physiologic characteristics of the IVC should be done in context of the patient’s clinical scenario and adjunctive data.

**Factors That Limit Visualization**

Adequate visualization may be compromised by morbid obesity, abdominal pain or distention, bowel gas, postoperative surgical dressings, an open chest or abdomen, subcutaneous emphysema, or talcum powder on the skin. Overcoming limitation of optimal visualization may be facilitated by expanding the repertoire of alternative ultrasound windows and techniques.

**SUMMARY**

We use ultrasound of the inferior vena cava as an integral part of the evaluation of relative intravascular volume status and to guide volume management. This is particularly crucial in hospitalized patients who are not in steady state and frequently have mismatch between intravascular volume and blood pressure or between intravascular and extravascular volume, which may not otherwise be evident on physical examination.

Recent data indicate that volume responsiveness can be predicted with similar accuracy for spontaneously breathing patients: a post hoc analysis of two prospective cohorts. Ann Intensive Care. 2020;10(1), article 168:1-10.

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