
Intensivist Use of Hand-Carried Ultrasonography to Measure IVC Collapsibility in Estimating Intravascular Volume Status: Correlations with CVP

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- BACKGROUND:** Volume status assessment is an important aspect of patient management in the surgical intensive care unit (SICU). Echocardiologist-performed measurement of IVC collapsibility index (IVC-CI) provides useful information about filling pressures, but is limited by its portability, cost, and availability. Intensivist-performed bedside ultrasonography (INBU) examinations have the potential to overcome these impediments. We used INBU to evaluate hemodynamic status of SICU patients, focusing on correlations between IVC-CI and CVP.
- STUDY DESIGN:** Prospective evaluation of hemodynamic status was conducted on a convenience sample of SICU patients with a brief (3 to 10 minutes) INBU examination. INBU examinations were performed by noncardiologists after 3 hours of didactics in interpreting and acquiring two-dimensional and M-mode images, and ≥ 25 proctored examinations. IVC-CI measurements were compared with invasive CVP values.
- RESULTS:** Of 124 enrolled patients, 101 had CVP catheters (55 men, mean age 58.3 years, 44.6% intubated). Of these, 18 patients had uninterpretable INBU examinations, leaving 83 patients with both CVP monitoring devices and INBU IVC evaluations. Patients in three IVC-CI ranges (<0.20 , 0.20 to 0.60 , and >0.60) demonstrated significant decrease in mean CVP as IVC-CI increased ($p = 0.023$). Although $<5\%$ of patients with IVC-CI <0.20 had CVP <7 mmHg, $>40\%$ of this group had a CVP >12 mmHg. Conversely, $>60\%$ of patients with IVC-CI >0.6 had CVP <7 mmHg.
- CONCLUSIONS:** Measurements of IVC-CI by INBU can provide a useful guide to noninvasive volume status assessment in SICU patients. IVC-CI appears to correlate best with CVP in the setting of low (<0.20) and high (>0.60) collapsibility ranges. Additional studies are needed to confirm and expand on findings of this study. (J Am Coll Surg 2009;209:55–61. © 2009 by the American College of Surgeons)
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Intravascular volume status assessment is an essential component in care of the critically ill. Clinical examination has been shown to be unreliable in the evaluation of intravascular volume, leading to the need for more objective means of assessment.^{1–3} Ultrasonographic evaluation of the IVC for volume assessment has been previously reported by

nephrologists and echocardiologists.^{4–12} Until recently, ultrasonography evaluation of the IVC in critical care settings depended on technicians to obtain the images and echocardiologists to interpret them. Temporal and logistical obstacles involved in this arrangement constitute serious disadvantages in managing critically ill and unstable patients.

Recent technological advances have made ultrasonography equipment increasingly compact, mobile, easy to use, and inexpensive.^{13–22} Clinician-performed bedside ultrasonography examinations are available around-the-clock and can be rapidly deployed for initial assessment and to guide subsequent therapy.^{13–15,18–20,22} The purpose of this study was to analyze intensivist-performed bedside ultrasonography (INBU) evaluation of the IVC in critically ill patients with invasive CVP monitoring to determine how well these modalities correlate.

Disclosure Information: Nothing to disclose.

Received January 19, 2009; Revised February 23, 2009; Accepted February 25, 2009.

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Abbreviations and Acronyms

INBU	=	intensivist-performed bedside ultrasonography
IVC-CI	=	IVC collapsibility index
RA	=	right atrial
SICU	=	surgical intensive care unit

One widely used parameter in IVC assessment of intravascular volume is the IVC collapsibility index (IVC-CI).⁴⁻¹³ IVC-CI is the difference between end-expiratory and end-inspiratory IVC diameter divided by the end-expiratory diameter (Fig. 1). Previous studies have shown a relationship between IVC-CI and right atrial (RA) pressure or CVP, where higher IVC-CI values correlate with low RA filling pressures and lower IVC-CI values correlate with higher RA filling pressures.^{4,7,10} The physiologic principle underlying IVC-CI is that the act of taking a breath leads to negative intrathoracic pressure, which in turn leads to three additional effects. First, the negative intrathoracic pressure augments right ventricular diastolic filling. Second, it increases the capacitance of the pulmonary vascular bed. Third, it decreases pulmonary vascular resistance. The effect of the latter two is to increase the right-sided cardiac output. All of these effects result in a relative increase in caval flow into the heart, resulting in a tendency for the IVC to collapse. During expiration, the process is reversed, leading to a diminution of RA filling, resulting in an increase in IVC diameter.

Many previous reports on this topic have focused on groups of patients with chronic renal and cardiac failure, with relatively high incidence of volume overload.⁴⁻¹² In the current study, we have assessed the use of IVC-CI for intravascular volume assessment in critically ill surgical patients at risk for intravascular volume depletion.

METHODS

A prospective evaluation of cardiac and hemodynamic status was conducted on 124 surgical intensive care unit (SICU) patients using a hand-carried ultrasonography unit (MicroMaxx with P17 1 to 5 MHz phased array probe; Sonosite). Evaluation included IVC assessment and evaluation of the heart for left ventricular ejection fraction, mitral valve inflow and tissue Doppler measurements, and cardiac filling.

Intensivist sonographers included emergency medicine faculty, emergency medicine ultrasonography fellows, emergency medicine residents, and surgical critical care fellows. All intensivists had earlier ultrasonography experience in general bedside sonography (including focused assessment with sonography for trauma, gallbladder, aorta, and first-trimester pregnancy evaluations) and an

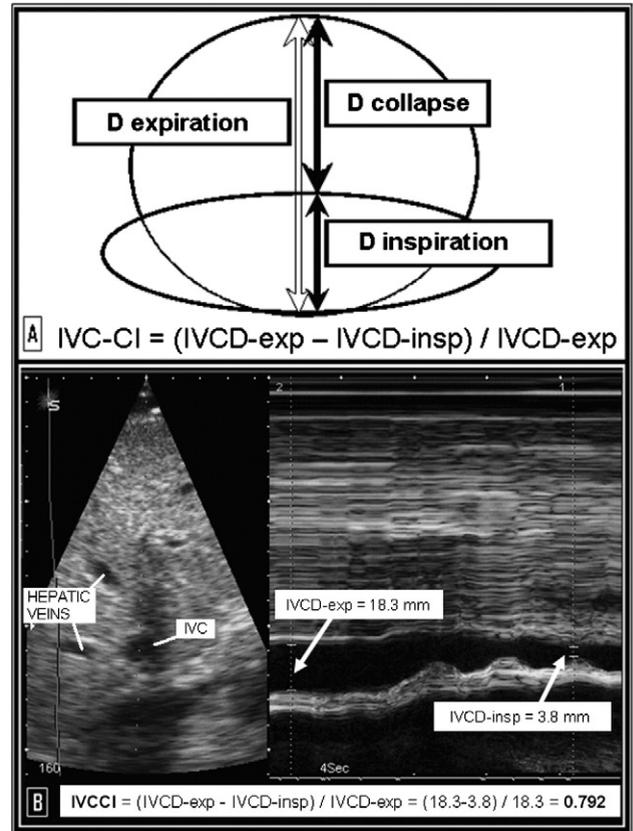


Figure 1. (A) Conceptual representation of the IVC collapse index (IVC-CI). IVCCI consists of the difference between the end-expiratory (IVCD-exp) and end-inspiratory IVC diameter (IVCD-insp) divided by IVCD-exp. (B) IVC diameter measurement using M-mode ultrasonography. Based on the measurements in this example, the IVC-CI would be $(18.3 - 3.80 \text{ mm}) / 18.3 \text{ mm}$, or 0.792.

additional 3 hours of didactic review of the techniques of acquisition and interpretation of sonographic images of the heart and IVC. For those intensivists who had not previously completed 25 adequate INBU examinations (judged adequate by direct proctoring or expert review of recorded video clips), additional examinations were required, up to a total of 25 adequate examinations.

Adult SICU patients (older than 18 years old) were eligible for enrollment. A record of each examination was stored in the form of static images and 6-second digital video clips. Sonographers recorded their interpretation of each examination and completion times on a standardized form blinded to the results of all invasive and noninvasive monitoring data. After completion of the ultrasonography examination, members of the SICU team caring for the patient, blinded to ultrasonography findings, provided data on a standardized form about patient demographics, vital signs, and invasive hemodynamic monitoring variables obtained at the time of the examination. Information

was recorded in a computerized database (Microsoft Access; Microsoft Corp).

IVC-CI was defined in one of two ways, depending on whether or not the patient was intubated. In nonventilated patients, the IVC-CI was defined as the difference between maximum (systolic) expiratory diameter and minimum (diastolic) inspiratory diameter divided by the maximum expiratory diameter (Fig. 1). To keep the test as simple as possible, and because the relationship between IVC diameter and respiratory cycle in intubated patients is controversial, in the ventilated patients maximum and minimum IVC diameter was measured without regard to phases of the respiratory cycle. IVC-CI measurements were obtained 1 to 2 cm below the level of the hepatic veins. Subcostal or subxiphoid windows were used based on available views, patient habitus, presence of external impediments (eg, drains, surgical dressings), and preference of the sonologist. Measurements in nonintubated patients were obtained during tidal respirations. Ventilated patients were evaluated during normal ventilatory cycling. Ventilatory mode and amount of positive end-expiratory pressure administered were recorded for each patient (see Table 1 for details about mechanical ventilation parameters among study patients).

The INBU-derived measurements of IVC-CI were compared with invasively measured CVP in patients with both CVP-monitoring devices and adequate INBU IVC evaluations. IVC-CI measurements were grouped by range (<0.20, 0.20 to 0.60, and >0.60) and analyzed for presence of substantial differences in CVP between the three IVC-CI groupings. These IVC-CI cut-off values were determined arbitrarily, with the intention of selecting groups with high, intermediate, and low collapsibility indices. CVP values were also grouped into three ranges: <7 mmHg, 7 to 12 mmHg, and >12 mmHg. These values were chosen based on ranges used as a basis for decision making in fluid management in our SICU.

Data analysis included descriptive statistics, coefficient of correlation, and analysis of variance, as appropriate. Statistical analysis was conducted using SPSS for Windows software (SPSS Inc). Statistical significance was set at $\alpha = 0.05$. This study was approved by the Institutional Review Board of the University of Pennsylvania.

RESULTS

The study was performed in a high-acuity combined trauma, general surgery, gynecology, otolaryngology, and thoracic SICU. A total of 124 patients were prospectively enrolled between October 2006 and April 2007. Of those patients, 101 had central venous catheters. This group consisted of 46 women and 55 men, with mean age of $58.3 \pm$

Table 1. Demographic and Clinical Characteristics of the Study Group

Parameter	Value
Total no. of patients enrolled	124
Intubated patients, n (%)	56/124 (45.2)
PEEP (cm H ₂ O) (n = 56), mean \pm SD (median)	8.1 \pm 4.9 (5)
Mechanical ventilatory modes (n, %)	
PEEP with pressure support	36/56 (64)
SIMV	3/56 (5.4)
Assist control	13/56 (23)
APRV/bilevel	4/56 (7.1)
Patients with CVP measurements (n)	101
Demographics, CVP group	
Male gender, n (%)	55/101 (54.4)
Age (y), mean \pm SD	58.3 \pm 18.6
Age (y), median (range)	60.5 (21–85)
Intubated, CVP group, n (%)	45/101 (44.6)
Echocardiography, ejection fraction (%), mean \pm SD (95% CI)	61.5 \pm 13.5 (59.1–64.0)
Patients with CVP in whom adequate IVC-CI exams could be attained	83
Reasons for inability to obtain IVC-CI views in 18 of 101 patients with CVP,* n (%)	
Surgical dressings	11/18 (61)
Chest	8/18 (44)
Abdomen	3/18 (17)
Difficult/large wound	4/18 (22)
Patient positioning	4/18 (22)
Patient obesity	2/18 (11)
Patient agitation	1/18 (5.6)

*Some patients had more than one factor listed.

APRV, airway pressure release ventilation; IVC-CI, inferior vena cava collapsibility index; SIMV, synchronized intermittent mandatory ventilation.

18.6 years (median age 60.5 years, range 21 to 85 years) and mean left ventricular ejection fraction of 61.5% by full-feature echocardiography. Among these patients, 44.6% were intubated (Table 1). Eighteen of 101 patients had ultrasonography examinations that were uninterpretable because of technical limitations or impediments, such as tubes, dressings, and patient positioning (Table 1). This left 83 patients with CVP monitoring devices and INBU IVC evaluations.

There was a significant, although weak correlation between IVC-CI and CVP measurements for continuous data ($R = -0.315$; $p = 0.007$) (Table 2). When stratified by IVC-CI (IVC-CI <0.20; IVC-CI 0.20 to 0.60; and IVC-CI >0.60), mean CVP values were inversely proportional to the IVC-CI ($p = 0.023$; Fig. 2). In patients with IVC-CI <0.20, the mean CVP was 12 mmHg, and in patients with IVC-CI >0.60 it was 7.4 mmHg. Fewer than

Table 2. Relationship Between IVC Collapsibility Index and CVP in This Study

Parameter	Value
Correlation (p value) between CVP and IVC-CI for patients grouped into high,* intermediate,† and low‡ IVC-CI ranges	R = -0.315 (0.023)§
High (n = 13)	
CVP (mmHg), mean ± SD	7.40 ± 4.67
Median CVP	6
% with CVP <7 mmHg	61.5
Intermediate (n = 41)	
CVP (mmHg), mean ± SD	9.75 ± 5.23
Median CVP	9
% with CVP <7 mmHg	34.1
Low (n = 29)	
CVP (mmHg), mean ± SD	12.0 ± 5.56
Median CVP	11
% with CVP <7 mmHg	3.4

*High >0.6.

†Intermediate 0.2–0.6.

‡Low <0.2.

§ANOVA.

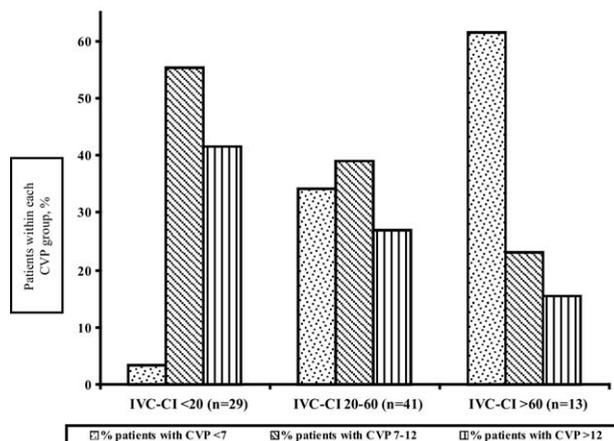
IVC-CI, inferior vena cava collapsibility index.

5% of patients with IVC-CI <0.20 had CVP <7 mmHg, and >40% of this group had a CVP >12 mmHg. Conversely, >60% of patients with IVC-CI >0.60 had a CVP <7 mmHg. An IVC-CI in the intermediate range (0.20 to 0.60) was not helpful in discriminating CVP.

DISCUSSION

Assessment of intravascular volume status is an essential component of the care of critically ill patients. A variety of devices and parameters, including pulmonary artery catheter, CVP, esophageal Doppler, arterial waveform analysis, and mitral valve inflow and tissue Doppler have been advocated for this purpose.²³ This range of options reflects the fact that that no single method is universally accepted. Likewise, each form of monitoring has its own spectrum of risks and benefits,^{1,24-27} and each is invasive, user-dependent, or time-consuming. A noninvasive modality that could be rapidly deployed would be desirable for diagnostic and therapeutic management of the critically ill.²⁸

Ultrasonography is a widely available noninvasive modality for cardiac and hemodynamic assessment. Until recently, ultrasonography was available to critical care patients only as a component of a full echocardiographic examination. This arrangement depends on the availability of highly trained technicians to obtain images, a mechanism for transferring the images to a qualified echocardiologist for interpretation, and the need to communicate the results back to the treating clinician who ordered the test.

**Figure 2.** CVP patterns according to the IVC collapse index (IVC-CI). The x-axis represents three ranges of IVC-CI, and the y-axis represents the percentage of patients within each IVC-CI range grouped by CVP.

The complicated nature of this process has precluded the rapid and widespread use of ultrasonography for this purpose in most critical care settings.²⁹

Recent technological advances have resulted in ultrasonography machines with improved image quality, despite being increasingly compact, mobile, inexpensive, and easy to use. This has allowed clinicians to obtain cardiovascular information from brief, focused ultrasonography examinations performed at the bedside. Although this is often referred to as “hand-carried” ultrasonography, ergonomic considerations have resulted in use of small cart-based systems in most critical care units, leading to the alternative terms *point-of-care*, *bedside*, or *clinician-performed* ultrasonography. A large number of scientific investigations have demonstrated the use of clinician-performed ultrasonography after appropriate training.^{13-16,18,20-22,30-32} One parameter, initially used by nephrologists for assessment of intravascular volume status, and subsequently by cardiologists, is the IVC-CI.⁴⁻¹² IVC assessment fulfills many of the candidate criteria for a reliable bedside ultrasonography tool because the IVC is relatively easily visualized and its quantitative and qualitative parameters can be measured using B-mode and M-mode, avoiding the need for more complex and time-consuming Doppler assessment. Recently, reports of its use in critical care settings have appeared.^{13,19,20,22,29,31,32} INBU provides more limited information than the full echocardiography examination. The relationship between the two types of examination is analogous to that between anteroposterior portable and erect posteroanterior and lateral chest radiography: in a critically ill patient, the information available from a limited but rapidly available examination can outweigh the benefits of a more comprehensive, time-consuming test as long as its

limitations are recognized by the clinician.¹⁶ Bedside assessment of the IVC-CI takes between 3 and 10 minutes, and can usually be completed in <5 minutes by appropriately trained clinician sonologists.

In a cohort of SICU patients, our group has previously compared the accuracy of blinded sonographers' assessment of volume status with that of treating clinicians with the benefit of detailed knowledge of the patient, including homodynamic monitoring.¹³ The current study was designed with a larger cohort, a number of methodological differences, and analysis of several variables not considered in the first study. We found a statistically significant but weak negative correlation between IVC-CI and CVP. In addition to the possibility that the relationship between these parameters in critically ill patients is actually weaker than that reported in the cardiology and nephrology literature, there are several features of the current study that should be considered because they might have diluted the correlation. First, there was a high proportion (45%) of mechanically ventilated patients in this study. Positive pressure ventilation reverses the normal inspiratory and expiratory pressure gradients between the thoracic and abdominal cavities. Earlier studies of IVC-CI and right atrial pressure in ventilated patients have shown variable results, leading to the preponderance of current evidence suggesting that this relationship is inconsistent in this group.³⁰⁻³³ Another factor that might have weakened the correlation between IVC-CI and CVP in our study is the high prevalence of increased intraabdominal pressures in SICU patients.³⁴ Other factors that affect IVC diameters that might have been present in an unknown number of our patients include elevated pulmonary artery pressures, tricuspid or pulmonic valve disease, and right and left ventricular dysfunction.

Despite these limitations, certain clinically useful observations emerged from our data. We noted a substantial and stepwise increase in the proportion of patients with CVP <7 mmHg as the IVC-CI increased from <0.20 to >0.60 (Fig. 2). In fact, <5% of patients with IVC-CI <0.20 had CVP <7 mmHg, and >60% of patients with IVC-CI >0.60 had CVP <7 mmHg. Considering the CVP values for the three IVC-CI groups (>0.60, 0.20 to 0.60, and <0.20), the mean CVP ranged from 7.4 mmHg to 12 mmHg, proceeding from the high IVC-CI to the low IVC-CI group, respectively. We believe that the ability to exclude a CVP <7 mmHg with an IVC-CI <0.20 provides clinically useful information by suggesting that additional fluid administration would be unlikely to be of additional benefit.

Of note, the IVC-CI was most strongly related to CVP in the groups with high or low IVC-CI values (<0.2 or >0.6).

Physiologically, a weak relationship between IVC-CI and CVP might be anticipated in the intermediate range of collapsibility. The IVC, in fulfilling its role as a capacitance vessel, might be expected to provide a relatively uniform preload despite fluctuations of intravascular volume. This would result in a range of normal values for both IVC diameter and IVC-CI. Within that range, relatively large changes in IVC diameter and collapsibility (eg, IVC-CI of 0.2 to 0.6) might be expected to correlate weakly or not at all with CVP.⁶ In this regard, IVC parameters might not have a cut-off value distinguishing normal and abnormal states. Instead, there would be a normal range, with abnormalities at extreme high or low values, akin to many physiologic parameters (eg, vital signs).^{7,35-37} This conceptual framework necessitates clinicians' use of pretest probability estimates in interpreting ultrasonography findings. It also suggests that the closer IVC-CI gets to 0.0 or to 1.0, the more likely it is that the patient is volume-overloaded or depleted, respectively. In our cohort, approximately half of the patients fell into the intermediate IVC-CI range (0.2 to 0.6) reflecting the fact that many had already received intravascular volume optimization based on invasive monitoring. It is possible that IVC assessment would have demonstrated a more clear-cut correlation with CVP in patients who had not already had prolonged ICU stays with extensive adjustments of intravascular fluids based on invasive hemodynamic monitoring devices.

Strengths of this study include the prospectively collected data and its generalizability to many critical care units and intensivists by our use of an undifferentiated SICU patient population and practicing intensivists with training and experience consistent with guidelines of the applicable specialty societies.³⁸⁻⁴⁰ The robustness of our results is enhanced by use of concurrently obtained sonographic and invasive hemodynamic information. Limitations include its observational character, the relatively small cohort with central venous catheters, and the 18% of patients with CVP monitoring devices in whom adequate images could not be obtained. Although this represents a higher proportion of limited examinations than that reported by Carr and colleagues,¹³ we believe that both studies reflect the challenges of this operator-dependent diagnostic modality being used in the clinical setting of critically ill surgical patients, and add to the generalizability of these studies. The failure to obtain images of the IVC for the variety of reasons (detailed in Table 1) in almost one-fifth of patients is a real limitation. It is a strength of ultrasonography that the inability to perform the test is instantly recognizable, in contrast to many invasive modalities of hemodynamic monitoring in which a variety of technical malfunctions can result in inaccurate results that can be undetected by the clinician relying on them. Of note in the current study,

although obesity is frequently mentioned as an impediment to ultrasonography, this was cited as the cause in only 11% of the failed attempts. Other impediments relating to patient habitus include emphysema and cachexia, but these were not found to prevent ultrasonography in any of the patients of this cohort.

Another important limitation of the current study is its inability to shed light on issues relating to IVC assessment in patients on positive pressure ventilation. First, the sample size does not provide the statistical power to permit comparison between ventilated and nonventilated patients when these groups are subdivided by IVC-CI and CVP ranges. Second, as we noted in the Methods section, we have found that even experienced intensivists sonographers do not reliably measure the fluctuating diameter of the IVC based on the respiratory phase of a ventilator in the midst of the many clinical tasks involved in caring for critically ill patients. In contrast, measurement of maximum and minimum diameters from an M-mode image (Fig. 1) is a relatively straightforward task. We have chosen to measure IVC-CI using maximum and minimum recorded diameters without regard to the respiratory phase in ventilated patients because we are mindful that in order for INBU to be of real-life use it needs to be simple, rapidly obtainable, and reproducible, and because there are many questions about the validity and performance of IVC measurements in these patients.³⁰⁻³³ In one respect this is a limitation of the study, but it adds to the generalizability of our findings by putting the ultrasonography test within the reach of clinicians without extensive advanced sonographic training. Additional study is needed to determine the use of IVC volume status assessment in critically ill patients on positive pressure ventilation. The many other factors known or postulated to affect IVC diameter and collapse including left and right ventricular function, pulmonary hypertension, and tricuspid and pulmonic valve dysfunction were not analyzed because of previously mentioned statistical limitations or because they were beyond the scope of this report, or both.

Directions for future research in intensivist bedside ultrasonography include the examination of the relationship between pulmonary artery catheter readings and sonographic measurements, including possibly flow Doppler, color Doppler, and tissue Doppler. Additional evaluation of IVC-CI and IVC diameter during active fluid or vasoactive agent resuscitation are needed to elucidate fluid responsive shock states, the use of ultrasonography in monitoring therapy, and to develop increasingly tailored pharmacotherapy in the management of shock.^{34,41}

Our data suggest that INBU measurement of IVC-CI can offer the treating clinician a rapid, easily repeated, and

noninvasive adjunct in the assessment and management of critically ill patients. IVC-CI is increasingly likely to offer definitive information at the extremes of its range (as it approaches 0% or 100%). In addition, large-scale prospective studies will be needed to confirm and expand on the findings of the present study, including the use of other bedside sonographic techniques and analysis of various techniques and clinical parameters in a variety of patient subgroups.

Author Contributions

Study conception and design: Stawicki, Kirkpatrick, Gracias, Dean

Acquisition of data: Panebianco, Hayden, Dean

Analysis and interpretation of data: Stawicki, Panebianco, Kirkpatrick, Hayden, Dean

Drafting of manuscript: Stawicki, Braslow, Panebianco, Gracias, Dean

Critical revision: Stawicki, Kirkpatrick, Gracias, Hayden, Dean

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