



Comparison of Serial Qualitative and Quantitative Assessments of Caval Index and Left Ventricular Systolic Function During Early Fluid Resuscitation of Hypotensive Emergency Department Patients

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Abstract

Objectives: The objective was to determine whether serial bedside visual estimates of left ventricular systolic function (LVF) and respiratory variation of the inferior vena cava (IVC) diameter would agree with quantitative measurements of LVF and caval index in hypotensive emergency department (ED) patients during fluid challenges. The authors hypothesized that there would be moderate inter-rater agreement on the visual estimates.

Methods: This prospective observational study was performed at an urban, regional ED. Patients were eligible for enrollment if they were hypotensive in the ED as defined by a systolic blood pressure (sBP) of <100 mm Hg or mean arterial pressure of ≤65 mm Hg, exhibited signs or symptoms of shock, and the treating physician intended to administer intravenous (IV) fluid boluses for resuscitation. Sonologists performed a sequence of echocardiographic assessments at the beginning, during, and toward the end of fluid challenge. Both caval index and LVF were determined by the sonologist in qualitative then quantitative manners. Deidentified digital video clips of two-dimensional IVC and LVF assessments were later presented, in random order, to an ultrasound (US) fellowship-trained emergency physician using a standardized rating system for review. Statistical analysis included both descriptive statistics and correlation analysis.

Results: Twenty-four patients were enrolled and yielded 72 caval index and LVF videos that were scored at the bedside prior to any measurements and then reviewed later. Visual estimates of caval index compared to measured caval index yielded a correlation of 0.81 ($p < 0.0001$). Visual estimates of LVF compared to fractional shortening yielded a correlation of 0.84 ($p < 0.0001$). Inter-rater agreement of respiratory variation of IVC diameter and LVF scores had simple kappa values of 0.70 (95% confidence interval [CI] = 0.56 to 0.85) and 0.46 (95% CI = 0.29 to 0.63), respectively. Significant differences in mean values between time 0 and time 2 were found for caval index measurements, the visual scores of IVC diameter variation, and both maximum and minimum IVC diameters.

Conclusions: This study showed that serial visual estimations of the respiratory variation of IVC diameter and LVF agreed with bedside measurements of caval index and LVF during early fluid challenges to symptomatic hypotensive ED patients. There was moderate inter-rater agreement in both visual estimates. In addition, acute volume loading was associated with detectable acute changes in IVC measurements.

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The emergency department (ED) management of patients with symptomatic hypotension can be challenging, especially when the etiology of a patient's hypotension is unclear. The early use of goal-directed echocardiography in critically ill patients has been shown to accurately narrow the differential diagnosis of acute undifferentiated hypotension and can alter the clinical management of patients.^{1,2} A better understanding of a patient's cardiac function and volume status in acute hypotension allows for more confident and timely clinical decision-making. Some of the most useful parameters evaluated by echocardiography are left ventricular systolic function (LVF) and inferior vena cava (IVC) size and dynamics. Right atrial pressure (a surrogate of central venous pressure [CVP] and volume status) and heart function can be safely obtained with bedside echocardiography without the need for invasive hemodynamic monitoring.³⁻⁵

Traditionally, comprehensive echocardiography has several primary indications that are pertinent to the assessment and management of critically ill patients in the ED and intensive care settings.⁶ Comprehensive echocardiography includes detailed calculations and measurements of systolic and diastolic function, chamber size, and quantitative valve function. While such details can be very useful, it is not always practical in the unstable patient. Goal-directed echocardiography is practiced in cardiology, emergency medicine, and critical care. Key time-sensitive clinical questions can often be answered by bedside qualitative echocardiographic assessments alone.⁷ The ability to consistently compare, contrast, and discern that the left heart function is "severely depressed" versus "normal" versus "hyperdynamic" has more immediate clinical implications than whether the measured ejection fraction is precisely 10% versus 15%.^{1,7-9}

The respiratory variation of IVC diameter (caval index) has been extensively studied as well and can influence clinical decision-making when framed in the clinical context. Assessment of caval index is performed by measuring the respiratory variation of the IVC diameter and can be broadly categorized as minimal (plethoric), normal, or fully collapsible. Previous studies have shown low caval indices were associated with congestive heart failure (CHF), while others suggest that similar caval indices in mechanically ventilated septic patients could suggest fluid responsiveness. Acute fluid loss (blood donation, hemodialysis) can increase the collapsibility of the IVC. Other studies have demonstrated lower size and increased collapsibility of the IVC in dehydrated children.^{10,11} Critical care studies have reported that caval index measurements are useful in predicting "fluid responsiveness" in mechanically ventilated septic intensive care unit (ICU) patients. However, many of the patients had already received fluid and adrenergic agents before enrollment.^{12,13} Serial echocardiography evaluations have been used to track volume status changes in those undergoing diuresis for pulmonary edema.¹⁴ We are not aware of any studies in the emergency medicine literature that report on serial ultrasound (US) evaluations during the early phase of medical treatment of hypotension.

The purpose of this study was to compare visual estimates of respiratory variation IVC diameter and left heart systolic function in ED patients with their respective quantitative measurements. The assessments were performed early in the ED presentation and during the course of fluid challenges. This is important because the trend of a patient's hemodynamic parameters is often more important than an isolated evaluation. Serial examinations can help a clinician to determine if selected therapeutic interventions are positively influencing a patient's hemodynamic status and allow the clinician an opportunity to reassess a patient's plan of care in frequent intervals. We hypothesized that early serial visual estimates of LVF and IVC respiratory dynamics by US would have moderate agreement with quantitative US measurements in hypotensive ED patients during fluid challenges.

METHODS

Study Design

This was a prospective, observational study. US was considered a minimal risk to the patient and an established feature in the clinical evaluation of hypotensive patients in our ED. The hospital's institutional review board approved the research study, and a waiver of informed consent was granted.

Study Setting and Population

The study was conducted over an 8-month period on a convenience sample of ED patients presenting with symptomatic hypotension. The ED has an annual census of 114,000 visits. Patients presenting to the ED with systolic blood pressure (sBP) readings of ≤ 100 mm Hg and accompanying signs and symptoms of inadequate organ perfusion were evaluated for further eligibility in the study. Inclusion criteria were: age ≥ 18 years, presence of hypotension as defined by sBP < 100 mm Hg or mean arterial pressure ≤ 65 mmHg, presence of symptoms or signs of shock, sinus rhythm, and the treating emergency physician's (EP's) intent to administer intravenous (IV) fluid challenges of 20 mL/kg or greater. Exclusion criteria were one or more of the following: age younger than 18 years, presence of an unstable or absent cardiac rhythm at presentation (or advanced cardiac life support protocol in progress), suspected CHF, inability to obtain adequate quality US images, known pregnancy, significant traumatic condition, inability of the patient to tolerate the positioning for the US examination, predictable ED stay of less than 45 minutes, the treating EP's decision to withhold fluid challenge, or if the patient was considered a technically difficult study. To determine "technical difficulty" and imaging feasibility, a quick preview of needed IVC and heart views was performed on the supine patient prior to enrollment. Signs and symptoms of shock included but were not limited to weakness, confusion, thirst, anxiety, chest discomfort, dyspnea, pallor, dizziness, syncope, lethargy, dry mucous membranes, and decreased pulses.

Study Protocol

Ultrasound Measurements. Emergency US division physicians performed all studies during research enrollment shifts. Investigators were trained in a standard method of M-mode measurements of LVF using the fractional shortening method as well as caval index. Each investigator completed training on the details of image acquisition, technique, details of scoring criteria, and the sequence of measurements to standardize the protocol. Caval index is an established parameter measuring the difference between IVC size at expiration and inspiration. Fractional shortening is another way to calculate a patient's systolic function, with a normal range approximately 30% to 45%. It is obtained by measuring the distance between the endocardial borders in systole and diastole with M-mode. It should be noted that fractional shortening and ejection fraction are different parameters and the values are not interchangeable.

A strict sequence of US evaluations and measurements was consistently used, beginning with assessment of the IVC. The protocol of sequenced imaging was programmed into a Philips CX50 (Philips Ultrasound, Andover, MA) US machine, and we used its S-5-1 phased array probe. Cardiac and IVC imaging began with two-dimensional US. Longitudinal views of the proximal IVC were obtained. Measurements of the IVC diameter were made approximately three centimeters caudal to the junction of the right atrium. The caval index was visually estimated with a three-point scale that we created based on studies of CVP estimations:⁸ 1) decreased caval index (0 to 0.3), 2) normal range caval index (0.31 to 0.69), and 3) increased caval index (0.70 to 1.00). A digital video of the IVC, during one to two full respiratory cycles, was captured. M-mode was then used to capture and calculate the caval index of a respiratory cycle as: $(\text{maximum IVC diameter} - \text{minimum IVC diameter}) / \text{maximum IVC diameter}$.

For evaluation of systolic function, a composite evaluation of LV myocardial systolic thickening, anterior mitral leaflet movement, and LV endocardial excursion was used for bedside and reviewer estimation. This is consistent with known practice for estimating systolic function with visual inspection. Sonographic characteristics of good systolic function include close

approximation of the anterior leaflet of the mitral valve to the septal wall, observable systolic thickening of the posterior ventricular wall measured at the mid to basal segment, and greater movement of the ventricular and septal wall endocardial surfaces toward each other. Characteristics of poor systolic function include wider separation between the anterior leaflet of the mitral valve and the septum, minimal thickening of the posterior ventricular wall during systole, and increased separation between the endocardial borders of the septum and posterior wall. We used a four-point cardiac rating scale: 1) severely depressed, 2) moderately depressed, 3) normal, and 4) increased. Increased LVF (hyperdynamic) was defined as "near or complete obliteration of the LV cavity," meaning that the endocardial surfaces of the septum and posterior wall came in close contact with each other. Tachycardia was not a factor in making this assessment (please see Figure 1 for further explanation). For quantitative assessment, we used fractional shortening to evaluate LVF. The parasternal long axis view was again used to visualize the long axis of the LV, followed by directional M-mode assessment to obtain measurements of the LV minor axis at the mid section of the LV. M-mode measurements of LV diameters at end diastole (LVEDD) and end systole (LVESD) were used to calculate fractional shortening (FS): $(\text{LVEDD} - \text{LVESD}) / \text{LVEDD}$. It should be noted again that normal values for FS are approximately 30% to 45% and the values are not interchangeable with ejection fraction.

Clinical Protocol. Ultrasound scoring and measurements were performed at three defined points per enrollment. Time 0 was defined as the start of the fluid challenges. Time 1 was defined as immediately after the first fluid challenge. At the discretion of the treating EP, the initial fluid challenge was followed by a second fluid challenge, maintenance fluid, and/or adrenergic agents. Time 2 was defined as 15 to 20 minutes after Time 1. A composite of caval index and LVF scores was assigned to each time-staged US evaluation. A minimum composite score was 2, and the maximum score was 7. CVP readings were not required in this study.

Left ventricle function and caval index results were disclosed to the treating physician, if requested.

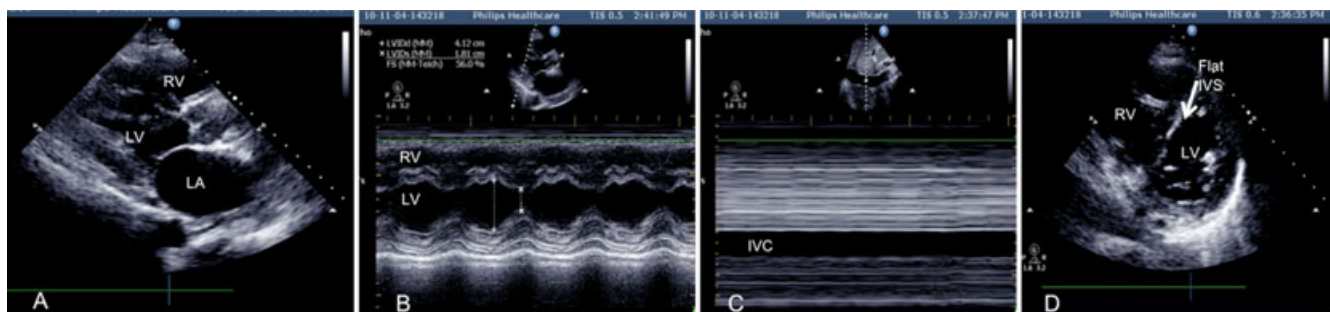


Figure 1. Parasternal long axis view. (A) This parasternal long-axis window shows a "hyperdynamic" heart with near obliteration of the left ventricle (LV) and an enlarged left atrium (LA) and (B) an elevated fractional shortening (FS) measurement of 56% using M-mode, with (C) longitudinal subcostal view of IVC with negligible diameter variation during a respiratory cycle (low caval index) due to right ventricle (RV) overload. In (D) the parasternal short-axis view depicts a dilated RV with flattening of interventricular septum (IVS). After the fluid challenge, the patient's caval index remained the same, but the blood pressure improved. IVC = inferior vena cava.

Significant findings such as tamponade and right heart strain were reported to the EP. The US performed by the investigator was allowed to replace the US performed by the treating EP, but the treating EP was free to perform US at any point in the patient management.

All US videos were deidentified and independently reviewed at a later date by an US fellowship-trained EP who was blinded to patient identifiers, the sequence of images, measurements, and interventions during the resuscitation. Each 3-second digital video clip showed the IVC during one or two respiratory cycles or several cardiac contractions for caval index and LVF estimations, respectively. The reviewer received training on the scoring criteria. Inter-rater variability was determined after independent reviews.

Data Analysis

With 24 subjects, an effect size of 0.85 between the time points can be detected with an alpha level of 0.05 and a power of 80%. An effect size of 0.85 is consistent with a mean difference between the time points equal to 0.85 of the standard deviation (SD; of the difference). It was felt that a difference of 1 SD (an effect size = 1) would be a significant clinical difference. Therefore, 24 subjects were more than sufficient to detect a difference of this magnitude with 80% power.

The SAS software, version 9.2, was used for all analyses (SAS Institute, Cary, NC). Descriptive statistics including means, SDs, medians, and interquartile ranges (IQR) are reported. If the data were on the nominal scale, counts and percentages were calculated. Repeated-measures analysis of variance was used to test for changes over time assumptions. Normality was tested using the Shapiro-Wilk test. If the data were not normally distributed, they were transformed by taking the logarithm of the measure. If the assumption of sphericity was violated, then the Geisser-Greenhouse adjustment to the p-value was reported. Pearson or Spearman's correlations were employed to test for linear relationships among the variables and between the changes in two variables. Cohen's kappa with its 95% confidence intervals (CI) was used to test for agreement. SAS uses the asymptotic variance of the kappa coefficient, as derived by Fleiss et al.¹⁵ to calculate the 95% CI for kappa. The verbal descriptors for kappa suggested by Landis and Koch¹⁶ were used in the manuscript. A two-tailed p-value of less than 0.05 was considered statistically significant.

RESULTS

Twenty-four patients were enrolled and 72 videos of LVF and caval index were obtained. Initial demographic and clinical characteristics are shown in Table 1. At Time 0, the mean volume of fluid administered prior to any US imaging or measurements was 397 mL (SD \pm 665 mL, range = 0–2,350 mL), with a median of 50 mL. The mean total protocol time was 102 minutes with a range of 54 to 175 minutes (SD \pm 28 minutes). The mean total fluid administered during the study protocol was 2,580 mL (SD \pm 1,586 mL, range = 1,100–9,000 mL). The mean time between the start of the ED fluid bolus and the second US survey was 50 (SD \pm 22) minutes.

Table 1
Patient and Protocol Characteristics

Characteristic	
Age (yr), mean (\pm SD)	63 (\pm 18)
Male sex, n (%)	11 (46%)
Diabetes mellitus	29%
Hypertension	58%
Chronic CHF	29%
Pulmonary disease	25%
Neoplasm	8%
Prehospital hypotension report (sBP < 100 mm Hg) en route to ED	23/24 enrollments (96%)
sBP (mm Hg)	
Mean (\pm SD)	84 (\pm 12)
Median (IQR)	85.50 (80.5–90.0)
Heart rate (beats/min)	
Mean (\pm SD)	88 (\pm 21)
Median (IQR)	79.5 (72.5–102.0)
Initial serum lactate (15/24 patients [62%]) mmol/dL	
Mean (\pm SD)	2.25 (\pm 1.1)
Median (IQR)	2.1 (1.2–2.90)
Volume of fluid received before enrollment (mL)	
Mean (\pm SD)	397 (\pm 665)
Median (IQR)	50.0 (0.0–500.0)
Total protocol time (minutes)	
Mean (\pm SD)	102 (\pm 28)
Median (IQR)	104.5 (86.0–20.0)
Total fluid volume given during protocol (mL)	
Mean (\pm SD)	2,580 (\pm 1,586)
Median (IQR)	2,200.0 (1,700.0–2,900.0)

CHF = congestive heart failure; IQR = interquartile range; sBP = systolic blood pressure.

As planned, the mean time between the second and third time points was 35 (SD \pm 13) minutes. There were no adverse events related to fluid toxicity. One patient developed cardiac arrest during the study, requiring advanced resuscitation and mechanical ventilation. This same patient had the third stage of US evaluations performed after institution of mechanical ventilation and administration of inotropic medications. An additional three patients received adrenergic agents during the study protocol. All were administered at or near Time 2. There was insufficient use of adrenergic agents in our study sample for aggregate data on any temporal association of LVF changes with adrenergic agent use. Serum lactate levels were obtained in 15 of 24 enrollments (62%), with a mean level of 2.25 mmol/dL (SD \pm 1.1 mmol/dL; see Table 2 for mean scores and measurements at each time point).

Caval Index

These results are shown in Figure 2. A three-point scale was used to assign a value for visual estimate of IVC respiratory variation, as outlined under the Methods section. The mean change in these visually estimated caval scores during this fluid challenge study protocol was -1 (a one point caval index score reduction) with a range of -2 to 0 . This correlated with change in measured M-mode caval indices. The Spearman's correlation was $r = 0.81$ ($p < 0.0001$).

Table 2
Simple Statistics for Heart Rate, sBP, IVC Evaluations, and LVF (Visual Scoring and Actual Measurements) at Defined Time Points

Number of evaluations (n = 24)	Time 0	Time 1	Time 2	p-value		
				Time Interval 0 to 1	Time Interval 1 to 2	Time Interval 0 to 2
Heart rate (beats/min)						
Mean (±SD)	87.79 (±21.73)	84.96 (±19.39)	86.29 (±19.61)	0.12	0.12	0.47
Median (IQR)	79.50 (72.5–102.0)	84.00 (73.5–93.0)	82.00 (72.0–100.0)			
Systolic blood pressure (mm Hg)						
Mean (±SD)	83.79 (±11.76)	99.04 (±18.16)	110.96 (±17.08)	<0.001	<0.001	0.01
Median (IQR)	85.50 (80.5–90.0)	96.00 (87.5–114.5)	109.00 (98.5–121.5)			
Caval index						
Mean (±SD)	0.45 (±0.31)	0.31 (±0.21)	0.22 (±0.18)	0.011	0.03	<0.001
Median (IQR)	0.43 (0.16–0.72)	0.27 (0.14–0.49)	0.20 (0.07–0.33)			
Visual estimate caval index score (3-point scale)						
Mean (±SD)	2.13 (±0.90)	1.58 (±0.72)	1.42 (±0.58)	<0.001	0.10	<0.001
Median (IQR)	2.00 (1–3)	1.00 (1–2)	1.00 (1–2)			
Maximum IVC diameter (mm)						
Mean (±SD)	15.45 (±7.32)	18.84 (±5.62)	20.65 (±4.87)	0.002	0.08	<0.001
Median (IQR)	15.75 (9.56–20.40)	17.75 (14.90–21.80)	20.95 (16.40–23.60)			
Minimum IVC diameter (mm)						
Mean (±SD)	10.13 (±8.63)	13.66 (±7.05)	16.39 (±5.84)	0.005	0.03	<0.001
Median (IQR)	7.58 (2.86–16.10)	11.45 (8.66–19.30)	15.50 (11.95–21.35)			
Fractional shortening						
Mean (±SD)	0.40 (±0.20)	0.43 (±0.16)	0.44 (±0.14)	0.46	0.36	0.26
Median (IQR)	0.37 (0.27–0.46)	0.41 (0.31–0.52)	0.44 (0.36–0.52)			
Visual estimate LVF score (4-point scale)						
Mean (±SD)	2.75 (±0.85)	2.92 (±0.78)	3.04 (±0.62)	0.10	0.08	0.03
Median (IQR)	3.0 (2.0–3.0)	3.0 (2.5–3.0)	3.0 (3.0–3.0)			

IQR = interquartile range; IVC = inferior vena cava; LVF = left ventricular systolic function; sBP = systolic blood pressure.

Statistically significant differences in mean values between Time 0 and Time 2 were found for caval index measurements, the visual scores of IVC diameter variation, and both maximum and minimum IVC diameters (Table 2). The differences in mean values between Time 0 and Time 1 for all IVC measurements and scores were statistically significant. Between Time 1 and Time 2 (a 20- to 30-minute interval), the differences in mean values were significant for measured caval index and minimal IVC diameter, but not for visual score of IVC diameter variation or maximum IVC diameter.

Left Ventricular Systolic Function

Bedside two-dimensional LVF visual scoring on the four-point scale was compared to contemporaneous M-mode measurements of fractional scoring using the parasternal long axis (PSLA) window. Scores of LVF and FS measurements are plotted in Figure 3. The Spearman’s correlation was $r = 0.84$ ($p < 0.0001$). LVF scores trended toward staying the same during the ED fluid challenges. The mean FS difference between Time 0 to Time 2 was 0.04 (SD for the difference ± 0.15 ; $p = 0.26$). The mean difference for LVF scores between Time 0 and Time 2 was 0.29 (SD for the difference ± 0.62 ; $p = 0.03$).

Inter-rater Agreement

Videos were independently reviewed by an US fellowship-trained EP. Bedside visual caval index scores compared to reviewer scores yielded simple and weighted kappa values of 0.70 (95% CI = 0.56 to 0.84) and 0.78 (95% CI = 0.67 to 0.89), respectively. There was complete agreement in caval index scoring in 59 of 72 videos. There was a one-point difference in caval index scoring in 13 of 72 evaluations (Table 3). With regard to LVF, there was scoring agreement in 47 of 72 LVF evaluations (Table 4). Twenty-four of the 25 disagreements (96%) were within one point on the LVF rating scale. One of 72 (1.3%) LVF scores comparisons had a difference of two. The simple and weighted kappa values of observer agreement of LVF using strict criteria were 0.46 (95% CI = 0.29 to 0.63) and 0.57 (95% CI = 0.41 to 0.72), respectively. This is considered to be a moderate strength of agreement.

DISCUSSION

This article reports on the comparison of qualitative assessments and quantitative measurements of LVF and IVC dynamics in hypotensive ED patients taken at baseline and after a fluid challenge. We tried to recruit patients as early in the course of ED presentation and

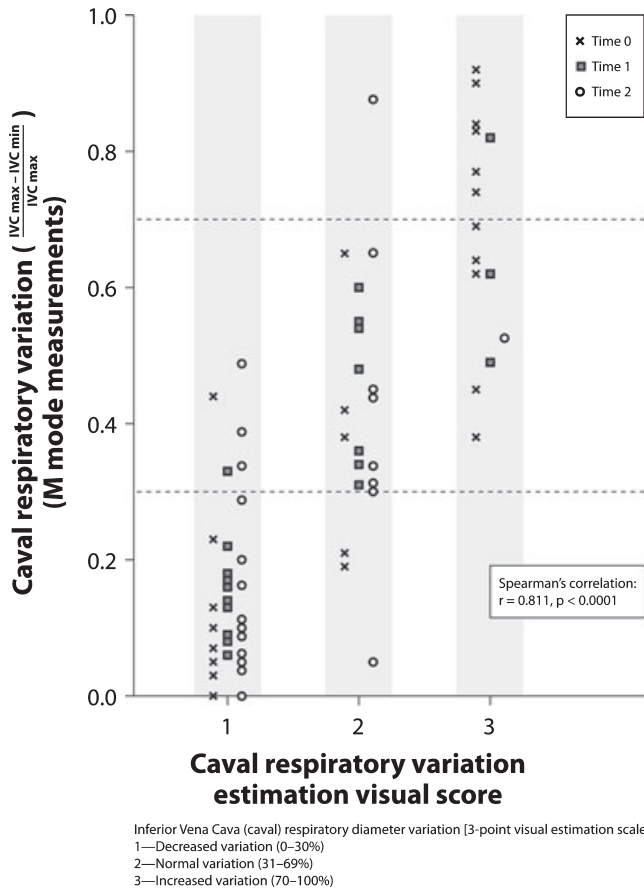


Figure 2. Visual estimate caval index scores compared to caval index measurements at defined protocol time points. IVC = inferior vena cava.

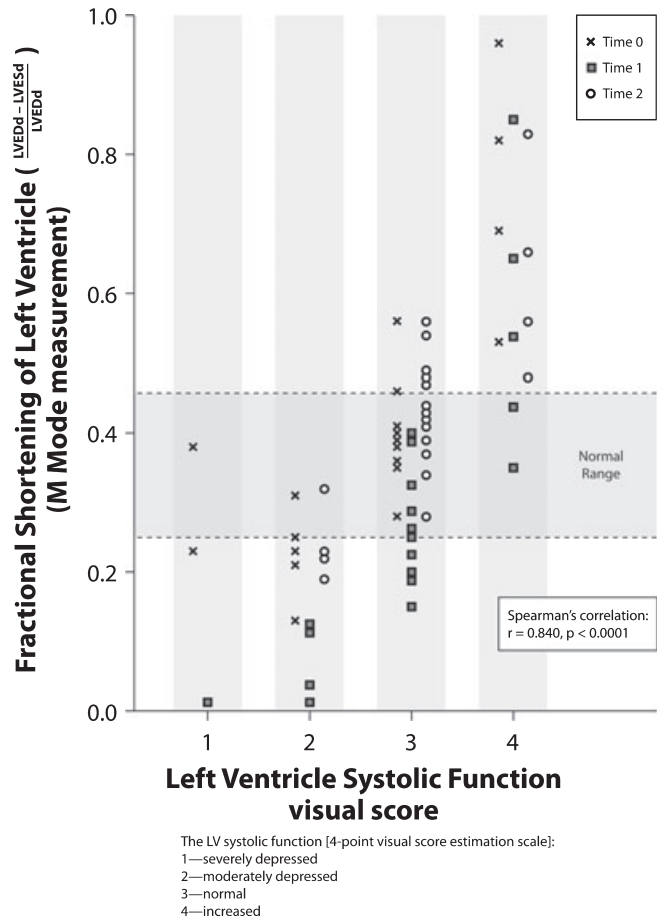


Figure 3. Measured left ventricle fractional shortening compared to bedside visual estimate LVF scoring at defined protocol time points. LVF = left ventricular systolic function.

fluid resuscitation as possible. The mean volume of fluid administered prior to enrollment and the first US assessment of the protocol was 397 mL (SD ± 665 mL). Although previous studies have attempted to correlate caval index or LVF with fluid resuscitation, this was not the primary goal of our study. Rather, this study was an attempt to correlate visual estimates of these parameters with variables measured by echocardiographic measurements using M-mode technology. The goal was not to determine the accuracy of the measurements. We believe that this is the first study to report serial visual estimations and measurements of LVF and caval index in ED patients. We were able to show a good correlation between visual estimates and measured parameters, even with changes associated with fluid challenges.

Early serial US qualitative caval index and LVF assessments can be quickly performed and may provide valuable information to the physician as the clinical condition evolves. The major finding of the study was that visual estimates of LVF and respiratory variation of IVC diameter correlate with FS and caval index. We obtained Spearman's correlation values of 0.84 for LVF visual estimates and FS measurements and 0.81 for visual scoring of IVC respiratory variation and caval index measurements. This is useful because most EPs do not perform quantitative measurements of left heart systolic function or caval index. The serial visual assessments are quick and easily reproducible.

Table 3
Comparison of Bedside Scoring Versus Blinded Reviewer Scoring of Caval Index

Visual Estimate IVC Diameter Respiratory Variation (Caval Index)	Blinded Reviewer Rating			
	1. Decreased	2. Normal	3. Increased	Total
1-Bedside rating	34	2	0	36
2-Bedside rating	6	13	2	21
3-Bedside rating	0	3	12	15
Total	40	18	14	72

Table 4
Comparison of Bedside Scoring Versus Blinded Reviewer Scoring of LVF

Visual Estimate LV Systolic Function	Blinded Reviewer Rating				Total
	1. Severely Depressed	2. Moderately Depressed	3. Normal	4. Hyperdynamic	
1-Bedside rating Severely depressed	2	1	0	0	3
2-Bedside rating Moderately depressed	1	10	3	1*	15
3-Bedside rating Normal	0	5	25	10	40
4-Bedside rating Hyperdynamic	0	0	4	10	14
Total	3	16	32	21	72

LVF = left ventricular systolic function.
*Considered potentially clinically significant difference.

There have been various uses and values of single caval index measurements. Blehar et al.¹⁷ concluded that a caval index of less than 0.15 was predictive of CHF. Studies by Barbier et al.¹² and Feissel et al.¹³ described caval index of greater than 0.12 and 0.18, respectively, as being predictive of fluid responsiveness in mechanically ICU patients with sepsis syndrome.

Variations in caval index measurements in response to interventions have been reported. Lyon et al.¹⁸ showed decreases in the mean inspiratory and expiratory IVC diameters in response to volume loss associated with blood donation in healthy volunteers. Krause et al.¹⁹ showed a decrease in mean IVC diameter and an increase in the mean caval index of pediatric patients after hemodialysis. Other studies report caval index cutoff values of 0.5 can noninvasively stratify CVP estimations.^{3,4,8}

In this observational study, we noticed that the majority of our patients had a rapid IVC filling and caval index reduction. The sole exception was a subject with an unchanged caval index score of 3. The intended ED fluid resuscitation was delayed and interrupted, and the patient received 1500 mL over 175 minutes. This was considered to be a suboptimal fluid challenge. This patient was later diagnosed with hypovolemia. We also observed that the patients with low caval indices at presentation received fluid challenges without complications, and the majority had associated right and/or left heart dysfunction signs (Figure 1). It should be noted that despite our findings of cardiac dysfunction, an exclusion criterion of the study was suspicion of acute CHF by the treating EP. If CHF is considered unlikely and a low caval index is found by US, the authors do suggest a prompt evaluation for right and left heart dysfunction.

Other authors have investigated the role for serial IVC measurements to track volume loading and volume removal in normal volunteers and patients with cardiogenic pulmonary edema, respectively.¹⁴ Although our observational study involved serial US assessments during early fluid challenges, it was not designed to investigate or report on an US assessment of volume status or volume expansion. However, our observations suggest that the ability to discern various levels of IVC collapsibility may be a valuable adjunct tool in

monitoring changes in intravascular volume status after interventions such as diuresis, afterload reduction, and volume expansion.

With a correlation of 0.84 for visual LVF scoring and FS measurements, we believe that the composite scoring evaluation of mitral leaflet movement, systolic thickening, and endocardium movement helps to appropriately differentiate various levels of LVF. Normal systolic function was indicated when the anterior leaflet of the mitral valve moved close to the septal wall during diastole. Greater separation of the mitral leaflet from the septal wall was considered an indicator of worse systolic function. Myocardial wall thickening during systole is another parameter to indicate normal LVF; diminished wall thickening is another indicator of worsening LVF. The last parameter, endocardial excursion, was evaluated by observing the inner walls of the mid and basal segments of the septal and posterior LV walls move toward each other on the PSLA views. With a hyperdynamic heart the walls approached each other and in some cases, even touched; while with severely depressed LVF the movements were relatively small. This LVF scoring system was only tested on the PSLA view. Previous studies have used a three-point LVF scale;^{1,2} we used a four-point LVF scale. We believe that the further distinction between a normal and a hyperdynamic LVF could lead to different clinical decisions.

Comprehensive echocardiography traditionally measures and describes left heart systolic function in terms of "ejection fraction." Ejection fraction measurement involves a volumetric assessment of ventricle chamber size changes between diastole and systole. The common method of determining ejection fraction involves the manual tracing of the endocardial surfaces of the LV in systole and diastole using the apical four-chamber and apical two-chamber window planes. However, it is not uncommon that endocardial surfaces are not clearly defined on the apical view. FS is considered a semi-quantitative method of evaluating LVF. It is quicker and easier to perform at the bedside than the ejection fraction. EPs performing ejection fraction measurements of hypotensive patients took an average of 17 minutes to do so in the study by Moore et al.⁹ In our study, 2 minutes was the maximum time needed to perform FS measurements using a single cardiac view. Visual

estimates of LVF were determined, using our scoring system, within several seconds. The FS calculation uses M-mode technology and involves the change in the internal diameter of the LV in a single cardiac view between diastole and systole. FS has its own normal range of values.

The overall mean FS measurements and LVF scores were similar at beginning and end of the fluid challenges. All 24 patients received fluid challenges, but only four patients received adrenergic agents, and that was only administered after the second stage (Time 1) of the study protocol. No patients were receiving adrenergic agents at the start of enrollment (Table 2). Although we observed minimal changes in LVF estimates during fluid challenges, future research should investigate monitoring of qualitative changes in LVF with various adrenergic interventions. EPs currently employ serial qualitative bedside assessments of the LVF during cardiac arrest resuscitations.²⁰ If visual estimates correlate with measurements, then LVF reevaluations could be readily repeated by the treating physician if indicated by changes in clinical status or after important interventions.

Multiple studies published in the cardiology literature agree that visual estimates of ejection fraction are, in some cases, superior to other more elaborate quantitative measures of LVF.^{21,22} Research has shown that a trained EP's estimation of LVF and CVP using bedside US in stable and hypotensive ED patients agrees with those of cardiologists, comprehensive echocardiograms, and invasive monitors.^{8,9}

With regards to inter-rater reliability, rating score differences of two or more were considered to be potentially clinically "significant" on either the four-point LVF scale or the three-point caval index scale. Disagreements, for example, between a LVF score as normal (3) and hyperdynamic (4) were considered unlikely to lead to major differences in clinical decision-making and were considered "not significant." It is the authors' opinion, however, that a scoring difference of two points could lead to clinical decision-making differences. For example, a disagreement between severely depressed and normal LVF could potentially alter concerns for cardiogenic shock, leading to different management decisions, and would be considered significant. A discordance of two points was reported in one of the 72 LVF comparisons. In this case, the LVF discordance was "hyperdynamic" versus "moderately depressed."

In summary, serial goal-directed echocardiography is often useful in the management of the critically ill, but repeating and tracking quantitative measurements can be time-consuming. We used a simple four-point LVF scale and a simple three-point caval index scale and found that visual estimates of LVF and caval index agreed with their measurements and were quicker to perform.

LIMITATIONS

Although we performed 72 IVC and 72 LVF evaluations, our subject sample size was small. Enrollment by convenience sampling method was limited to investigator availability because of the time-sensitive, labor-intensive

nature of the research protocol. Several critically ill patients offered technically difficult cardiac and IVC windows due to physical characteristics (obesity or postsurgical chest wall deformities) or severe pulmonary illness (such as chronic obstructive pulmonary disease) that created low quality image transmission. We did not report the number of patients who were excluded based on technical difficulty (poor windows) and cannot therefore report on its feasibility. Our enrollment criteria excluded patients suspected of having acute CHF. The strict inclusion and exclusion criteria limit generalization of our results.

There are other limitations to this study. Two EP investigators (AW and HT) enrolled all patients. AW enrolled 19 patients and HT enrolled five patients. Both are experienced emergency US faculty. Each investigator performed bedside scoring followed by measurements, potentially introducing bias. It is also possible that awareness of the clinical scenario could have influenced the bedside scoring by the EP. Each investigator, however, was given detailed didactic training on the strict criteria for evaluating, measuring, and scoring in a standard manner. The reviewer, an EP with completed emergency US fellowship training, was not privy to the clinical scenario or outcome of any of the subjects. Having only two investigators and one reviewer, all with significant emergency US experience, did limit the generalizability of the results to other EPs.

Another potential limitation of our study was the use of FS to evaluate LVF. FS is a two-dimensional evaluation of the LV chamber, which actually contracts in a more complex manner. FS may reflect global LV function, but may erroneously do so if segmental wall motion abnormalities exist where measurements were taken. However, use of M-mode technology was considered more readily available to physicians using goal-directed cardiac US than other methods of measuring LVF. Future research studies could examine the utility of the FS method in assessing LVF in ED patients. Diastolic function was not addressed.

This study does not attempt to address the clinical usefulness of caval index and LVF measurements for patients. Myocardial compliance, systolic function, and IVC size and dynamics may differ between healthy individuals and patients with similar illnesses and even within an individual from time to time. The change in these variables can become even more dramatic as a consequence of progression through stages in an undifferentiated hypotensive syndrome (e.g., sepsis) or in response to therapeutic interventions such as fluid resuscitation. The critically ill patient often has an evolving hemodynamic profile, and patients may have preexisting conditions that influence their baseline cardiac and IVC features.

The interpretation of echocardiographic findings may depend on the surrounding clinical information. A patient with pulmonary hypertension and acute gastroenteritis can become volume-depleted, yet have a dilated IVC (due to chronic right heart strain features) with normal left heart function. A hyperdynamic LV in another patient with a very collapsible IVC may suggest more aggressive fluid resuscitation and a low-

ering of the current inotropic medication dose. A finding of severely depressed LVF may suggest cardiogenic shock in some scenarios, and the advantages and disadvantages of using different adrenergic agents and fluid challenge may then become apparent to the clinician.

We showed that there was reproducibility, a key element in reliability, but we cannot state that the trend of caval index accurately addressed the volume status of the patient. This study was an observational study, and our patients had many permutations of comorbid conditions and hypotension etiologies. Also, they received different fluid challenges (volumes and rates). Future studies with a larger sample size and controlled interventions may better elucidate the role of serial assessments of caval index and LVF in the noninvasive monitoring of critically ill patients.

CONCLUSIONS

Early serial ultrasound monitoring of hypotensive ED patients during fluid challenges showed that estimations of caval index and left ventricular function correlated with contemporaneous measurements of caval index and fractional shortening. Significant inter-rater agreements were also demonstrated. We observed that fluid challenges were associated with reductions in subjects' initial normal/high caval index, while low caval indices persisted and were associated with heart dysfunction. Future studies that address intersubject and intrasubject variability in inferior vena cava and left ventricular function indices and their response to fluid loading or adrenergic agent use are indicated.

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