Bedside assessment of right atrial pressure in critically ill septic patients using tissue Doppler ultrasonography☆

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1. Background

Right atrial pressure (RAP) is considered a surrogate for right ventricular filling pressure or cardiac preload. It is commonly approximated by the central venous pressure (CVP) either invasively using a catheter placed in the superior vena cava or by bedside ultrasound, in which the size and respiratory variations of the inferior vena cava (IVC) are measured from the subcostal view. Doppler imaging of the tricuspid valve from the apical 4-chamber view has been proposed as an alternative approach for the estimation of RAP. The tricuspid E/Ea ratio is measured, where E is the peak velocity of the early diastolic tricuspid inflow and Ea is the peak velocity of the early diastolic relaxation of the lateral tricuspid annulus. We hypothesized that the tricuspid E/Ea ratio may represent an alternative to IVC metrics, using invasive CVP as the criterion standard, for the assessment of RAP in critically ill septic patients.

Materials and methods: A convenience sample of 30 septic patients, both mechanically ventilated and non–mechanically ventilated, was enrolled. Using a portable ultrasound system, maximum velocity of tricuspid E and Ea was measured from the apical 4-chamber view; and IVC diameter and degree of collapse were measured from the subcostal view. Decision tree induction was used to determine the performance of each model compared with invasive CVP.

Results: Our results suggest that a tricuspid E/Ea ratio of greater than 4.7 can predict a CVP greater than 10 mm Hg in septic patients with sensitivity greater than 85% and specificity greater than 90%.

Conclusions: In this pilot study, Doppler imaging of the tricuspid valve provided a valuable alternative for noninvasive bedside estimation of RAP in septic patients.
the early diastolic tricuspid inflow measured with pulse Doppler and Ea is the peak velocity of the early diastolic relaxation of the lateral tricuspid annulus measured using TDI. In early studies, this approach was shown to be accurate in both mechanically ventilated and non–mechanically ventilated patients [8,11].

The goal of this pilot study was to investigate whether bedside echocardiography using the tricuspid E/Ea ratio could be a viable alternative to IVC metrics for the assessment of RAP in critically ill septic patients using invasive CVP as the criterion standard.

2. Methodology

2.1. Inclusion criteria

A convenience sample of critically ill septic patients was enrolled, depending on physician availability. Inclusion criteria were the presence of severe sepsis or septic shock, and a preexisting internal jugular or subclavian vein central venous catheter available for CVP measurements. Sepsis was defined using the standard Surviving Sepsis Campaign criteria. Both mechanically ventilated and non–mechanically ventilated patients were included in the study. The institution’s internal review board approved the study (Stanford University Medical Center IRB number 18358). Written informed consent was obtained from all patients or their designated representatives for publication of this original research and any accompanying images.

2.2. Exclusion criteria

Patients with atrial dysrhythmias, atrioventricular block, ventricular-paced rhythm, prosthetic tricuspid valves, or severe tricuspid regurgitation were excluded from the study.

2.3. Data acquisition and evaluation

After careful calibration of the central venous catheter pressure transducer, end-expiratory CVP was recorded at the patient’s bedside at the time of the ultrasound examination. A portable ultrasound system (M-Turbo, SonoSite, Inc., Bothell, Wash) with a phased-array cardiac transducer was used for ultrasound examinations. A critical care medicine fellow (JEA) with training in goal-directed echocardiography obtained all ultrasound data. With the critical care medicine fellow, a cardiologist board-certified in echocardiography (ASB) and blinded to CVP recordings reviewed the quality of all ultrasound images, verified tissue Doppler and IVC measurements, and semiquantitatively assessed right and left ventricular function [7].

2.4. Measurements

Tricuspid E and Ea were measured from the apical 4-chamber view. The maximum velocity of the early tricuspid inflow (E) was measured using pulse Doppler with a 5-mm sample volume placed at the tips of the tricuspid valve during diastole (Fig. 1). The maximum velocity of the early tricuspid annulus relaxation (Ea) was measured using pulse TDI with a 3-mm sample placed on the lateral tricuspid annulus (Fig. 2). For all measurements, 5 to 10 cardiac cycles were recorded using a sweep speed of 100 mm/s. Final values for E and Ea were calculated by taking the average of all measures over 5 to 10 cardiac cycles, representing at least 1 respiratory cycle. The IVC diameter and respiratory collapsibility were measured 2 to 3 cm proximal to the atriocaval junction from the subcostal window.

2.5. Statistical analysis

We categorized the degree of IVC collapse as “none” (0%), “mild” (<50%), “moderate” (50–90%), or “complete” (100%). For the purpose of labeling the outcome of interest, we classified the CVP measurements as less than 10 mm Hg or at least 10 mm Hg.

To maximize the simplicity and interpretability of our model, we chose to generate a decision tree to classify CVP as either less than 10 mm Hg or at least 10 mm Hg. For comparison, we also created a decision tree based on IVC diameter and degree of collapse. The optimal cutoff values for IVC diameter and E/Ea were determined automatically during the process of decision tree induction, in which all possible cutoff values are evaluated sequentially and the value providing optimal separation of classes is selected.

To determine the performance of each of these models, we next ran each of the observations through each of the decision trees and

Fig. 1. E = maximum velocity of the early tricuspid inflow in centimeters per second.
compared the classification generated by the decision tree to the actual measured value. These comparisons were used to calculate the sensitivity, specificity, positive predictive value, negative predictive value, and accuracy of each of the 2 decision tree models.

We used a Bland-Altman plot to compare E/Ea ratio with IVC diameter as measures of estimating CVP. To generate a single measure incorporating both IVC diameter and IVC collapse, we multiplied IVC diameter by \((1 - \% \text{ collapse})\). This calculation modified the IVC diameter based on collapsibility, while maintaining the direction of the relationship between IVC and CVP so that they varied directly with one another. We generated estimates of CVP from both the E/Ea and combined IVC/collapse values by interpolating from linear models.

3. Results

Thirty-two patients were screened for the study. Two patients were excluded, one for severe tricuspid regurgitation and one for inadequate image quality of the apical 4-chamber view. A total of 33 examinations were performed on the remaining 30 patients. Patient characteristics are summarized in Table 1. Comorbidities were evenly distributed among mechanically ventilated and non–mechanically ventilated patients.

Semiquantitative echocardiographic analysis demonstrated 27% of patients (8 of 30) to have impaired left ventricular function. Thirteen percent of patients (4 of 30) demonstrated moderate to severe right ventricular dysfunction; 27% of patients (8 of 30) demonstrated mild right heart dysfunction.

The decision trees generated are shown in Fig. 3. The classification model based on the E/Ea ratio performed better than the model based on IVC diameter and collapse. Specifically, the E/Ea index predicted a CVP at least 10 with a sensitivity of 85% and a specificity of 90%, whereas IVC and collapse demonstrated a sensitivity and specificity of 46% and 90%, respectively. The E/Ea model also yielded superior positive predictive value, negative predictive value, and accuracy. These differences in performance measures are summarized in Table 2. The Bland-Altman plot is shown in Fig. 4. The plot showed

![Fig. 2. Ea = maximum velocity of the early tricuspid relaxation in centimeters per second.](image)

![Fig. 3. Decision trees for predicting CVP class using E/Ea ratio (top) or IVC diameter and collapse (bottom).](image)
good agreement between the IVC and E/Ea methods of estimating CVP, with no obvious bias.

4. Discussion

The results of our pilot study suggest that an elevated tricuspid E/Ea ratio may represent a new index to detect elevated CVP in critically ill septic patients. Specifically, our study demonstrated a tricuspid E/Ea ratio of greater than 4.7 to be predictive of an elevated CVP with a sensitivity of 85% and specificity of 90%.

Previous studies have demonstrated an elevated mitral E/Ea ratio to be a strong predictor of elevated left ventricular filling pressure [12–14]. Mitral E velocity reflected left ventricular filling pressures, and mitral annulus Ea velocity reflected left ventricular relaxation. Accounting for left ventricular relaxation decreased the effects of load variations in the estimation of left ventricular filling pressures.

Tricuspid E/Ea was subsequently investigated as a measure of right ventricular filling pressure that accounted for both transtricuspid driving pressure and right ventricular relaxation. In 1 study [8], a heterogeneous mix of patients (n = 62) either admitted to the intensive care unit and requiring central line placement, or undergoing right heart cardiac catheterization were examined. Using regression analysis, an E/Ea ratio of greater than 6 was found to have a sensitivity of 79% and a specificity of 73% for a mean RAP greater than 10 mm Hg. The measure was found to perform equally well in mechanically ventilated and non–mechanically ventilated patients, as well as patients with or without right ventricular dysfunction. A second study [11] enrolled a similarly diverse group of intensive care unit and postsurgical patients (n = 36 with surgery, n = 53 without surgery). Also using regression analysis, an E/Ea of greater than 4 was found to be 88% sensitive and 85% specific for a RAP of 10 mm Hg or greater. This correlation existed only for the nonsurgical group and remained accurate in both mechanically ventilated and non–mechanically ventilated patients.

The results of our study build on these findings and strongly suggest that the tricuspid E/Ea ratio may be considered a valuable predictor of CVP, equivalent or better than IVC metrics, in a patient sample that is more focused and homogenous (septic critically ill patients). Importantly, these findings were robust despite a mix of mechanically ventilated and non–mechanically ventilated patients, and in patients with and without right heart dysfunction.

Previous studies relied on a cardiologist trained in echocardiography using a full-range nonportable ultrasound device. In our study, a clinician operator with training in goal-directed echocardiography used a bedside echocardiography device for all image acquisition and measurement. Our results suggest the tricuspid E/Ea ratio to be a reliable and relatively easily obtained index, making it particularly useful in the acute care setting prior to the placement of invasive monitoring devices.

4.1. Limitations

Patients were enrolled in a nonconsecutive manner as limited by physician availability. This may have introduced an unaccounted-for

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<td>Test characteristics of both the E/Ea model and the IVC model for predicting CVP ≥ 10</td>
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bias. All measures were taken by a single operator but validated independently. Because a single operator was used and most patients underwent only 1 ultrasound evaluation, we could not assess inter-/ intraobserver variability. Finally, the sample size of this study was small, which limited our capacity to divide the patients into separate derivation and validation cohorts. Although the results are encouraging, future studies are needed to validate the decision rules derived herein. A larger study, with results trended over time, would be useful to confirm the findings of this pilot study.

5. Conclusion

Early management of sepsis is aided by a better understanding of a patient’s right ventricular filling pressure. Doppler imaging of the tricuspid inflow and anulus relaxation is an easily learned technique that provides a valuable noninvasive alternative for bedside estimation of RAP in critically ill septic patients in whom the IVC cannot be visualized.

5.1. Consent

Written informed consent was obtained from all patients or their designated representatives for publication of this original research and any accompanying images. A copy of the written consent is available for review by the Editor-in-Chief of this journal.

Acknowledgments

Each author significantly contributed to the manuscript. Dr Arbo performed all bedside echocardiography, Dr Beraud reviewed all echocardiography images, and Dr Maslove provided statistical analysis. All authors contributed to the drafting of the manuscript. All authors have read and approved the manuscript. Dr Arbo is the guarantor of the content of this manuscript.

References