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Diagnostic Accuracy of Dynamic Ultrasound Indices for Fluid Responsiveness Using Bioreactance as the Reference Method in Shock Patients

Pervin Hanci,[1] Volkan Inal[2]

Abstract

Aim: Predicting fluid responsiveness in patients with shock is critical. This study aimed to evaluate the diagnostic accuracy of dynamic ultrasound-derived indices in predicting fluid responsiveness, using bioreactance-based cardiac output monitoring as the reference standard.

Study Design: A total of 39 adult patients diagnosed with shock who were receiving mechanical ventilation were included. Hemodynamic parameters were assessed using ultrasound [left ventricular outflow velocity-time integral (LVOT-VTI), respirophasic variability of LVOT-VTI, corrected carotid flow time (cCFT), respirophasic variability of carotid artery peak flow velocity (ΔVpeak), and the inferior vena cava distensibility index (dIVC)] and pulse pressure variation (PPV) via invasive arterial monitoring. The bioreactance-derived stroke volume index change after passive leg elevation (ΔSVI ≥10%) served as the reference standard for fluid responsiveness.

Results: Fluid responsiveness was present in 53.8% of patients according to ΔSVI. LVOT-VTI variability (area under the curve [AUC] 0.847, 95% confidence interval [CI]: 0.726–0.968, sensitivity 85.0%, specificity 66.6%) and PPV (AUC 0.832, 95% CI: 0.679–0.985, sensitivity 94.4%, specificity 70.5%) demonstrated the highest predictive accuracy. Carotid flow variability showed moderate performance (AUC 0.754), while dIVC yielded the lowest diagnostic accuracy (AUC 0.676). A strong correlation was observed between bioreactance-derived cardiac index and LVOT-VTI (r=0.835, p<0.001), whereas cCFT was not significantly correlated.

Conclusions: Left ventricular outflow velocity-time integral variability demonstrated strong diagnostic accuracy in predicting fluid responsiveness in mechanically ventilated patients with shock when confirmed using bioreactance monitoring. IVC distensibility and carotid flow variability showed limited reliability.

Keywords: Bioreactance; Fluid responsiveness; Shock; Ultrasound.

[1]*Department of Pulmonology, Division of Intensive Care Medicine, Trakya University Faculty of Medicine, Edirne, Türkiye*
[2]*Department of Internal Medicine, Trakya University Faculty of Medicine, Edirne, Türkiye*

Address for correspondence:
Pervin Hanci, MD. Department of Pulmonology, Division of Intensive Care Medicine, Trakya University Faculty of Medicine, Edirne, Türkiye.
E-mail: pervinhanci@trakya.edu.tr

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Introduction

Hemodynamic instability is a common and rapidly changing condition that requires immediate intervention in critically ill patients experiencing shock. Effective and timely fluid resuscitation plays a pivotal role in restoring tissue perfusion and improving cardiac output (CO), both of which are essential for op-

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timizing patient outcomes in the intensive care setting.[1] However, the hemodynamic response to fluid loading can vary widely among patients. While some may experience a beneficial increase in cardiac output, others may not respond significantly, rendering fluid administration ineffective. In addition, unnecessary or excessive fluid administration carries significant risks, including pulmonary edema, tissue edema, intra-abdominal hypertension, and longer stays in the intensive care unit (ICU). Therefore, the ability to accurately predict fluid responsiveness is essential for optimizing patient management and minimizing iatrogenic complications.[2]

Invasive hemodynamic monitoring methods, such as pulmonary artery catheterization and transpulmonary thermodilution, have traditionally served as the gold standard for volume assessment. However, their complexity, risk of complications, and limited accessibility have led to growing interest in less invasive, bedside alternatives.[3] Among these, thoracic bioreactance and point-of-care ultrasound (POCUS) have emerged as two valuable techniques for evaluating fluid responsiveness in critically ill patients.[4]

Thoracic bioreactance, a refinement of bioimpedance technology, measures phase shifts in oscillating electrical currents as they traverse the thorax, thereby estimating cardiac output.[5,6] The clinically validated bioreactance monitor offers continuous, noninvasive measurement of key hemodynamic variables, including CO, stroke volume index (SVI), and total peripheral resistance (TPR). Notably, it allows for dynamic assessment of fluid responsiveness by calculating changes in SVI in response to the passive leg raising (PLR) maneuver, which simulates a reversible autotransfusion of approximately 300 mL of venous blood.[7-9]

Simultaneously, dynamic indices derived from bedside ultrasonography, particularly left ventricular outflow tract velocity-time integral (LVOT-VTI), corrected carotid flow time (cCFT), and inferior vena cava distensibility (IVCd), have shown considerable promise as reliable predictors of fluid responsiveness.[10-12]

In addition to baseline measurements, respirophasic variability in these ultrasound-derived indices has emerged as a valuable dynamic marker. Higher respiratory variability typically indicates fluid responsiveness, particularly when the threshold exceeds clinically validated cut-off values.[13] However, there are limited studies in the literature directly comparing the diagnostic accuracy of POCUS-based parameters with bioreactance-based monitoring.[14] In critical care settings where invasive methods are risky or impractical, such comparative analyses can facilitate clinical decision-making and improve patient safety. This study investigated the comparative diagnostic reliability of ultrasound-based dynamic indices and bioreactance measurements in determining fluid responsiveness in patients with shock.

Materials and Methods

Study Population

This observational study was conducted in the Respiratory Intensive Care Units at Trakya University Faculty of Medicine from March 2023 to April 2025. It included adult patients aged 18 to 90 years who were intubated, sedated, and mechanically ventilated with a tidal volume of at least 7 mL/kg of predicted body weight, using volume-controlled ventilation and a positive end-expiratory pressure (PEEP) of 5 cmH2O. All patients were under deep sedation with continuous intravenous infusion of midazolam and/or propofol, targeting a Richmond Agitation-Sedation Scale (RASS) score of -4 to -5. No neuromuscular blocking agents were administered. Spontaneous respiratory efforts were absent during measurements, as confirmed by clinical assessment and ventilator waveform monitoring. Patients had no arrhythmias and displayed signs of hypoperfusion, including hypotension, tachycardia, decreased skin turgor and tone, mottled skin, a capillary refill time exceeding 2 seconds, confusion, low urine output, or lactate levels above 2 mmol/L. All patients had been diagnosed with shock upon ICU admission. The definitions and standard treatment protocols for septic shock followed the guidelines of the 2016 European Society of Intensive Care Medicine and the Society of Critical Care Medicine.[15]

Patients with arrhythmias, significant valvular heart disease, poor acoustic windows, or contraindications to PLR (e.g., lower limb trauma or surgery, deep venous thrombosis, spinal or pelvic instability, intracranial hypertension) were excluded.

Hemodynamic Monitoring and Ultrasonographic Assessment

All hemodynamic and ultrasonographic measurements were conducted by a single experienced sonographer with expertise in critical care ultrasonography to minimize inter-observer variability, following a standardized sequence. These measurements were taken within

the first 24 hours of ICU admission, after hemodynamic stabilization with titration of vasoactive drugs and before fluid resuscitation. First, pulse pressure variation (PPV) was measured using an invasive arterial catheter connected to a bedside monitor [Mindray BeneView T8 monitor systems (Mindray©, Shenzhen Mindray Bio-Medical Electronics Co., Ltd., China)] with continuous waveform analysis. The monitor's software automatically calculated PPV as: $(PP_{max} - PP_{min}) / PP_{mean}$. Ultrasound-based assessments were performed next, using a Sonosite Edge II Portable Ultrasound System (FUJIFILM Sonosite Inc., Bothell, WA, USA) equipped with phased-array (1–5 MHz), linear (5–12 MHz), and curvilinear (2–5 MHz) transducers. Sequentially, the inferior vena cava (IVC) distensibility index (dIVC), LVOT-VTI and its respirophasic variability, cardiac index (CI), cCFT, and the respirophasic variability of carotid peak flow velocity (ΔV_{peak}) were measured using ultrasonography. All measurements were completed within 10–15 minutes.

dIVC: IVC measurements were obtained using a subxiphoid approach in the longitudinal plane with a phased-array transducer (2–5 MHz). The maximum (IVCmax) and minimum (IVCmin) diameters of the IVC during the respiratory cycle were measured approximately 2 cm caudal to the right atrium. The distensibility index was calculated using the following formula:

$$dIVC = [(IVC_{max} - IVC_{min}) / (IVC_{min})] \times 100$$

LVOT-VTI and LVOT-VTI respirophasic variability: LVOT-VTI was measured using pulsed-wave Doppler in the apical five-chamber view. The sample gate was placed just proximal to the aortic valve in the LVOT. Three consecutive respiratory cycles were recorded, and the average velocity–time integral (VTI) was calculated. Respiratory variation in LVOT-VTI was determined by identifying the maximum and minimum values over a full respiratory cycle. LVOT-VTI variability was calculated using the following formula:

$$\text{LVOT-VTI variability}\,(\%) = [(VTI_{max} - VTI_{min})] / [(VTI_{max} + VTI_{min}) / 2] \times 100$$

Cardiac index: Cardiac output was calculated as:

$$CO = VTI \times LVOT\ Area \times HR$$

where the LVOT area was derived from the LVOT diameter (D) measured in the parasternal long-axis view [LVOT Area = $\pi \times (D/2)^2$]. CI was then obtained by normalizing CO to the body surface area.

cCFT and ΔV_{peak}: The corrected carotid flow time was measured on the right common carotid artery using pulsed-wave Doppler, with the sample volume positioned in the mid-segment of the artery and the patient in a supine position. The raw carotid flow time (CFT) was obtained from the onset of the systolic upstroke to the dicrotic notch on the Doppler waveform. The cCFT was calculated using Wodey's formula:[16]

$$cCFT = CFT + 1.29 \times (HR - 60)$$

The maximum carotid flow velocities (V_{peak}) during inspiration and expiration were recorded, and the respiratory variation was expressed as:

$$\Delta V_{peak}\,(\%) = (Vpeaki_{nsp} - Vpeak_{exp}) / [(Vpeaki_{nsp} + Vpeak_{exp})/2] \times 100$$

After ultrasound-based measurements, the Starling™ bioreactance-based noninvasive cardiac output monitor (Cheetah Medical, USA) was used to obtain bioreactance-based hemodynamic measurements for comparison.

CI and ΔSVI with the bioreactance method: The Starling™ monitor was connected to the patient, and CI was measured using the bioreactance method. The patient started in a head-up, 45° semi-recumbent position for the PLR maneuver. Then, their legs were passively raised to 45° while the upper body was lowered to a horizontal supine position. SVI was recorded before and between 30 and 90 seconds after PLR, with the monitor's software calculating the percentage change in SVI (ΔSVI) as:

$$\Delta SVI\,(\%) = [(SVI_{post\text{-}PLR} - SVI_{baseline}) / SVI_{baseline}] \times 100$$

Data Collection

The patient's sex, age, Charlson Comorbidity score, Acute Physiology and Chronic Health Evaluation (APACHE II) score, and Sequential Organ Failure Assessment (SOFA) score at ICU admission were recorded. The dIVC, LVOT-VTI, CI, respirophasic variability of LVOT-VTI, cCFT, and ΔV_{peak} were measured using sonography and recorded, while PPV, CI, total peripheral resistance, and ΔSVI with PLR were measured and recorded using a bioreactance monitor. Shock types were determined by the primary physician based on clinical characteristics and bioreactance monitor results (CI, TPR). Fluid responsiveness was defined as ΔSVI ≥10%, following established hemodynamic criteria. ICU length of stay (LOS) and patient outcomes were also recorded.

Statistical Analysis

Categorical variables are presented as frequencies and proportions (n, %), whereas continuous variables are reported as median [25th–75th percentile]. Fisher's exact test was used for categorical data, but, and the Mann-Whitney U test was used for numerical variables. Cronbach's alpha reliability, specificity, sensitivity, and kappa measures of agreement were computed for dIVC, CF variability, LVOT-VTI variability, and PPV compared with ΔSVI, and for CI assessed by ultrasonography and cCFT compared with CI recorded by the bioreactance monitor. Cohen's kappa coefficient was calculated to evaluate the categorization agreement between the two distinct approaches. The degree of agreement among the methodologies was categorized and statistically assessed using kappa values. Internal consistency of the methods was assessed using Cronbach's Alpha coefficient. To evaluate their ability to determine volume responsiveness compared to ΔSVI, correlation analyses and receiver operating characteristic (ROC) curve area under the curve (AUC) analyses were performed for dIVC, CF variability, LVOT-VTI variability, and PPV. Two-tailed analyses were used, and 95% confidence intervals (CI) were calculated. A P-value of less than 0.05 was deemed statistically significant. Established cut-off values of dIVC (18%), ΔV_{peak} (12%), LVOT-VTI variability (20%), and PPV (12%) for evaluating fluid responsiveness were used. The method described by DeLong et al.[17] was used for comparison of the ROC curves. Data management and analyses were performed using the statistical software SPSS (IBM® SPSS® Statistics v25, IL, USA, 2017).

Ethical Aspects

The study was approved by Trakya University Non-Interventional Scientific Research Ethics Committee (Protocol Number: TÜTF-GOBAEK 2025/276, Approval Number: 12/14, Date: 07.07.2025). The study was conducted in compliance with the 2008 Declaration of Helsinki. In accordance with the clinic's regulatory protocols, patients or their legally authorized family members provided written informed consent at admission for the processing and publication of their medical records for scientific purposes.

Results

A total of 39 patients who met the inclusion criteria were enrolled in the study. The median age of the cohort was 70 years [60–77], and 51.3% (n=20) were male. The median APACHE II score at ICU admission was 29.5 [22.7–33.2], corresponding to a predicted mortality rate (APACHE PMR) of 67.2% [47.8–83.0]. The median SOFA score was 12 [11–13], indicating high baseline illness severity (Table 1).

Baseline hemodynamic characteristics obtained from invasive arterial monitoring revealed a median heart rate of 98 [74–116], a median mean arterial pressure of 70 [63–78], and a PPV of 13% [8%–17%]. Eighteen (51.4%) patients had a PPV value of 12 or above. Among ultrasound-derived parameters, CI measured via LVOT-VTI Doppler was 3.6 [2.6–4.1] L/min/m², and cCFT was 317.9 [278.5–358.6] ms. The median IVC distensibility index was 17% [12%–28%], LVOT-VTI variability was 23% [18%–26%], and carotid flow ΔV_{peak} was 14% [11%–21%]. Based on dIVC, 21 (53.8%) patients were classified as fluid responsive, while 20 (52.63%) were classified as responsive according to LVOT-VTI variability and ΔV_{peak};

Table 1. Patient characteristics, severity scores, hemodynamic measurements at the time of Intensive Care Unit admission, and outcomes

Characteristics	N=39
Age (years)	70 [60–77]
Gender, male*	20 (51.3)
Charlson Comorbidity Index	5 [3–7]
APACHE II	29.5 [22.7–33.2]
SOFA	12 [11–13]
IVC distensibility	17 [12–28]
CI (LVOT-VTI) (L/min/m²)	3.6 [2.6–4.1]
LVOT-VTI variability	23 [18–26]
cCFT (ms)	317.9 [278.5–358.6]
ΔV_{peak}	14 [11–21]
PPV	13 [8–17]
CI (bioreactance) (L/min/m²)	3.4 [2.5–4.1]
TPR (dyn·s/cm⁵)	984 [858–1216]
ΔSVI with PLR	11 [4–16]
Shock type*	
Distributive	26 (66.7)
Hypovolemic	9 (23.1)
Cardiogenic	2 (5.1)
Obstructive	2 (5.1)
ICU LOS	14 [7–26]
Hospital LOS	29 [7–45]
28-day mortality*	19 (48.7)

APACHE II: Acute Physiology and Chronic Health Evaluation; SOFA: Sequential Organ Failure Assessment; IVC: Inferior vena cava; CI: Cardiac index; LVOT-VTI: Left ventricular outflow tract velocity time integral; cCFT: Corrected carotid flow time; ΔVpeak: Carotid flow peak velocity respirophasic variability; PPV: Pulse pressure variation; TPR: Total peripheral resistance; ICU: Intensive care unit; LOS: Length of stay. Data expressed as median [25th-75th percentile]. *n (%).

and according to ΔV_{peak} alone, 18 (56.2%) patients. In the bioreactance-based measurements, CI was 3.4 L/min/m² [2.5–4.1], TPR was 984 dyn·s/cm⁵ [858–1216], and the PLR-induced ΔSVI was 11% [4–16]. The distribution of shock types, according to the monitor's measurements, was as follows: distributive shock in 26 patients (66.7%), hypovolemic shock in nine patients (23.1%), cardiogenic shock in two patients (5.1%), and obstructive shock in two patients (5.1%). Based on the bioreactance-derived ΔSVI with PLR, 53.8% (n=21) of patients were classified as volume responsive (Table 1).

A strong correlation was observed between CI measurements obtained using LVOT-VTI and those obtained using the monitor, with a Spearman's rank correlation coefficient of 0.835 (p<0.001). However, no significant correlation was found between CI measured by the monitor and cCFT, with a Spearman's rank correlation coefficient of 0.156 (p=0.395). The sensitivity and specificity values for predicting volume responsiveness were highest for PPV, with a sensitivity of 94.4% and a specificity of 70.5%. LVOT-VTI variability also demonstrated high sensitivity (85.0%) but slightly lower specificity (66.6%). Kappa measures of agreement were 0.538 for PPV and 0.463 for LVOT-VTI variability (p=0.01 and p=0.003, respectively). Cronbach's alpha indicated the highest internal consistency for PPV (0.728), followed by LVOT-VTI variability (0.656), ΔV_{peak} (0.568), and IVC distensibility (0.559) (Table 2). LVOT-VTI variability and PPV demonstrated the highest predictive ability for volume responsiveness, with AUC values of 0.847 (95% confidence interval [CI]: 0.726–0.968, p<0.001) and 0.832 (95% CI: 0.679–0.985, p=0.001), respectively. CF variability showed moderate correlation (r=0.36, p=0.03) with an AUC of 0.754 (95% CI: 0.587–0.921, p=0.01), while IVC distensibility demonstrated weaker correlation (r=0.21, p=0.20) with a lower AUC of 0.676 (95% CI: 0.495–0.857, p=0.06) (Table 3, Fig. 1). There was no difference in the pairwise comparisons of the ROC curves for PPV, LVOT-VTI variability, ΔV_{peak}, or dIVC in predicting fluid responsiveness (Supplementary Table 1). ICU mortality was 48.7% (n=19), and the standardized mortality ratio (SMR) was calculated as 72.4%. Median ICU LOS was 14 [7–26] days, and median hospital LOS was 29 [interquartile range [IQR]: 7–45] days.

Table 2. Specificity, sensitivity, agreement, and reliability of inferior vena cava distensibility, carotid flow variation, left ventricular outflow tract velocity-time integral variability, and pulse pressure variation in discriminating volume responsiveness compared to the stroke volume index change during passive leg raising

	Cut-off	Specificity	Sensitivity	Kappa measure of agreement	p	Cronbach's Alpha
IVC distensibility	18%	72.2	66.6	0.386	0.015	0.559
ΔV_{peak}	12%	78.5	61.1	0.385	0.02	0.568
LVOT-VTI variability	20%	66.6	85	0.463	0.003	0.656
PPV	12%	70.6	94.4	0.538	0.01	0.728

IVC: Inferior vena cava; ΔVpeak: Carotid flow peak velocity respirophasic variation; LVOT-VTI: Left ventricular outflow tract velocity time integral; PPV: Pulse pressure variation.

Table 3. Correlation and receiver operating characteristic–area under the curve (ROC-AUC) analysis of inferior vena cava distensibility, carotid flow variability, left ventricular outflow tract velocity–time integral (LVOT-VTI) variability, and pulse pressure variation for assessing volume responsiveness determined by stroke volume change during passive leg raising

	Correlation		ROC		
	r	p	AUC	95% CI	p
IVC distensibility	0.21	0.20	0.676	0.495–0.857	0.06
ΔVpeak	0.36	0.03	0.754	0.587–0.921	0.01
LVOT-VTI variability	0.46	0.003	0.847	0.726–0.968	<0.001
PPV	0.44	0.008	0.832	0.679–0.985	0.001

ROC-AUC: Receiver operating characteristic – area under the curve; IVC: Inferior vena cava; ΔVpeak: Carotid flow peak velocity respirophasic variation; LVOT-VTI: Left ventricular outflow tract velocity time integral; PPV: Pulse pressure variation.

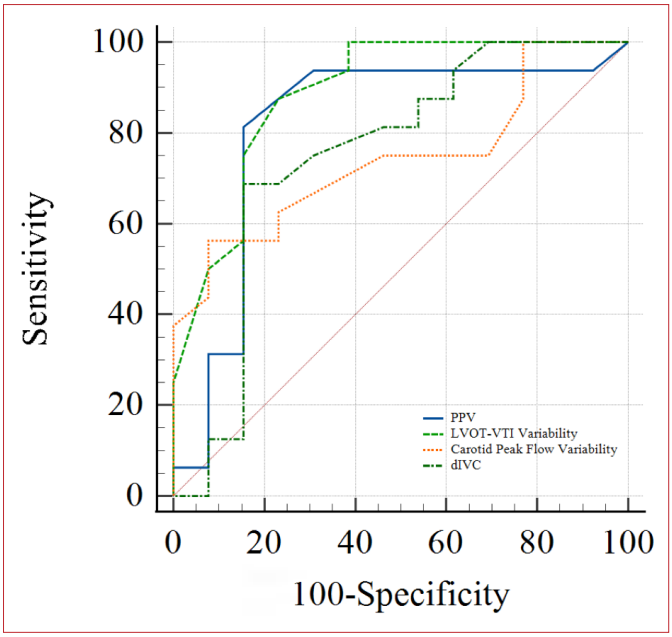

Figure 1. Receiver operating characteristic curve analysis for predicting fluid responsiveness.

Discussion

In this observational study, we investigated the comparative diagnostic performance of ultrasound-based dynamic indices for assessing fluid responsiveness in mechanically ventilated patients with shock, using bioreactance-based noninvasive CO monitoring measurements. Our findings indicate that LVOT-VTI respirophasic variability and PPV parameters exhibit high sensitivity, specificity, and predictive value compared to the ΔSVI reference standard obtained via PLR. LVOT-VTI variability demonstrated the highest accuracy among all ultrasound parameters in terms of AUC value (AUC=0.847), while PPV showed the highest sensitivity (94.4%). In contrast, the correlation coefficients and AUC values of dIVC and ΔV_{peak} measurements were lower in predicting fluid responsiveness compared to the bioreactance-based SVI change during PLR.

In intensive care practice, fluid therapy has long been based on "static" cardiac preload indices such as central venous pressure. However, static parameters (central venous pressure, pulmonary artery occlusion pressure, E/e' ratio on echocardiography, left ventricular end-diastolic surface/volume, or global end-diastolic volume) are insufficient for predicting the effectiveness of fluid loading.[18,19] The main reason for this is that the slope of the Frank–Starling curve varies from patient to patient, and the same preload level may lead to a responsive state in some patients but not in others. For this reason, "dynamic" approaches have come to the fore in fluid therapy decisions rather than static measurements. Dynamic indices and tests enable the determination of preload responsiveness by observing changes in stroke volume, cardiac output, or their surrogate parameters during controlled or spontaneous alterations in cardiac preload. As a result of the cardiopulmonary interactions of positive-pressure mechanical ventilation, changes in intrathoracic pressure cyclically affect ventricular filling and emptying conditions, leading to predictable stroke volume changes during inspiration and expiration in preload-sensitive patients. The superiority of this physiologically based dynamic approach over static methods has been conclusively demonstrated, and considering the potential side effects of fluid therapy, it is recommended that preload responsiveness be assessed using these methods prior to treatment.[20] Among dynamic indices, PPV reflects stroke volume variability by measuring the change in systolic–diastolic pressure difference throughout the respiratory cycle and is one of the parameters with the highest level of evidence for predicting fluid responsiveness in mechanically ventilated patients.[21,22] A cut-off value of 12% is generally accepted. In the absence of invasive arterial monitoring, the respiratory variation in LVOT-VTI measured by echocardiography can also be used to assess preload responsiveness.

The findings of our current study demonstrate that respiratory variation in LVOT-VTI and PPV have significant diagnostic value in predicting fluid responsiveness. These results partially align with data obtained by Xie et al.[23] in critically ill postoperative patients who were mechanically ventilated with low tidal volumes (<8 mL/kg). In the study by Xie et al.,[23] variation in LVOT-VTI showed the highest predictive value, with an AUC of 0.919, 78.1% sensitivity, and 96.4% specificity, while PPV demonstrated moderate accuracy with an AUC of 0.797. In our study, however, LVOT-VTI variability emerged as a key indicator, with an AUC of 0.847, 85% sensitivity, and 66.6% specificity. PPV achieved the highest sensitivity at 94.4%, with an AUC of 0.832. Correlation analyses revealed a moderate relationship between LVOT-VTI variability and bioreactance-based ΔSVI (r=0.46, p=0.003). In contrast, the correlation coefficient between PPV and ΔSVI was higher, indicating that PPV is a relatively stronger parameter for determining fluid responsiveness. In the study by Xie et al.,[23] a very

strong correlation (r=0.798, p<0.001) was reported between LVOT-VTI variation and stroke volume change after PLR, along with a high correlation (r=0.704, p<0.001) with PPV. This discrepancy may arise from differences in patient populations and ventilation parameters, as well as methodological differences in reference measures. In our study, bioreactance-based ΔSVI was used as the reference standard, relying on technology that eliminates operator dependence and provides continuous, objective measurements. Conversely, Xie et al.'s study[23] defined fluid responsiveness based on stroke volume changes measured via transthoracic echocardiography, a method that is highly dependent on the sonographer's experience and image quality. Therefore, the use of a more objective and reproducible reference method in our study may have contributed to findings that were less susceptible to measurement bias. Feissel et al.[24] investigated ΔV_{peak} measured with transesophageal echocardiography as a predictor of fluid responsiveness in septic shock patients, using fluid bolus administration as the reference method and defining responsiveness by an increase in CI after volume expansion. They reported that a 12% ΔV_{peak} threshold yielded 100% sensitivity and 89% specificity, with a very strong linear correlation between baseline ΔV_{peak} and fluid-induced CI change (r^2=0.83; p<0.001). The superior performance observed in Feissel et al.'s study[24] may be attributed to differences in the measurement techniques used (transthoracic versus transesophageal echocardiography), reference standards (fluid bolus versus PLR), and variations in patient characteristics and technical factors. Nevertheless, across studies, dynamic indices based on respiratory variations in LVOT or large-vessel blood flow velocities consistently emerge as strong and clinically applicable predictors of fluid responsiveness in appropriately selected patients.

Although LVOT-VTI variation measured by transthoracic or transesophageal echocardiography is highly reliable for determining fluid responsiveness, it requires high-quality images from specific windows, and the process is highly operator-dependent because it demands advanced echocardiographic expertise.[25] Especially in emergency and intensive care settings, the patient's position, lung pathology, or chest wall anatomy can negatively affect image quality. In contrast, measurements based on carotid artery ultrasound (cCFT and ΔV_{peak}) are easier to learn, can be performed quickly via neck access, and are relatively less operator-dependent. Although these methods do not provide as much central hemodynamic information as LVOT-VTI, they stand out as noninvasive and practical alternatives when LVOT-VTI measurement is impractical. Thus, they can contribute to the rapid and repeatable assessment of fluid responsiveness in critically ill patients. The meta-analysis by Singla et al.[11] evaluated the clinical value of several predictive parameters in patients undergoing elective surgery with general anesthesia and mechanical ventilation. The analysis included 10 studies that examined the predictive power of cCFT and ΔV_{peak} parameters for fluid responsiveness. The overall sensitivity for cCFT was 75.8%, while the overall specificity was 88.3%, indicating moderate to low heterogeneity. The summary ROC curve demonstrated an AUC of 0.909, with a Q value of 0.841. For ΔV_{peak}, heterogeneity ranged from absent to moderate, yielding a pooled sensitivity of 82.8% and a pooled specificity of 80.5% (95% CI: 73.6%–86.4%). In our study, the correlation coefficients and AUC values for ΔV_{peak} were lower compared to bioreactance-based changes in SVI. This may be related to differences within the patient population, the reference methods used, and the impact of technical factors on the results. Various technical errors that could affect the reliability of carotid Doppler-based measurements may be present, including minor changes in the insonation angle of the ultrasound probe, causing disproportionate errors in velocity measurement; variability in vessel diameter depending on the cardiac cycle or respiratory phase; probe pressure partially compressing the arterial lumen and affecting flow velocity; and other anatomical structures interfering with image quality during measurement.[26] The fact that our study was conducted in intensive care conditions, on hemodynamically unstable patients with limited mobility, may have accentuated the effects of these technical limitations. Therefore, the relatively low correlation and AUC values obtained should be viewed as reflecting the combined influence of both the patient population and technical factors.

Inferior vena cava ultrasonography is one of the most widely used and applied methods for estimating fluid responsiveness. As intrathoracic pressure fluctuates throughout the respiratory cycle, a cyclical change in venous return occurs, resulting in changes in IVC diameter.[27] Respirophasic changes in IVC diameter have been studied in both mechanically ventilated and spontaneously breathing patients. Because the minimum and maximum values of intrathoracic pressure during spontaneous breathing and mechanical ventilation differ

across the respiratory cycle, the use of the IVC collapsibility index is necessary in spontaneously breathing patients,[28] whereas the distensibility index is necessary under mechanical ventilation.[27] However, this variability can be influenced by many factors in both spontaneously breathing and mechanically ventilated patients and can be misleading when estimating fluid responsiveness.[29] Factors that decrease venous return (tricuspid insufficiency, tamponade, pulmonary hypertension, etc.) or increase intra-abdominal pressure affect IVC size regardless of fluid status.[30,31] In addition, variations in inspiratory effort in spontaneously breathing patients affect measurement accuracy.[32] While better diagnostic performance is generally observed in mechanically ventilated patients without spontaneous breathing,[33,34] settings such as high PEEP[35,36] and low tidal volume may affect variability.[37] Many meta-analyses have yielded different results regarding the diagnostic performance of the dIVC index in predicting fluid responsiveness.[12,33,34,37] However, these studies agree on the heterogeneity of the patient populations examined, which may explain the conflicting results. In a recent meta-analysis of 15 studies evaluating the diagnostic performance of the dIVC index for assessing fluid responsiveness in sepsis patients, the sensitivity and specificity of dIVC were reported as 0.79 (95% CI: 0.68–0.86) and 0.82 (95% CI: 0.73–0.89), respectively; the diagnostic odds ratio was 17.1 (8.1–36.0), and the AUC was 0.88 (95% CI: 0.84–0.90).[38] In our study, the correlation of dIVC with the reference method was weak, and its diagnostic performance was lower than that reported in other studies. In our study, measurements were taken while patients without spontaneous breathing were ventilated with an invasive mechanical ventilator, a tidal volume of 7 mL/kg or higher, and a fixed PEEP value. Although the cause of shock was mostly sepsis, other shock types were also included, which may explain the differences in our results.

This study has several limitations that should be acknowledged. First, the relatively small sample size from a single center limits the generalizability of the findings to broader critically ill populations. Second, the study population included patients with different shock etiologies, which may have introduced heterogeneity in hemodynamic responses. This clinical diversity could influence the diagnostic performance of dynamic ultrasound indices and potentially limit the generalizability of our findings to more homogeneous patient groups.

Third, although a single experienced operator performed ultrasonographic measurements to minimize inter-observer variability, this design prevents the evaluation of reproducibility and inter-operator reliability. Fourth, the inclusion criteria were limited to patients under controlled mechanical ventilation without spontaneous breathing and with fixed ventilatory settings (tidal volume ≥7 mL/kg, fixed PEEP), which restricts the applicability of the results to spontaneously breathing patients or those managed with protective ventilation strategies. Lastly, although bioreactance-based ΔSVI with PLR was chosen as the reference standard because of its noninvasive and reproducible nature, it is important to emphasize that it is not an absolute gold standard compared with invasive methods such as transpulmonary thermodilution, especially in cases of severe shock with poor peripheral perfusion. Under such conditions, its reliability may be compromised. In addition, two patients with obstructive shock in our cohort demonstrated echocardiographic signs of right ventricular pressure overload, including septal flattening and elevated pulmonary artery pressure. As right ventricular dysfunction may impair the transmission of preload changes to the left heart, the accuracy of PPV in these specific cases may have been affected, representing a physiological limitation worth noting.

In conclusion, this study demonstrates that the dynamic ultrasound-derived indices LVOT-VTI variability and PPV provide significant diagnostic value in predicting fluid responsiveness in mechanically ventilated patients with shock. Although dIVC and carotid flow variability showed weaker correlations with bioreactance-derived ΔSVI in our study, they can still serve as complementary tools when optimal echocardiographic windows or invasive monitoring are not available. Together, our findings suggest that physiologically based dynamic indices may serve as practical alternatives to invasive monitoring in predicting fluid responsiveness. However, these results should be interpreted as exploratory and primarily hypothesis-generating. Larger, multicenter studies in more homogeneous populations are warranted to validate these preliminary observations and enhance clinical applicability. Additionally, future studies might incorporate alternative methods, such as the mini fluid challenge, alongside PLR when using bioreactance-based monitoring, which may further improve diagnostic performance and generalizability.

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References

1. Michard F, Teboul JL. Predicting fluid responsiveness in ICU patients: a critical analysis of the evidence. Chest 2002;121(6):2000-8. [CrossRef]
2. Malbrain ML, Marik PE, Witters I, et al. Fluid overload, de-resuscitation, and outcomes in critically ill or injured patients: a systematic review with suggestions for clinical practice. Anaesthesiol Intensive Ther 2014;46(5):361-80. [CrossRef]
3. Marik PE, Cavallazzi R, Vasu T, Hirani A. Dynamic changes in arterial waveform derived variables and fluid responsiveness in mechanically ventilated patients: a systematic review of the literature. Crit Care Med 2009;37(9):2642-7. [CrossRef]
4. Barjaktarevic I, Toppen WE, Hu S, et al. Ultrasound Assessment of the Change in Carotid Corrected Flow Time in Fluid Responsiveness in Undifferentiated Shock. Crit Care Med 2018;46(11):e1040-6. [CrossRef]
5. Keren H, Burkhoff D, Squara P. Evaluation of a noninvasive continuous cardiac output monitoring system based on thoracic bioreactance. Am J Physiol Heart Circ Physiol 2007;293(1):H583-9. [CrossRef]
6. Fagnoul D, Vincent JL, Backer de D. Cardiac output measurements using the bioreactance technique in critically ill patients. Crit Care 2012;16(6):460. [CrossRef]
7. Monnet X, Rienzo M, Osman D, et al. Passive leg raising predicts fluid responsiveness in the critically ill. Crit Care Med 2006;34(5):1402-7. [CrossRef]
8. Chopra S, Thompson J, Shahangian S, et al. Precision and consistency of the passive leg raising maneuver for determining fluid responsiveness with bioreactance non-invasive cardiac output monitoring in critically ill patients and healthy volunteers. PLoS One 2019;14(9):e0222956. [CrossRef]
9. Hu C TH, Cai G, Teboul J, et al. Bioreactance-based passive leg raising test can predict fluid responsiveness in patients with sepsis. Crit Care 2015;19:P177. [CrossRef]
10. Schmidt S, Dieks JK, Quintel M, Moerer O. Hemodynamic profiling by critical care echocardiography could be more accurate than invasive techniques and help identify targets for treatment. Sci Rep 2022;12(1):7187. [CrossRef]
11. Singla D, Gupta B, Varshney P, Mangla M, Walikar BN, Jamir T. Role of carotid corrected flow time and peak velocity variation in predicting fluid responsiveness: a systematic review and meta-analysis. Korean J Anesthesiol 2023;76(3):183-93. [CrossRef]
12. Orso D, Paoli I, Piani T, Cilenti FL, Cristiani L, Guglielmo N. Accuracy of Ultrasonographic Measurements of Inferior Vena Cava to Determine Fluid Responsiveness: A Systematic Review and Meta-Analysis. J Intensive Care Med 2020;35(4):354-63. [CrossRef]
13. Monnet X, Teboul JL. Assessment of volume responsiveness during mechanical ventilation: recent advances. Crit Care 2013;17(2):217. [CrossRef]
14. Marik PE, Levitov A, Young A, Andrews L. The use of bioreactance and carotid Doppler to determine volume responsiveness and blood flow redistribution following passive leg raising in hemodynamically unstable patients. Chest 2013;143(2):364-70. [CrossRef]
15. Rhodes A, Evans LE, Alhazzani W, et al. Surviving Sepsis Campaign: International Guidelines for Management of Sepsis and Septic Shock: 2016. Intensive Care Med 2017;43(3):304-77. [CrossRef]
16. Wodey E, Carre F, Beneux X, Schaffuser A, Ecoffey C. Limits of corrected flow time to monitor hemodynamic status in children. J Clin Monit Comput 2000;16(3):223-8. [CrossRef]
17. DeLong ER, DeLong DM, Clarke-Pearson DL. Comparing the areas under two or more correlated receiver operating characteristic curves: a nonparametric approach. Biometrics 1988;44(3):837-45. [CrossRef]
18. Bentzer P, Griesdale DE, Boyd J, MacLean K, Sirounis D, Ayas NT. Will This Hemodynamically Unstable Patient Respond to a Bolus of Intravenous Fluids? JAMA 2016;316(12):1298-309. [CrossRef]
19. Marik PE, Cavallazzi R. Does the central venous pressure predict fluid responsiveness? An updated meta-analysis and a plea for some common sense. Crit Care Med 2013;41(7):1774-81. [CrossRef]
20. Monnet X, Marik PE, Teboul JL. Prediction of fluid responsiveness: an update. Ann Intensive Care 2016;6(1):111. [CrossRef]
21. Teboul JL, Monnet X, Chemla D, Michard F. Arterial Pulse Pressure Variation with Mechanical Ventilation. Am J Respir Crit Care Med 2019;199(1):22-31. [CrossRef]
22. Michard F, Boussat S, Chemla D, et al. Relation between respiratory changes in arterial pulse pressure and fluid responsiveness in septic patients with acute circulatory failure. Am J Respir Crit Care Med 2000;162(1):134-8. [CrossRef]
23. Xie J, Wan J, Xu L, Zhang Y, Chen J. The Accuracy of Velocity-Time Integral Variation and Peak Velocity Variation of the Left Ventricular Outflow Tract in Predicting Fluid Responsiveness in Postoperative Patients Mechanically Ventilated at Low Tidal Volumes. J Cardiothorac Vasc Anesth 2023;37(6):911-8. [CrossRef]
24. Feissel M, Michard F, Mangin I, Ruyer O, Faller JP, Teboul JL. Re-

spiratory changes in aortic blood velocity as an indicator of fluid responsiveness in ventilated patients with septic shock. Chest 2001;119(3):867-73. [CrossRef]

25. Desai N, Garry D. Assessing dynamic fluid-responsiveness using transthoracic echocardiography in intensive care. BJA Educ 2018;18(7):218-26. [CrossRef]
26. Kenny JS. The left ventricular outflow tract and carotid artery velocity time integrals. Front Med Technol 2024;6:1320810. [CrossRef]
27. Barbier C, Loubières Y, Schmit C, et al. Respiratory changes in inferior vena cava diameter are helpful in predicting fluid responsiveness in ventilated septic patients. Intensive Care Med 2004;30(9):1740-6. [CrossRef]
28. Airapetian N, Maizel J, Alyamani O, et al. Does inferior vena cava respiratory variability predict fluid responsiveness in spontaneously breathing patients? Crit Care 2015;19:400. [CrossRef]
29. Via G, Tavazzi G, Price S. Ten situations where inferior vena cava ultrasound may fail to accurately predict fluid responsiveness: a physiologically based point of view. Intensive Care Med 2016;42(7):1164-7. [CrossRef]
30. Mandelbaum A, Ritz E. Vena cava diameter measurement for estimation of dry weight in haemodialysis patients. Nephrol Dial Transplant 1996;11 Suppl 2:24-7. [CrossRef]
31. Cavaliere F, Cina A, Biasucci D, et al. Sonographic assessment of abdominal vein dimensional and hemodynamic changes induced in human volunteers by a model of abdominal hypertension. Crit Care Med 2011;39(2):344-8. [CrossRef]
32. Gignon L, Roger C, Bastide S, et al. Influence of Diaphragmatic Motion on Inferior Vena Cava Diameter Respiratory Variations in Healthy Volunteers. Anesthesiology 2016;124(6):1338-46. [CrossRef]
33. Zhang Z, Xu X, Ye S, Xu L. Ultrasonographic measurement of the respiratory variation in the inferior vena cava diameter is predictive of fluid responsiveness in critically ill patients: systematic review and meta-analysis. Ultrasound Med Biol 2014;40(5):845-53. [CrossRef]
34. Long E, Oakley E, Duke T, Babl FE; Paediatric Research in Emergency Departments International Collaborative (PREDICT). Does Respiratory Variation in Inferior Vena Cava Diameter Predict Fluid Responsiveness: A Systematic Review and Meta-Analysis. Shock 2017;47(5):550-9. [CrossRef]
35. Charbonneau H, Riu B, Faron M, et al. Predicting preload responsiveness using simultaneous recordings of inferior and superior vena cavae diameters. Crit Care 2014;18(5):473. [CrossRef]
36. Jellinek H, Krenn H, Oczenski W, Veit F, Schwarz S, Fitzgerald RD. Influence of positive airway pressure on the pressure gradient for venous return in humans. J Appl Physiol (1985) 2000;88(3):926-32. [CrossRef]
37. Si X, Xu H, Liu Z, et al. Does Respiratory Variation in Inferior Vena Cava Diameter Predict Fluid Responsiveness in Mechanically Ventilated Patients? A Systematic Review and Meta-analysis. Anesth Analg 2018;127(5):1157-64. [CrossRef]
38. Zhang H, Jiang J, Dai M, Liang Y, Li N, Gao Y. Predictive accuracy of changes in the inferior vena cava diameter for predicting fluid responsiveness in patients with sepsis: A systematic review and meta-analysis. PLoS One 2025;20(5):e0310462. [CrossRef]

Supplementary Table 1. Pairwise comparison of receiver operating characteristic (ROC) curves

Comparison	Difference	Standard Error	95% CI	z statistic	p
PPV ~ LVOT_VTI_variability	0.0721	0.0996	-0.123-0.267	0.724	0.4692
PPV ~ ΔVpeak	0.0721	0.121	-0.165-0.309	0.597	0.5503
PPV ~ dIVC	0.0649	0.125	-0.180-0.309	0.52	0.6027
LVOT_VTI_variability ~ΔVpeak	0.144	0.0823	-0.017-0.306	1.752	0.0797
LVOT_VTI_variability ~ dIVC	0.137	0.109	-0.075-0.35	1.262	0.207
ΔVpeak ~ dIVC	0.00721	0.12	-0.227-0.242	0.0602	0.952

PPV ~ LVOT_VTI: Pulse pressure variation, LVOT-VTI: Left ventricular outflow velocity-time integral, ΔVpeak: Respirophasic variability of carotid artery peak flow velocity, dIVC: Inferior vena cava distensibility index.