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Ultrasound assessment of the change in Carotid Corrected Flow Time in Fluid Responsiveness in Undifferentiated Shock

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Abstract

Objective: Adequate assessment of fluid responsiveness in shock necessitates correct interpretation of hemodynamic changes induced by preload challenge. This study evaluates the accuracy of point-of-care Doppler ultrasound assessment of the change in carotid corrected flow time (ccFT) induced by a passive leg raise (PLR) maneuver as a predictor of fluid responsiveness. Noninvasive cardiac output monitoring (NICOM™) was the comparison standard.

Design: Prospective, non-interventional study.

Setting: Intensive care unit at a large academic center

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Authorship: IB has initiated the project as an investigator-initiated study and made substantial contributions to the conception or design of the work, the acquisition, analysis, or interpretation of data for the work. WT has made a substantial contribution to patient enrollment, data collection, management, analysis and write-up of the manuscript. MC has significantly contributed in manuscript preparation and data analysis. DM and SH have contributed significantly in data management and analysis. EAM and SO have participated in the recruitment, data collection and processing and have coordinated the study performance. SC, TW, RB and IJD have participated in the design of the study, patient recruitment and testing and preparation of the manuscript. DB and TR have participated in the design of the study and helped in the preparation of the manuscript. DE participated in statistical analysis.

Conflicts of interest

The remaining authors have disclosed that they have no relevant financial conflicts of interest.

Patients: Patients with new, undifferentiated shock and vasopressor requirements despite fluid resuscitation were included. Patients with significant cardiac disease and conditions that precluded adequate passive leg raising were excluded.

Intervention: ccFT was measured via ultrasound before and after a PLR maneuver. Predicted fluid responsiveness was defined as >10% increase in stroke volume on NICOM™ following PLR. Images and measurements were reanalyzed by a second, blinded physician. The accuracy of ΔccFT to predict fluid responsiveness was evaluated using ROC analysis.

Results: Seventy-seven subjects were enrolled with 54 (70.1%) classified as fluid responders by NICOM™. The average ΔccFT after PLR for fluid responders was 14.1 ± 18.7 msec vs. −4.0 ± 8 msec for non-responders (P<0.001). ROC analysis demonstrated that ΔccFT is an accurate predictor of fluid responsiveness status (AUC 0.88, 95% CI 0.80–0.96) and a 7 msec increase in ccFT post PLR was shown to have a 97% positive predictive value and 82% accuracy in detecting fluid responsiveness using NICOM™ as a reference standard. Mechanical ventilation, respiratory rate, and high PEEP had no significant impact on test performance. *Post-hoc* blinded evaluation of bedside acquired measurements demonstrated agreement between evaluators.

Conclusions: ΔccFT can predict fluid responsiveness status after a PLR maneuver. Using point-of-care ultrasound to assess ΔccFT is an acceptable and reproducible method for non-invasive identification of fluid responsiveness in critically ill patients with undifferentiated shock.

Keywords

Fluid responsiveness; corrected flow time; ultrasound; shock

Introduction:

Fluid responsiveness assessment is defined as an increase in cardiac output (CO) in response to preload augmentation, and is used in resuscitation from shock [1, 2]. Temporary intravascular fluid shift maneuvers such as the passive leg raise (PLR) test [3] transiently increase venous return, thus enabling the assessment of CO change with an intervention that mimics fluid administration. Unfortunately, CO monitoring technology is expensive, not widely available, and imprecise. New technologies to assess the hemodynamic response to PLR are needed.

Flow time (FT), or left ventricular ejection time, reflects the duration of systole, and is measured from the beginning of the upstroke to the trough of the incisural notch on a pulse waveform analysis [4]. Corrected for the heart rate variability, it is called *corrected* FT and the change in its duration may reflect changes in stroke volume. Point-of-care ultrasound is noninvasive and increasingly available in critical care settings [5, 6], and the assessment of corrected FT via Doppler ultrasound [7–9] is a safe and simple method which does not require extensive ultrasonographic expertise by the operator.

In this study, we hypothesize that the change in carotid corrected FT (ΔccFT) induced by a PLR maneuver may predict fluid-responsive status in early, undifferentiated shock. The non-invasive bioreactance CO monitoring (NICOM™, Cheetah Medical, Newton Center, MA) system was used as the reference standard as it has been validated in the assessment of fluid responsiveness in combination with PLR [10–14].

Materials and Methods:

This prospective, non-interventional study was conducted in a single academic quaternary care center. Adult patients with early (<24 hours duration), undifferentiated shock, who were admitted to a medical or surgical intensive care unit with persistent vasopressor requirements despite pre-enrollment fluid resuscitation of >1 liter of IV fluids were enrolled after informed consent. Patients were excluded if they presented with a history of left or right heart failure, pulmonary hypertension, cardiac rhythm other than sinus, significant peripheral vascular disease, suspected or known increased intracranial pressure, recent abdominal surgery, recent history of venous thromboembolism, and body-mass-index (BMI) <15 or >40 kg/m^2. Enrollment period was from May 2016 to April 2017. Approval for this study was granted by the University of California, Los Angeles Institutional Review Board (IRB#15–001768).

Fluid responsiveness assessment:

Measurements of ccFT were made at an increment of a tenth of a milliseconds (msec) and were obtained analyzing Doppler images of common carotid artery pulse waveforms (LOGIQ e, GE Healthcare, Wauwatosa, WI) by a trained physician sonographer (Figure 1). A linear array probe was used to obtain and record Doppler images of the vessel in long-axis view. Patients were evaluated using Ultrasound and NICOM™ simultaneously. Measures we obtained at baseline (prior to PLR, with the patient in a semi-recumbent position with 45° head of bed elevation for at least 10 minutes), and during the PLR maneuver performed using NICOM™ manufacturer's protocol (patient in supine position for three minutes with legs passively supported by an inflated wedge at 45° elevation, Supplemental Figure 1). ccFT measurements were captured after 120 seconds of the PLR maneuver. Fluid-responsive status was defined as ≥10% increase in SV via NICOM™ [15]. Systolic and cycle times were analyzed by the bedside operator's interpretation of ultrasound-captured images and ccFT values were calculated using Wodey's formula, $FT_{corrected} = FT_{measured} + 1.29(HR - 60)$, which has been shown to better correct for fast heart rates in comparison to widely used Bazett's formula ($FT_{corrected} = \frac{FT_{measrured}}{\sqrt{RR \quad interval}}$) [16, 17]. A second, blinded investigator reevaluated unprocessed bedside images to avoid treatment bias and assessinter-user variability.

Statistical Methods:

The NICOM™ and carotid Doppler measures were compared by response status using the two-sample t-test. The accuracy of ΔccFT as a predictor of fluid responsive status was assessed using ROC analysis. The best threshold of ΔccFT to detect fluid responsiveness was chosen to maximize the sensitivity for a target specificity of at least 96%. The accuracy of ΔccFT as a predictor of fluid response status was evaluated by the following potential covariates: mechanical ventilation, passive breathing on mechanical ventilation, and positive end-expiratory pressure (PEEP) > 5 among the mechanically ventilated subset of subjects.

The AUCs were compared by level of each specified covariate [18]. The agreement between the bedside and blinded ccFT measures was evaluated using the Bland-Altman plot, a plot of the differences vs. the means. Accuracy was calculated as an average value of specificity and sensitivity of the test. P values < 0.05 were considered statistically significant. Data are presented as mean +/− SD or median [IQR].

Results:

79 patients were enrolled in the study. Two of the enrolled patients (2.5%) developed complications during PLR and did not complete the protocol. One of this pair developed atrial fibrillation, and the other had a significant decrease in the oxygen saturation of hemoglobin as measured by pulse oximetry (Supplemental Figure 2). Baseline characteristics of the 77 patients who completed the full PLR protocol are displayed in Table 1. These patients were grouped according to their stroke volume response to a PLR as measured by NICOM. “Fluid responders” included patients that had a stroke volume increase ≥10% by NICOM after a PLR. “Non-responders” included patients demonstrating a stroke volume increase <10% by NICOM after a PLR. The majority of the patients (70.1%) were designated as fluid responsive based on these criteria.

Fluid responsive patients had a greater increase in ccFT after PLR than non-responsive patients [14.1 ± 19 (SD) vs −4.0 ± 8 msec, p<0.001, Table 2]. The percentage increase from baseline in ccFT was also higher among responders than non-responders [+4.8 ± (SD) 6.4 vs −1.4 ± 2.9%, p<0.001]. Dot-plot analysis presented in Figure 2 demonstrates the differences in ΔccFT between NICOM-defined fluid responders and non-responders. Receiver operating characteristic curve analysis for ΔccFT ability to predict fluid responsiveness is presented in Figure 3, and we show that using a cut-off value of 7 msec as a ΔccFT to define fluid responsiveness had a specificity of 96%, sensitivity of 68%, positive predictive value of 97% and 82% accuracy. Additional sub-group analyses found that mechanical ventilation, respiratory rate, and positive-end-expiratory pressure (PEEP) >5cmH_2O had no significant impact on the test performance (Supplemental Table 1). Blinded vs. bedside-obtained results were compared via Bland-Altman plot showing a mean difference score of 0 at baseline (non-significant, 95% limits of agreement were –6.7 and +6.6) and a mean difference score of −0.2 (non-significant, 95% limits of agreement were −6.6 and +6.4) after PLR, showing good agreement between investigators (Supplemental Figure 3).

Discussion:

The results suggest that ΔccFT induced by a PLR maneuver can determine fluid responsiveness in a selected population of patients with early undifferentiated shock. The area under the receiver operator curve suggests that ΔccFT can be used in place of the reference method, which was a 10% increase in stroke volume measured by NICOM. A cutoff of a 7 msec increase in ΔccFT gave excellent positive predictive value and accuracy. Moreover, the PLR protocol was well tolerated and able to be completed in 97.5% of patients.

There is no consensus about the best way to predict fluid responsiveness [19]. In contrast to other novel hemodynamic monitoring systems, point-of-care ultrasound is widely present in ICU settings [20], and the number of indications for its use continue to grow [21]. Ultrasonographic measures such as respiratory change in inferior vena cava diameter [22], respiratory change in peak aortic velocity [23], or change in echocardiography-measured end-diastolic area of left ventricle [24] have been used for hemodynamic evaluation of a patient in shock [25]. The use of ultrasound to measure Doppler velocity time integral (VTI) of large arteries following PLR maneuver can predict fluid responsiveness assessment [26–28], although variability in the angle of insonation between measurements limits its precision [29].

Despite conflicting data from earlier studies [15, 30, 31], there is an increasing body of published evidence showing the usefulness of corrected flow time evaluation in fluid management [32–38]. However, there are a number of limitations of using the absolute value of corrected flow time. First, it is not a simple metric of preload but also depends on heart rate, inotropy and afterload conditions [4, 39, 40]. Second, its absolute duration does not correlate with the SV [41]. Instead, the change in duration of ccFT can identify changes in left ventricular stroke volume due to altered loading conditions. In order to determine if a change in preload leads to a change in the duration of flow time, the heart's afterload and contractility must be constant and the flow time must be corrected for a heart rate [17]. Accordingly, ΔccFT decreases with fluid or blood removal [36, 42, 43], and increases with fluid administration in volume-depleted patients [38, 43, 44]. A number of pilot studies show that ΔccFT also increases after intravenous fluid bolus challenge [33, 35] or PLR [36, 38] in fluid responsive patients. Using ultrasonographic CO monitoring [35], pulse contour based analysis [37], or the more widely used, esophageal Doppler-based assessment of SV index to define preload responsiveness [33, 34], fluid responders show significantly higher ΔccFT in comparison to non-responders. Combining Doppler evaluation of ΔccFT with a well-validated PLR maneuver [10–14] offers several advantages in comparison to other methods of fluid responsiveness assessment. Measuring ΔccFT is less subject to artifact that many other measures of stroke volume, it is almost universally applicable and, based on results presented here, there is an excellent agreement between bedside and blinded investigator measurements.

There are several strengths of this study. This is the largest study to our knowledge evaluating ΔccFT after PLR as a predictor of fluid responsiveness in shock. All patients were on fixed vasopressor support during the test, thus minimizing the alteration of systemic vascular resistance during the evaluation. The study included patients spontaneously breathing and on passive mechanical ventilation. Positive pressure ventilation had no significant impact on the ability of ΔccFT to predict fluid responsiveness.

Our study has several limitations. We did not assess fluid responsiveness directly. Instead, we compared ΔccFT to a reference method. NICOM™ was used as a reference standard for fluid responsiveness because it has acceptable agreement with other CO monitoring systems [11, 13, 19, 45, 46], is easy to apply and has been studied in both spontaneously breathing and mechanically ventilated patients with shock in combination with PLR [13, 47, 48].

The exclusion of patients with congestive heart failure reduces the generalizability of conclusions, although post-hoc analysis of echocardiographic results obtained within the same hospital stay indicated that left ventricular ejection fraction was reduced in at least 13.7% of cases (10/73). The same applies for excluding conditions which can potentially lead to a suboptimal, or potentially harmful PLR – lower extremity thromboembolism, recent abdominal surgery or hip fractures, suspected elevated intracranial pressure or significant peripheral vascular disease. Broadening the inclusion criteria in the future should help understand better the general applicability of this method. Despite good interrater agreement, manual measurement can lead to misinterpretation of results, both due to measurement bias, or skill of the operator. Additionally, ccFT slightly varies throughout the respiratory cycle, and random averaging of the ccFT between the three beats [41] may not be able to sufficiently correct potential inaccuracy in interpretation of ccFT measurements. Automated identification of pulse waveform components combined with respiratory tracing may improve accuracy of ΔccFT interpretation in the future. More importantly, appreciating complex relationship between hemodynamic determinants and understanding the limits of currently used dynamic parameters which act as surrogates for SV change, future critical care research may lean toward utilization of composite measures of fluid responsiveness capable of predicting fluid responsiveness with better accuracy [49]. We can speculate that one such example could be combining carotid Doppler-derived parameters ΔVTI and ΔccFT.

Conclusion:

In patients with early, undifferentiated shock, ΔccFT induced by a PLR maneuver was able to predict fluid responsiveness. It compares favorably with NICOM™, with an AUC of 0.88 suggesting that it is an alternative to other methods. Its effectiveness is not affected by mechanical ventilation, respiratory rate, or PEEP >5mmH_2O. Further studies focused on clarification of the role of ΔccFT in the assessment of fluid responsiveness are warranted.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Take home:

The change in carotid corrected flow time (ΔccFT) induced by a passive leg raise maneuver can predict fluid responsiveness in patients in early, undifferentiated shock. The ability to use this parameter, together with other ultrasonographic measures which reflect the dynamic changes induced by preload challenge, make point-of-care ultrasound an attractive tool in routine assessment of fluid responsiveness in shock

Tweet (Mandatory):

The change in carotid corrected flow time measured by Doppler sonography after a passive leg raise can predict fluid responsiveness in shock

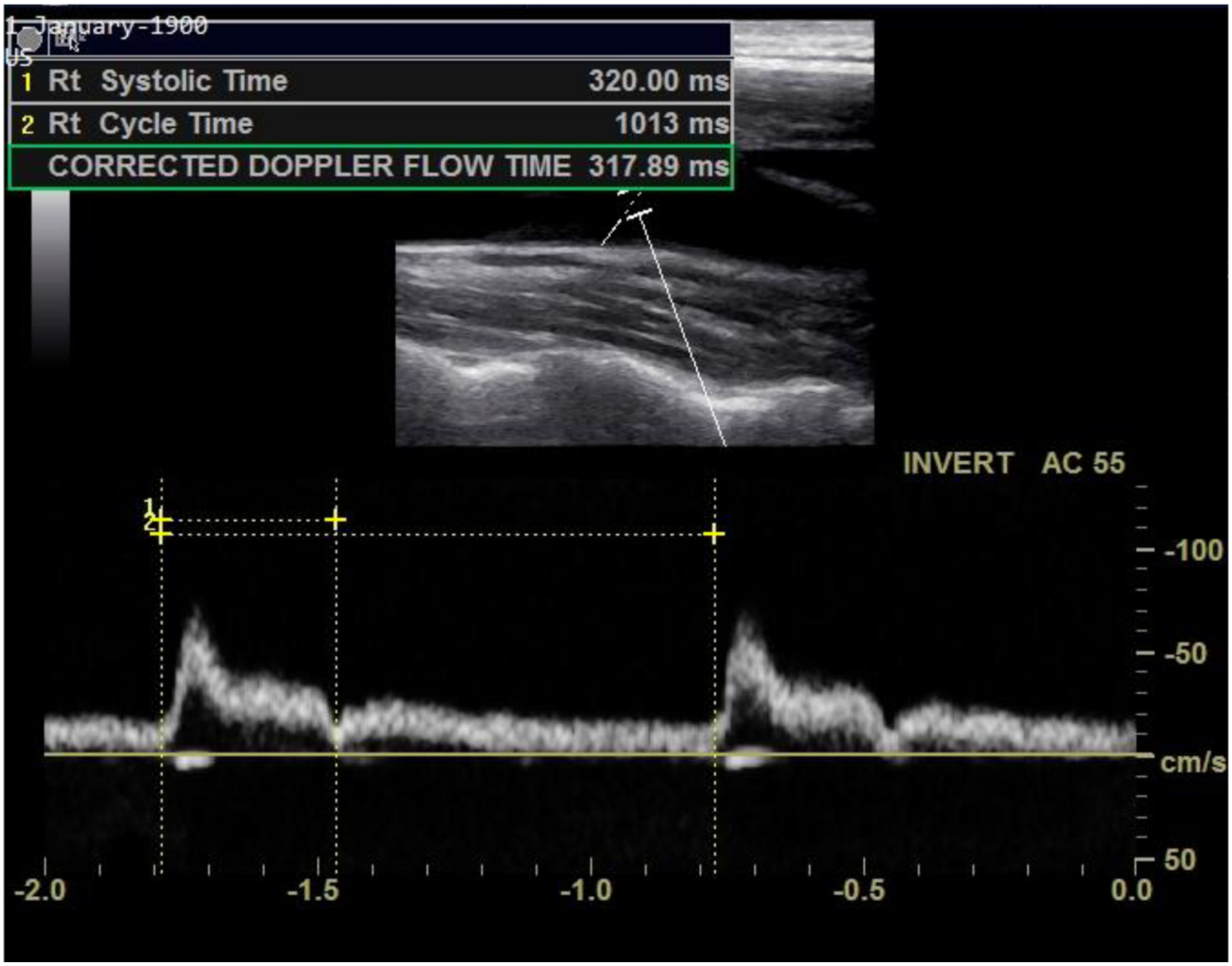


Figure 1.

Carotid Doppler waveform with markings: 1) flow time (FT), 2) cycle time. ccFT = FT + 1.29 × (HR-60)

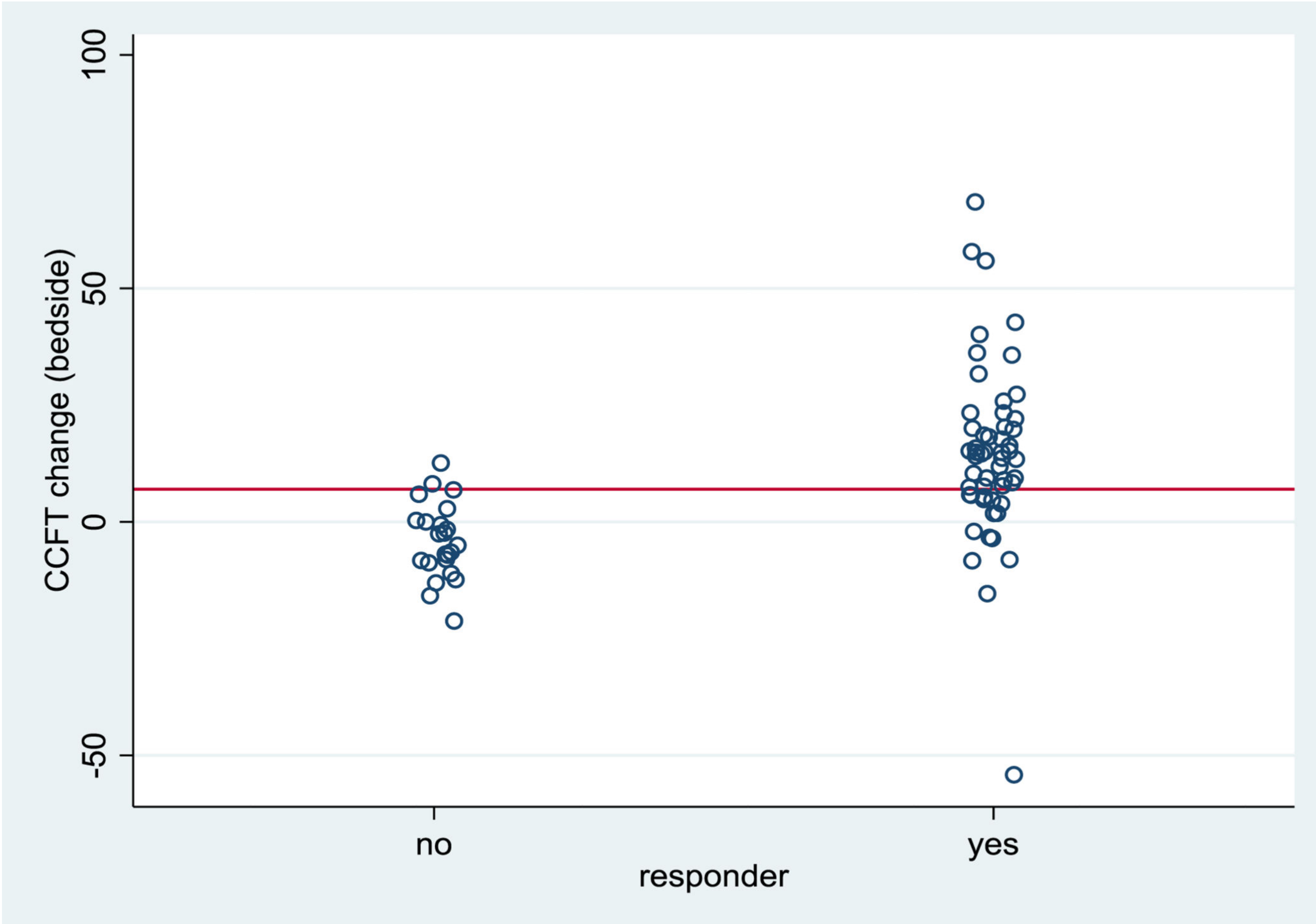
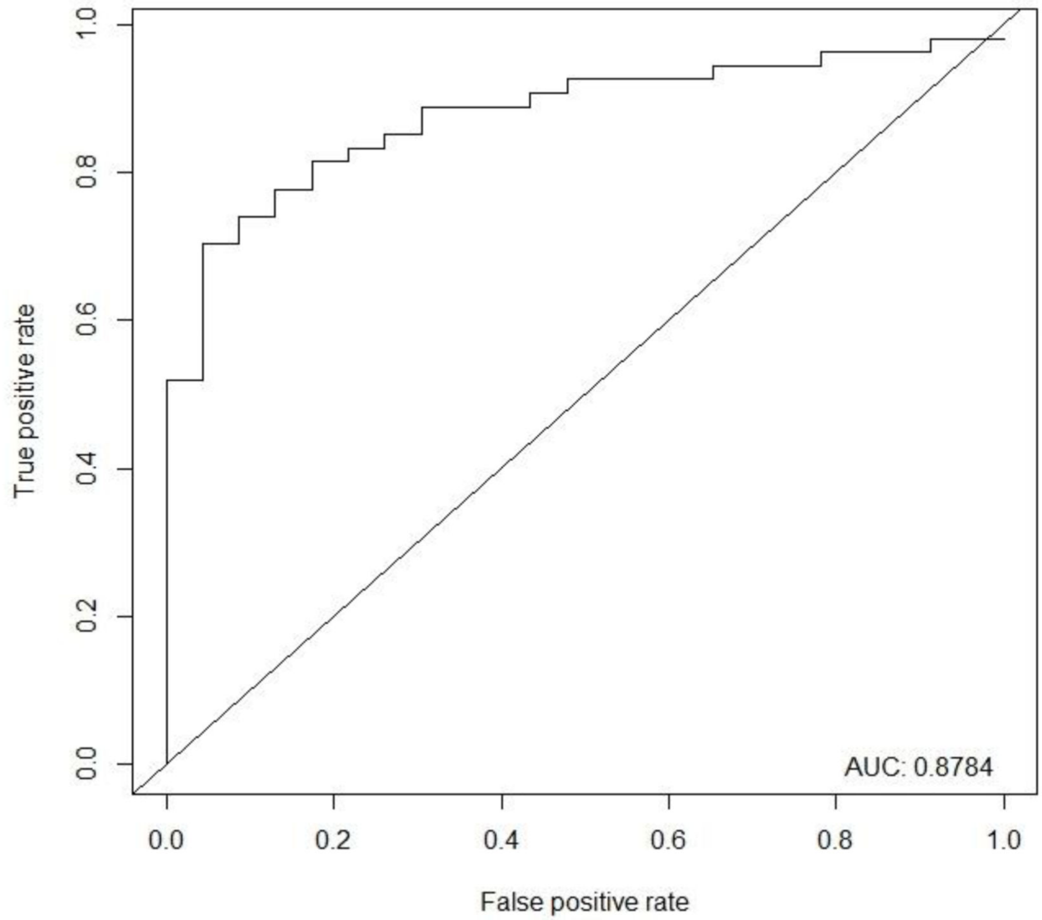


Figure 2.
Dot plot analysis of ΔccFT by fluid responder status

A)



B)

Absolute ccft (msec)	Sensitivity	Specificity	Accuracy	PPV	NPV
-3.1	88.9%	69.6%	79.2%	87.3%	72.7%
4.1	81.5%	82.6%	82.0%	91.7%	65.5%
5.5	75.9%	87.0%	81.4%	93.2%	60.6%
6.7	68.5%	95.7%	82.1%	97.4%	56.4%
9.1	59.3%	95.7%	77.5%	97.0%	50.0%
10.6	53.7%	95.7%	74.7%	96.7%	46.8%
12.1	51.9%	95.7%	73.8%	96.6%	45.8%
15.4	40.7%	100.0%	70.4%	100.0%	41.8%

Figure 3.

A) Receiver operating characteristic curve analysis for ΔccFT ability to predict fluid responsiveness; B) ΔccFT test characteristics when cut-off values are used to predict fluid responsiveness

Table 1.

Patient baseline characteristics

Patient Characteristic	Total (N=77)
Age, (mean ± SD), years	60.6 ± 17
Female, (%)	51%
Body-mass-index, (mean ± SD), kg/m^2	24 ± 8
Hematocrit, (mean ± SD), %	29.4 ± 7
End-stage renal disease or dialysis, (%)	42%
Total fluids received, (mean ± SD), L	8 ± 5
Mechanical ventilation (%)	59%
– Passive ventilation, (% of ventilated patients)	47%
PEEP >5 mmHg	25%
Pressor Used	
– Norepinephrine, (%)	71%
– Dopamine, (%)	5%
– Vasopressin, (%)	3%
– Phenylephrine, (%)	6%
– Combination, (%)	14%
APACHE II, (mean ± SD)	24.5 ± 10

PEEP, positive-end-expiratory-pressure; SD, standard deviation; APACHE II, Acute Physiology And Chronic Health Evaluation II.

Table 2.

ccFT and NICOM™ results pre and post PLR

	Parameter	Total, N=77	Responders, N=54 (70.1%)	Non-Responders, N=23 (29.9%)	P=value
	Mean arterial pressure, (mean ± SD), mmHg	60 ± 8	61 ± 8	**68 ± 7**	**0.15**
	Heart rate, (mean ± SD), beats/min	103 ± 24	101 ± 25	108 ± 21	0.28
NICOM™	Baseline cardiac index, L/min/m2	3.7 ± 5.1	4.0 ± 6.1	3.1 ± 0.9	0.51
	Post PLR Cardiac index, L/min/m2	4.3 ± 3.7	4.8 ± 4.3	3.0 ± 0.8	0.06
	Baseline SV, ml	64.1 ± 24.7	65.0 ±24.5	62.0 ± 25.6	0.63
	Post PLR SV, ml	77.7 ± 32.2	85.9 ± 31.7	59.1 ± 25	0.01
	ΔSV, %	24.7 ± 23.6	33.9 ± 22.1	3.1 ± 6.9	
Carotid Doppler	Baseline ccFT, msec	301 ± 33	300 ± 32	302 ± 35	0.86
	Post PLR ccFT, msec	310 ± 37	315 ± 36	298 ± 37	0.067
	ΔccFT, msec	**8.7 ± 18**	**14.1 ± 19**	**−4.0 ± 8**	**<0.001**
	ΔccFT, %	**3.0 ± 6.3**	**4.8 ± 6.4**	**−1.4 ± 2.9**	**<0.001**

ccFT, corrected carotid flow time; PLR, passive leg raise; SV, stroke volume