Bridging the gap: Hybrid cardiac echo in the critically ill

Jacob J. Glaser, MD, Cassandra Cardarelli, MD, Samuel Galvagno, Jr, DO, PhD, Thomas M. Scalea, MD, *and* **Sarah B. Murthi, MD***, San Antonio, Texas*

BACKGROUND: Point-of-care ultrasound often includes cardiac ultrasound. It is commonly used to evaluate cardiac function in critically ill patients but lacks the specific quantitative anatomic assessment afforded by standard transthoracic echocardiography (TTE). We developed the Focused Rapid Echocardiographic Examination (FREE), a hybrid between a cardiac ultrasound and TTE that places an emphasis on cardiac function rather than anatomy. We hypothesized that data obtained from FREE correlate well with TTE while providing actionable information for clinical decision making.

METHODS: FREE examinations evaluating cardiac function (left ventricular ejection fraction), diastolic dysfunction (including early mitral Doppler flow [E] and early mitral tissue Doppler [E′]), right ventricular function, cardiac output, preload (left ventricular internal dimension end diastole), stroke volume, stroke volume variation, inferior vena cava diameter, and inferior vena cava collapse were performed. Patients who underwent both a TTE and FREE on the same day were identified as the cohort, and quantitative measurements were compared. Correlation analyses were performed to assess levels of agreement.

RESULTS: A total of 462 FREE examinations were performed, in which 69 patients had both a FREE and TTE. FREE ejection fraction was strongly correlated with TTE ($r = 0.89$, 95% confidence interval). Left ventricular outflow tract, left ventricular internal dimension end diastole, E, and lateral E′ derived from FREE were also strongly correlated with TTE measurements ($r = 0.83$, $r = 0.94$, $r = 0.77$, and $r = 0.88$, respectively). In 82% of the patients, right ventricular function for FREE was the same as that reported for TTE; pericardial effusion was detected on both examinations in 94% of the cases. No significant valvular anatomy was missed with the FREE examination.

CONCLUSION: Functionally rather than anatomically based hybrid ultrasound examinations, like the FREE, facilitate decision making for critically ill patients. The FREE's functional assessment correlates well with TTE measurements and may be of significant clinical value in critically ill patients, especially when used in remote operating environments where resources are limited. (*J Trauma Acute Care Surg.* 2016;81: S157–S161. Copyright © 2016 Wolters Kluwer Health, Inc. All rights reserved.)

LEVEL OF EVIDENCE: Diagnostic test, level III.

KEY WORDS: FREE; echocardiography; point-of-care ultrasound; critical care ultrasound.

Cardiac dysfunction can lead to life-threatening hemodynamic instability and requires accurate, efficient evaluation. The optimal modality to evaluate cardiac function remains controversial. When further insight about a patient's cardiac function is needed, a transthoracic echocardiography (TTE) is often used.[1,2] TTE offers a noninvasive, nonradiating, point-of-care option for evaluating cardiac function.[3] The information gained from the traditional TTE offers excellent anatomic information but is commonly reported in a manner that does not facilitate clinical decision making (i.e., fluid responsiveness, need for inotropes or vasopressors). Furthermore, the formal TTE has logistic limitations, such as requiring a technologist to perform the examination and a cardiologist to interpret the examination. Decreased availability combined with delays in reporting of a study can limit the utility of TTE in the intensive care unit (ICU) setting.[4] The limitations of TTE are especially germane in antiaccess, area-denial military conflicts where threats may necessitate the provision of critical care in remote locations with limited resources.

Standard interpretation of TTE reports important anatomic information but may fail to identify or provide details regarding essential hemodynamic parameters. While ejection fraction (EF) is consistently stated, additional hemodynamic data are not included on a standard TTE. Specifically, the TTE does not typically address overall intravascular volume status or the inherent ability of the cardiovascular system to respond to a fluid bolus with an increase in stroke volume (SV).[5] This is a highly relevant and necessary information for any provider charged with caring for critically ill patients.

There is a movement in emergency medicine and critical care as well as surgery toward use of point-of-care ultrasound (POCUS).[1,6–9] POCUS allows the bedside provider to independently perform ultrasound examinations and to answer specific questions regarding the status of the patient in real time, facilitating immediate decision making. This allows early diagnosis, real-time development of treatment strategies, image-guided interventions to be made, and progress to be tracked via repeat imaging. The prototype example of this is a Focused Assessment with Sonography in Trauma (FAST) examination.[10] This same principle can be applied to cardiac physiology with regard to

Submitted: December 8, 2015, Revised: January 20, 2016, Accepted: January 21, 2016, Published online: March 7, 2016.

From the Division of Trauma and Surgical, Critical Care (J.J.G., T.M.S., S.B.M.), Department of Surgery, and Department of Anesthesiology (S.G.), University of Maryland School of Medicine, R Adams Cowley Shock Trauma Center, Baltimore; and Walter Reed National Military Medical Center (C.C.), Bethesda, Maryland.

Reference to any product neither constitutes nor implies its endorsement, recommendation, or favoring by the US Government or any agency thereof. The views and opinions of the authors do not necessarily state or reflect those of the US Government.

Portions of this work were presented at the 2015 Annual Convention of the AIUM (American Institute of Ultrasound in Medicine) and 2014 Military Health System Research Symposium (MHSRS).

Address for reprints: Jacob J. Glaser, MD, 3503 Puesta De Sol, San Antonio, TX 78261; email: jacob.glaser1@gmail.com.

DOI: 10.1097/TA.0000000000001020

Copyright © 2016 Wolters Kluwer Health, Inc. All rights reserved.

fluid bolus and inotrope or vasopressor use. POCUS is supported by The American Society of Echocardiography as well as the American College of Emergency Physicians[11] and has been shown to improve treatment of critically ill patients.[12–15]

Basic cardiac POCUS examinations address direct concerns such as hypovolemia, cardiac function, presence of pericardial effusion, tamponade physiology, and obvious valvular abnormalities. More advanced examinations include Doppler assessments of blood flow, dynamic assessments of cardiac contraction and relaxation, calculation of cardiac output (CO)/cardiac index, pulmonary hypertension, and inferior vena cava (IVC) collapsibility. At the R Adams Cowley Shock Trauma Center in Baltimore, Maryland, a uniquely formulated quantitative echocardiogram called a Focused Rapid Echocardiographic Examination (FREE) is used. The FREE is the primary tool for hemodynamic assessment at this busy trauma center. It is a hybrid of the POCUS cardiac echo and the anatomic assessment of the TTE. It was designed specifically to address hemodynamic status.[1] The FREE includes measurements and calculations found on TTE as well as SV, CO, cardiac index, IVC diameter (IVCd), and change in internal jugular diameter with change in position. These additional findings provide information on cardiac function, diastolic dysfunction, and the inherent ability of the heart to respond to a fluid bolus with an increase in SV.[16]

The FREE is performed by the bedside intensivist and used primarily to guide management decisions regarding the fluid resuscitation as well as addition of inotropes or vasopressors or to confirm ongoing interventions. In previous studies, the FREE examination has been deemed useful by the consulting primary team for 95% of patients and results in a management change 57% of the time.[16] The FREE has been studied in comparison with the pulmonary artery catheter, has been found to have excellent agreement,[17] and has essentially replaced the pulmonary artery catheter as a viable, noninvasive resuscitation tool in some centers.[2,17,18]

The FREE has significant potential as an adaptable, mobile, low-cost diagnostic modality that can be used in a wide variety of operational environments. We hypothesized that data obtained from FREE correlates well with TTE in terms of anatomic data, while providing additional functional cardiac data that can be considered for clinical decision making.

PATIENTS AND METHODS

With institutional review board approval, a prospectively collected database of all patients who underwent a FREE at a shock trauma center was retrospectively reviewed. A 1-year sample was selected from January 2013 to December 2013 for evaluation. Patients who underwent both a FREE examination and formal TTE on the same calendar day were included (n = 69). All patients were surgical or trauma admissions. All FREE examinations were performed on a portable cardiovascular ultrasound machine (Philips CX 50, Andover, MA) using a phased array probe. The examinations were performed by ultrasound-trained critical care physicians and interpreted by a single surgical intensivist (S.B.M.). All TTE examinations were performed and interpreted by the cardiology service. The final imaging interpretations and measurements compared were EF, left ventricular outflow tract (LVOT), left ventricular internal diameter in diastole (LVIDd), E (E-wave, representing the early, passive filling of the left ventricle on pulse wave doppler), and lateral E′ (wave representing passive filling on tissue Doppler imaging).

The FREE Examination

The FREE, as described earlier, is a hybrid of the point-of-care examination and TTE. Similar to the TTE, the FREE requires four standard views: the parasternal long (PSL), parasternal short, four-chamber, and subxyphoid view. Within these views, further hemodynamically relevant measurements are made and interpreted in the context of the patient's clinical status.[1] In the PSL view, LVOT size is measured as well as LVIDd. The contractility and global function of the left heart can also be visualized in this view. By combining these measurements with Doppler flow across the aortic valve in the four-chamber view, SV can be obtained, thus providing CO and cardiac index.[17] The four-chamber view also provides visualization of both the right and left heart for a qualitative assessment, as well as measurement by tissue Doppler (E′) through the lateral mitral annulus. This measurement provides assessment of left heart stiffness and the diastolic function of the heart. The subxyphoid view provides visualization of the diameter of the IVC, which can provide information regarding fluid status.[1] Volume assessments of the internal jugular vein are made using a high-frequency transducer over the internal jugular vein in the neck.

Statistical Analysis

The covariance (correlation) between variables was calculated with the Pearson product moment correlation.[19] Confidence intervals (CIs) for correlations were calculated based on Fisher's transformation. Bland-Altman plots were constructed to evaluate the difference between paired variables versus their average.[20] In addition, concordance correlation coefficients were calculated to determine agreement between FREE and ECHO (echocardiography) continuous data using the method of Lin.[21] Concordance correlation coefficients offer the advantage of measuring both precision and accuracy to determine how far the observed data deviate from a line of perfect concordance. All tests were performed in Stata version 11.2 (Stata Corp, College Station, TX). A $p < 0.05$ was considered statistically significant.

RESULTS

Data consisted of 69 patients who underwent both a TTE and FREE on the same calendar day from January 2013 to December 2013. Sixty-one percent of the cohort was male, and the average age was 63 years. No differences were noted in sex, body surface area, or age between groups receiving a FREE examination (from the entire FREE database) and those getting both a TTE and FREE examination. This choice is most often clinician preference. Each patient in the cohort had a traditional TTE performed and interpreted by the cardiology service as well as a FREE performed by a surgical intensivist or cardiac sonographer.

In the PSL view, the left heart was evaluated for LVOT size and LVIDd. When comparing the FREE measurements with the criterion standard, the LVOT and LVIDd correlated well with a Pearson product moment correlation of $r = 0.83$ ($p = 0.05$; CI, 0.72–0.89) and $r = 0.94$ ($p = 0.81$; CI, 0.90–0.97). Bland-Altman plots were constructed to evaluate the difference between the

© 2016 Wolters Kluwer Health, Inc. All rights reserved.

Copyright © 2016 Wolters Kluwer Health, Inc. All rights reserved.

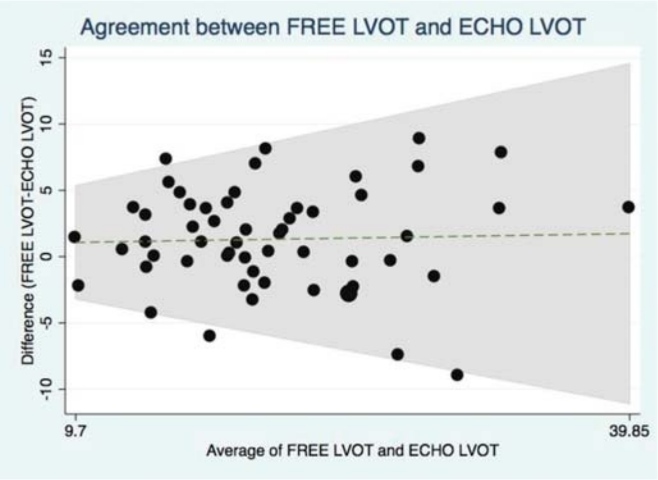

Figure 1. Agreement between FREE versus ECHO for LVOT, Pearson $r = 0.83$ ($p = 0.05$; CI, 0.72–0.89).

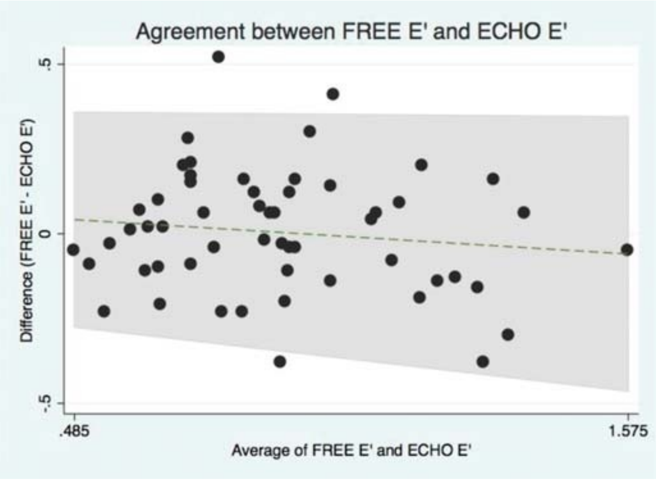

Figure 3. Agreement between FREE versus ECHO for E′. Pearson $r = 0.77$ ($p = 0.64$; CI, 0.63–0.86).

paired variables (Figs. 1 and 2). No fixed bias was detected, and the level of agreement was satisfactory.

The four-chamber view provided information regarding the diastolic dysfunction of the heart and was evaluated measuring E and lateral E′. These parameters from the FREE correlated strongly with the TTE ($r = 0.77$, $p = 0.64$, CI, 0.63–0.86; $r = 0.88$, $p = 0.26$, CI, 0.59–0.84) (Figs. 3 and 4).

The left ventricular EF is expressed as a percent after interpreting all views obtained in the FREE. The EF estimated by the FREE when compared with that of the TTE was evaluated and showed excellent correlation as well as concordance with a Pearson r of 0.89 ($p = 0.84$; CI, 0.82–0.93) (Fig. 5).

In the assessment of right ventricular function, aortic valve anatomy and mitral valve anatomy were congruent in 82%, 83%, and 83% of the patients. No hemodynamically significant valvular anatomy was overlooked (Fig. 6).

DISCUSSION

The results of this study show that a hybrid echo, such as the FREE, provides an acceptable anatomic evaluation when compared with the criterion standard TTE. Comparable anatomy, in addition to the hemodynamic answers gained with hybrid echo, can translate to better patient care, especially in medical scenarios involving prolonged field care, delayed evacuation, prolonged rotary and fixed wing evacuations, prolonged entry operations by sea or air, and search and rescue of injured in a hostile territory.

The FREE bridges the diagnostic gap left by standard TTE, as its findings are hemodynamically interpreted, versus identification of anatomic variants.[1] The FREE is dually equipped to provide both important pieces of information, and this study lends evidence that it can do without compromising accuracy. Previous studies have determined that POCUS can be a useful tool for evaluating fluid status in both the ICU and trauma setting.[18,22]

Assessment of volume status demonstrates the usefulness of the hybrid echo, and volume measurements were compared for accuracy in this study. One accepted surrogate for preload is LVIDd. LVIDd, when interpreted along with IVCd, can indicate whether a patient is euvolemic, hypovolemic, or fluid

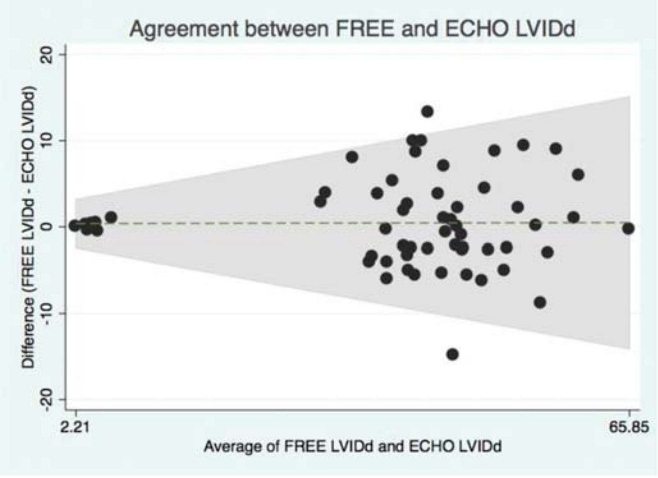

Figure 2. Agreement between FREE versus ECHO for LVIDd Pearson $r = 0.94$ ($p = 0.81$; CI, 0.90–0.97).

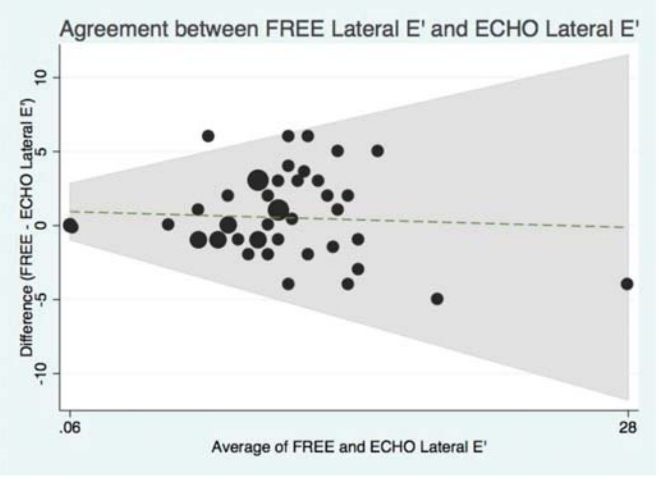

Figure 4. Agreement between FREE versus ECHO for Lateral E′. Pearson $r = 0.88$ ($p = 0.26$; CI, 0.59–0.84).

© 2016 Wolters Kluwer Health, Inc. All rights reserved.

Copyright © 2016 Wolters Kluwer Health, Inc. All rights reserved.

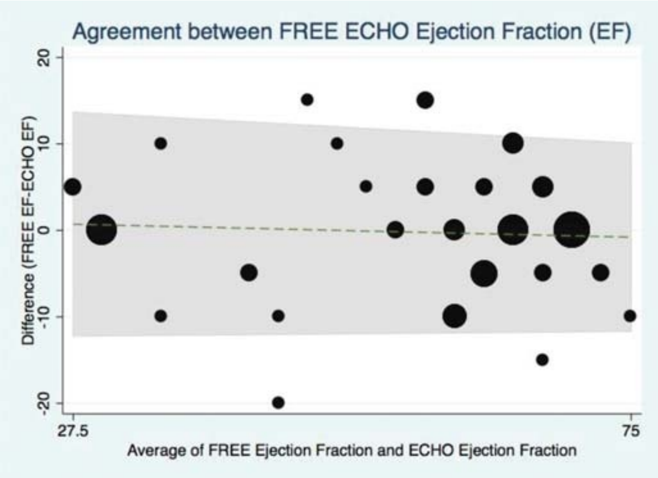

Figure 5. Agreement between FREE versus ECHO for EF. Pearson $r = 0.89$ ($p = 0.84$; CI, 0.82–0.93).

overloaded. The hybrid echo takes these measurements, interprets them, and then places them in categories identifying patients as being normal, underfilled, dysfunctional, or vasodilated. Once determined, more dynamic measures included in the FREE, such as SV variation and IVCd change, can provide insight into patients' inherent volume responsiveness. The FREE reports these findings as "likely" or "unlikely" volume responsive, ideally guiding the clinician at the bedside.[18,23,24] This information is immediately accessible to a clinician requesting the study or interpreted at the point of care. Standard TTE does not afford clinicians this insight or the immediate feedback to guide clinical management. Ferrada et al.[18] demonstrated that a quantitative echo performed and interpreted by an intensivist is useful for evaluating cardiac function. In this study, bedside evaluation performed by a noncardiologist (a FREE) altered management in 57% of the patients. The most frequent change in management prompted by interpretation of the FREE was fluid resuscitation, followed by continued monitoring and diuresis.

Noncardiologist physicians performed the FREE examinations in this study. These critical care specialists underwent ultrasound training specifically directed toward bedside echocardiography and were trained by certified echocardiographers. As the applicability of point-of-care cardiac ultrasound–guided resuscitation continues to be demonstrated, many educational programs are seeking to define the optimal training curricula for this technology, and the need for educational guidelines in the critical care setting is clear.[13,14] Ferrada et al.[25] demonstrated that limited TTE can be performed accurately by trauma attendings with minimal training. Vignon et al.[6] concluded that a 12-hour training program dedicated to noncardiologist residents without ultrasound experience provided enough basic echocardiography skills to provide competence of a basic bedside examination. More information is needed to determine the training requirements for performing quantitative examinations such as the FREE, but for military providers preparing to deploy, obtaining training for the FREE would be much more cost-effective than training for TTE. At our institution, after performing a 1-month rotation, critical care providers are able to obtain the required echocardiographic views for the FREE and formulate a functional interpretation.

POCUS studies commonly use a basic examination and ultrasound platform without cardiac capability. The FREE requires advanced measurements and machine capable of obtaining the requisite views. Not all institutions have a sophisticated critical care ultrasound department with formal training in echocardiography, and the capital expenditure may seem daunting. However, our data argue that a noncardiologist can accurately perform an advanced examination, thereby saving the considerable expense of telemedicine and down-range or up-range support from cardiologists.

Our study has several limitations. The time frames between examinations, while on the same calendar day, were not standardized. Profound hemodynamic changes can transpire over short intervals in an ICU, and our data would be more accurate if examinations had been closer temporally. In addition, we perform echocardiography commonly in our center, and familiarity with the technique is ubiquitous. This data are from a single center, a noted limitation, and therefore, this level of correlation may not be as likely in centers with less expertise. While relying on a local expert for quality assurance and confirmatory ultrasound interpretation, FREE examinations are most often performed by critical care fellows or staff. Again, single-center expertise not only may limit generalizability but also speaks to the ability to train physicians to proficiency even within the clinical demands of a busy hospital.

CONCLUSION

This study confirms that a hybrid cardiac echo such as the FREE can accurately assess cardiac function and anatomy when quantitatively compared with formal TTE. The unique feature of the FREE is that it can assess a patient's hemodynamic status and can provide additional information to guide the clinical management of a critically ill patient. Accurate measurements can be obtained by a noncardiologist, and these data can impact care. Further studies are warranted to evaluate the use of the hybrid echo on clinical outcomes and to identify the ideal protocols for training and safe use. In a future operational environment fraught with uncertainty and unique challenges, the FREE stands as a portable, practical, and cost-effective diagnostic option for critically ill patients.

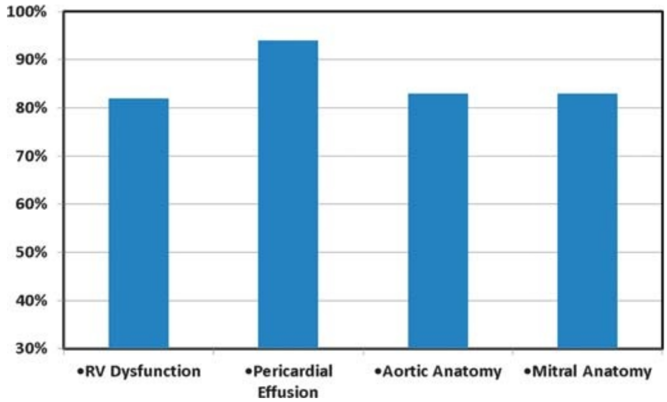

Figure 6. Agreement between FREE versus ECHO for right ventricular dysfunction, presence of effusion, and valvular anatomy.

© 2016 Wolters Kluwer Health, Inc. All rights reserved.

Copyright © 2016 Wolters Kluwer Health, Inc. All rights reserved.

AUTHORSHIP

J.J.G. and S.B.M. designed this study. J.J.G., C.C., and S.G. conducted the literature search. J.G., C.C., S.G., T.S., and S.M. contributed to the data collection and analysis. All authors participated in the data interpretation, writing, and critical revision of the manuscript.

DISCLOSURE

The authors declare no conflicts of interest.

REFERENCES

1. Ferrada P, Murthi S, Anand RJ, Bochicchio GV, Scalea T. Transthoracic focused rapid echocardiographic examination: real-time evaluation of fluid status in critically ill trauma patients. *J Trauma*. 2011;70:56–64.
2. Gunst M, Ghaemmaghami V, Sperry J, Robinson M, O'Keeffe T, Friese R, Frankel H. Accuracy of cardiac function and volume status estimates using the bedside echocardiographic assessment in trauma/critical care. *J Trauma*. 2008;65(3):509–516.
3. Walley PE, Walley KR, Goodgame B, Punjabi V, Sirounis D. A practical approach to goal-directed echocardiography in the critical care setting. *Crit Care*. 2014;18(6):681.
4. Huang SJ, McLean AS. Appreciating the strengths and weaknesses of transthoracic echocardiography in hemodynamic assessments. *Cardiol Res Pract*. 2012;2012:894308.
5. Gardin JM, Adams DB, Douglas PS, Feigenbaum H, Forst DH, Fraser AG, Grayburn PA, Katz AS, Keller AM, Kerber RE, et al. American Society of Echocardiography. Recommendations for a standardized report for adult transthoracic echocardiography: a report from the American Society of Echocardiography's Nomenclature and Standards Committee and Task Force for a Standardized Echocardiography Report. *J Am Soc Echocardiogr*. 2002;15(3):275–290.
6. Vignon P, Mucke F, Bellec F, Marin B, Croce J, Brouqui T, et al. Basic critical care echocardiography: validation of a curriculum dedicated to non-cardiologist residents. *Crit Care Med*. 2011;39(4):636–642.
7. Mjølstad OC, Andersen GN, Dalen H, Graven T, Skjetne K, Kleinau JO, Haugen BO. Feasibility and reliability of point-of-care pocket-size echocardiography performed by medical residents. *Eur Heart J Cardiovasc Imaging*. 2013;14(12):1195–1202.
8. Frederiksen CA, Juhl-Olsen P, Andersen NH, Sloth E. Assessment of cardiac pathology by point-of-care ultrasonography performed by a novice examiner is comparable to the gold standard. *Scand J Trauma Resusc Emerg Med*. 2013;21:87.
9. Sobczyk D, Nycz K, Andruszkiewicz P. Validity of a 5-minute focused echocardiography with A-F mnemonic performed by non-echocardiographers in the management of patients with acute chest pain. *Cardiovasc Ultrasound*. 2015;13:16.
10. Scalea TM, Rodriguez A, Chiu WC, Brenneman FD, Fallon WF Jr, Kato K, McKenney MG, Nerlich ML, Ochsner MG, Yoshii H. Focused Assessment with Sonography for Trauma (FAST): results from an international consensus conference. *J Trauma*. 1999;46(3):466–472.
11. Labovitz AJ, Noble VE, Bierig M, Goldstein SA, Jones R, Kort S, Porter TR, Spencer KT, Tayal VS, Wei K. Focused cardiac ultrasound in the emergent setting: a consensus statement of the American Society of Echocardiography and American College of Emergency Physicians. *J Am Soc Echocardiogr*. 2010;23(12):1225–1230.
12. Gaspar HA, Morhy SS, Lianza AC, de Carvalho WB, Andrade JL, do Prado RR, Schvartsman C, Delgado AF. Focused cardiac ultrasound: a training course for pediatric intensivists and emergency physicians. *BMC Med Educ*. 2014;14:25.
13. Boyd JH, Walley KR. The role of echocardiography in hemodynamic monitoring. *Curr Opin Crit Care*. 2009;15:239–243.
14. Mayo PH, Beaulieu Y, Doelken P, Feller-Kopman D, Herrod C, Kaplan A, Oropello J, Viellard-Baron A, Axler O, Lichtenstein D, et al. American College of Chest Physicians/La Société de Réanimation de Langue Française statement on competence in critical care ultrasonography. *Chest*. 2009;135:1050–1060.
15. Pershad J, Myers S, Plouman C, Rosson C, Elam K, Wan J, Chin T. Bedside limited echocardiography by the emergency physician is accurate during evaluation of the critically ill patient. *Pediatrics*. 2004;114(6):e667–e671.
16. Murthi SB, Markandaya M, Fang R, Hong CM, Galvagno SM, Lissuaer M, Stansbury LG, Scalea TM. Focused comprehensive, quantitative, functionally based echocardiographic evaluation in the critical care unit is feasible and impacts care. *Mil Med*. 2015;180(3 Suppl):74–79.
17. Murthi SB, Hess JR, Hess A, Stansbury LG, Scalea TM. Focused rapid echocardiographic evaluation versus vascular catheter-based assessment of cardiac output and function in critically ill trauma patients. *J Trauma Acute Care Surg*. 2012;72(5):1158–1164.
18. Ferrada P, Vanguri P, Anand RJ, Whelan J, Duane T, Aboutanos M, Malhotra A, Ivatury R. A, B, C, D, echo: limited transthoracic echocardiogram is a useful tool to guide therapy for hypotension in the trauma bay—a pilot study. *J Trauma Acute Care Surg*. 2013;74(1):220–223.
19. Pearson K. Mathematical contributions to the theory of evolution—III. Regression, heredity, and panmixia. *Philos Trans R Soc Lond A*. 1896;187: 253–318.
20. Bland JM, Altman DG. Statistical methods for assessing agreement between two methods of clinical measurement. *Lancet*. 1986;1:307–310.
21. Lin LIK. A note on the concordance correlation coefficient. *Biometrics*. 2000;56:324–325.
22. Poelaert J, Schmidt C, Colardyn F. Transoesophageal echocardiography in the critically ill. *Anaesthesia*. 1998;53:55–68.
23. Machare-Delgado E, Decaro M, Marik PE. Inferior vena cava variation compared to pulse contour analysis as predictors of fluid responsiveness: a prospective cohort study. *J Intensive Care Med*. 2011;26(2):116–124.
24. Stawicki SP, Braslow BM, Panebianco NL, Kirkpatrick JN, Gracias VH, Hayden GE, Dean AJ. Intensivist use of hand-carried ultrasonography to measure IVC collapsibility in estimating intravascular volume status: correlations with CVP. *J Am Coll Surg*. 2009;209(1):55–61. Epub 2009 May 1.
25. Ferrada P, Anand RJ, Whelan J, Aboutanos MA, Duane T, Malhotra A, Ivatury R. Limited transthoracic echocardiogram: so easy any trauma attending can do it. *J Trauma*. 2011;71(5):1327–1332.

© 2016 Wolters Kluwer Health, Inc. All rights reserved.

Copyright © 2016 Wolters Kluwer Health, Inc. All rights reserved.