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# Accuracy of Echocardiographic Cardiac Output Assessment by Critical Care Fellows

**Jordan Talan[1], Keshav Mangalick[1], Deepak Pradhan[1], and Harald Sauthoff[1,2]**

[1]Division of Pulmonary, Critical Care, and Sleep Medicine, New York University Langone Health, New York, New York; and [2]Division of Pulmonary and Critical Care Medicine, Westchester Medical Center Health Network, Valhalla, New York

## ABSTRACT

**Background:** Advanced critical care echocardiography comprises a specific set of qualitative and quantitative point-of-care echocardiography skills, including a reliable, noninvasive method to measure cardiac output. This technique requires echocardiographic measurement of left ventricular outflow tract (LVOT) diameter and LVOT velocity time integral (VTI). Although there is a demand among critical care fellows to learn these advanced techniques, there are no data describing the acquisition of mastery in these skills.

**Objective:** This pilot study aims to describe the accuracy of echocardiographic measurement of LVOT diameter and LVOT VTI obtained by critical care fellows after an educational intervention, as well as to enhance validation evidence for an image scoring assessment that is applicable to these measurements.

**Methods:** We implemented a brief mastery learning intervention to teach the measurement of LVOT diameter and VTI. Fellow measurements of these parameters, along with the corresponding echocardiographic images, were compared with a gold standard of measurements obtained by professional echocardiography technicians and interpreted by cardiologists.

**Results:** Seven fellows performed 35 echocardiograms on 32 patients. The average fellow-reported LVOT VTI was 17.0 ± 4.37 cm, whereas the average

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**Correspondence and requests for reprints should be addressed to** Jordan Talan, M.D., M.H.P.E., New York University Langone Health, 550 1st Avenue, 15th Floor, New York, NY 10016. E-mail: jordan.talan@gmail.com.

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cardiologist-reported VTI was 17.3 ± 5.19 cm. The correlation ($r$) between fellow and cardiologist-reported VTI was 0.73 ($P < 0.001$), with a mean percent difference of 19.5 ± 12.0%. The average fellow-reported LVOT diameter was 2.07 ± 0.23 cm, whereas the average cardiologist-reported LVOT diameter was 2.08 ± 0.22 cm. The correlation ($r$) between fellow and cardiologist-reported LVOT diameter was 0.51 ($P = 0.004$), with a mean percent difference of 8.05 ± 7.0%. The sensitivity for fellows to detect an abnormal LVOT VTI was 91%, with a specificity of 43%.

**Conclusion:** Critical care fellow measurement of LVOT VTI and LVOT diameter demonstrated strong and moderate positive correlations with cardiologist-reported values, respectively, with acceptable clinical agreement. However, interrater reliability and percent differences showed room for improvement. Education in these advanced skills is resource intensive, and additional research is needed to determine the most effective approach to training fellows.

**Keywords:**
ultrasonography; echocardiography; hemodynamic monitoring; point-of-care systems; graduate medical education

Despite a growing interest among critical care fellows and junior faculty in learning advanced echocardiographic techniques, there is a paucity of data regarding the acquisition of mastery in these skills, and there are no data describing the accuracy or reliability of critical care fellows in advanced critical care echocardiography (ACCE).

ACCE comprises a specific set of point-of-care ultrasound skills that includes image acquisition and interpretation of all relevant components of echocardiography, including quantitative techniques, with a special focus on critically ill patients (1). ACCE has proven to be a reliable, noninvasive method of hemodynamic monitoring that can be repeated at the bedside as frequently as indicated (2, 3). One particularly useful component of ACCE is the measurement of cardiac output by left ventricular outflow tract (LVOT) velocity time integral (VTI). This technique requires the measurement of LVOT diameter and LVOT VTI to calculate stroke volume. The stroke volume can be multiplied by the heart rate to calculate cardiac output (4). Determination of cardiac output can help differentiate shock states, clarify discrepancies between left ventricle contractile function and stroke volume, and guide the use of vasoactive therapies at the bedside (2). Echocardiographic measurement of cardiac output by LVOT VTI has been shown to correlate well with pulmonary artery catheter measurements by thermodilution while also avoiding complications associated with invasive monitoring (2, 5, 6) Additionally, monitoring of LVOT VTI is recommended by the American Society of Echocardiography for characterization of fluid responsiveness (7).

Given the clinical utility of these skills, it is not surprising that there is a growing interest among critical care fellows and junior faculty to learn these ACCE techniques (8). In response to this need, the National Board of Echocardiography began offering national certification for this special competence in 2019 (with the Examination of Special Competence in Critical Care Echocardiography, or CCEeXAM) (8, 9). However, despite the enthusiasm to learn these skills, there are limited data to characterize the learning curve for fellows as they acquire mastery of these skills. Furthermore, there are little data to describe the accuracy of fellow ACCE measurements in the clinical setting. Unlike basic critical care echocardiography, in which fellows can become proficient with relatively limited educational interventions, achieving proficiency in ACCE is thought to be more challenging and time consuming (8, 10–12). Although a study of two emergency medicine attending physicians showed reliable measurements of the echocardiographic cardiac index after 20 hours of dedicated hands-on instruction, these results have not been repeated by other institutions, and no such data for critical care trainees are available (13).

To best meet the demand from our fellows to teach ACCE, we must first better understand the acquisition of mastery in these skills. Characterizing fellow accuracy and reliability in advanced echocardiographic measurements could allow better identification of interventions necessary for ACCE education.

This pilot study aims to describe the accuracy of critical care fellows in the transthoracic echocardiographic measurement of LVOT diameter and LVOT VTI after an educational intervention, as well as to build further validation evidence for an image scoring assessment that can be used for these measurements.

## METHODS

We implemented a brief mastery learning curriculum to teach the measurement of LVOT diameter and VTI. We subsequently compared fellow measurements to formal echocardiographic results in patients who are in intensive care.

### Educational Intervention

We developed an educational intervention that is based on the mastery learning model, which is known for its effectiveness in teaching specific objectives and may be superior to nonmastery instruction (14). This model requires an individualized approach to instruction in which education is tailored to learning objectives and proficiency is assessed with a minimum passing standard (MPS). Learners must achieve the MPS before moving on to further steps in training.

Critical care fellows were recruited during their clinical rotations at the Manhattan Veterans Affairs New York Harbor Healthcare Center. They were provided with a previously published prereading and instructional video before participating in bedside teaching sessions in a 1:1 ratio with ACCE faculty (2, 4). All bedside teaching sessions occurred over 20 minutes in the medical intensive care unit (ICU), with echocardiographic techniques performed on consenting patients in the ICU. In each fellow's initial bedside session, they received stepwise guidance with full support from the instructor on measuring LVOT diameter and LVOT VTI. Fellows were taught to measure LVOT diameter in a zoomed-in parasternal long axis (PLAX) view, in midsystole, 3–10 mm from the aortic valve insertion point, using the inner edge–to–inner edge technique. LVOT VTI was measured in both the apical five-chamber (A5C) and apical three-chamber (A3C) views, optimizing the Doppler angle and positioning the sample volume in the LVOT (4). After the initial session, each fellow underwent subsequent hands-on teaching sessions, practicing the two described techniques with decreasing instructor support until the fellow was able to perform both measurements independently. Once the fellow no longer required the instructor to handle the probe, adjust the machine, or provide corrective verbal feedback, the fellow was assessed for the MPS. Fellows were determined to achieve the MPS if they were able to independently measure LVOT diameter and VTI within 20% difference compared with simultaneous measurement by an expert with extensive experience in teaching ACCE (H.S.). Fellows who achieved the MPS were approved for study participation. If the fellow failed to meet the MPS, further training sessions were completed until the fellow either met MPS or completed their clinical rotation, becoming lost to follow-up.

### Patient Recruitment for Study Echocardiograms

Patients were recruited from the medical, surgical, and cardiac ICUs who were ordered for formal echocardiography by their clinical care team. After formal echocardiography, but before results were available, participating fellows performed measurements of LVOT diameter and VTI. The corresponding still images, as well as the corresponding ultrasound videos from the PLAX, A5C, and A3C views, were stored and scored according to an adaptation of a previously validated scoring tool (*see* Figure E1 in the online supplement) (15). The larger of the VTI measurements from the two recorded views was used in the analysis. The results were compared with a gold standard of formal echocardiography performed by professional technicians (registered diagnostic cardiac sonographers) and interpreted by board-certified cardiologists. Patients were excluded if they had a procedure between the formal and the fellow echocardiography, such as a coronary angiogram or pericardiocentesis; if they had new vasoactive medication started or stopped between exams; if they had over 4 hours elapsed between exams; if they had an aortic valve prosthesis; if they had severe aortic stenosis or regurgitation; or if they had been examined previously during ACCE teaching sessions.

### Data Analysis

Statistical analysis was performed using Jamovi 2.3.18, unless otherwise described. All mean values are reported with standard deviations. The primary statistical methodology was Bland-Altman analysis, of which the reported results include bias, upper and lower limits of agreement, and Bland-Altman plot. Pearson correlation ($r$) was also performed and reported with 95% confidence intervals. Cohen's kappa (κ) was performed to study agreement, which required the transformation of VTI data into categorical values of "normal" (18–22 cm) and "abnormal." This analysis was reported with 95% confidence intervals and was performed using SPSS 28.0.1.1. Sensitivity and specificity were calculated for the performance of fellow VTI measurement, with an abnormal VTI representing a positive test result.

### Ethical Approval

The study was approved by the New York Harbor VA Healthcare System Institutional Review Board.

## RESULTS

Eleven fellows were recruited from March through October 2022. Seven of the 11 fellows (64%) met the MPS on the training assessment during the study period. These included fellows in Postgraduate Year (PGY) 4 ($n = 2$), PGY 5 ($n = 3$), PGY 6 ($n = 1$), and PGY 7 ($n = 1$). All participating fellows were previously assessed as proficient in basic critical care echocardiography to institutional standards, but none had received previous formal training in ACCE.

Fellows required an average of 4.5 ± 1.4 training sessions before reaching MPS. Once approved for study participation, these fellows performed 35 echocardiograms on 32 patients. The demographics of the patient population are described (Table 1). VTI measurements were unobtainable by fellows on 3 patients and by technicians on 4 patients because of technically challenging windows and poor image quality, with overlap on 2 patients.

The average fellow-reported LVOT VTI was 17.0 ± 4.37 cm, whereas the average cardiologist-reported VTI was 17.3 ± 5.19 cm. The mean percent difference between fellow-reported VTI and cardiologist-reported VTI was 19.5 ± 12.0. The correlation between fellow- and cardiologist-reported VTI was 0.73 ($P < 0.001$) (Figure 1).

As fellows performed subsequent echocardiograms, up to a maximum of seven echocardiograms, the correlation of absolute deviation from the gold standard with the number of sequential exams was 0.37 ($P = 0.042$), indicating a weak positive correlation between fellow error and number of previous exams performed during the study period.

When VTI was clinically stratified into "normal" or "abnormal," there was clinical agreement in 80% of cases with a Cohen's κ of 0.379 (Table 2). The sensitivity for a fellow to detect an abnormal VTI was 91%, with a specificity of 43%.

The average fellow-reported LVOT diameter was 2.07±0.23 cm, whereas the average cardiologist-reported LVOT diameter was 2.08 ± 0.22 cm. The percent difference between fellow- and cardiologist-reported LVOT diameter was 8.05 ± 7.0. The correlation between fellow- and cardiologist-reported LVOT diameter was 0.51 ($P = 0.004$) (Table 2). We do not report the percentage of clinical agreement between "normal" and "abnormal" LVOT diameter, because this measurement has limited clinical utility (7). However, the Cohen's κ for agreement in LVOT diameter between fellows and cardiologists was 0.384 (Table 2).

To assess the agreement between fellow and cardiologist-reported values, and also to identify any systematic bias or random error in interrater differences, we performed a Bland-Altman analysis (Figure 2). Bias and upper and lower limits of agreement are reported for both LVOT VTI and diameter (Table 2).

To further characterize fellow proficiency in image acquisition and measurement, we recorded images from the PLAX, A5C, and A3C views and scored them using an image quality assessment tool (Figure E1). Images were scored for fellows and compared with the formal images, showing a significant difference in A3C view quality but no significant difference in PLAX or A5C view quality (Table 3).

To explain possible sources of fellow error, we examined the Doppler windows and spectral analyses corresponding to each fellow-reported measurement. Fellow error in caliper placement for LVOT diameter measurements occurred once (2.9%). Fellow error in pulsed-wave sample volume placement occurred three times (8.6%). Fellow VTI tracing error occurred two times (5.7%), and Doppler angle error greater than 20° occurred once (2.9%).

## DISCUSSION

In this study, we evaluated the effectiveness of a brief educational

**Table 1.** Demographics of the recruited patient population ($N = 32$)

| | M ± SD or *n* (%) |
|---|---|
| Patient demographics | |
| Age, yr | 71.1 ± 12.34 |
| Body mass index | 26.6 ± 6.19 |
| Male | 31 (96.9) |
| Female | 1 (3.1) |
| Vasopressors used | 7 (21.9) |
| Inotropes used | 1 (3.1) |
| Intubated | 2 (6.3) |
| Reduced ejection fraction | 3 (9.4) |
| Chronic obstructive pulmonary disease | 6 (18.8) |
| Primary diagnosis | |
| Severe sepsis/septic shock | 7 (21.9) |
| Myocardial infarction | 6 (18.8) |
| Decompensated heart failure | 4 (12.5) |
| Peripheral vascular emergency | 4 (12.5) |
| Hypoxemic/hypercarbic respiratory failure | 3 (9.4) |
| Arrythmia | 3 (9.4) |
| Neurologic emergency | 2 (6.3) |
| Cardiac tamponade | 1 (3.1) |
| Pulmonary embolism | 1 (3.1) |
| Diabetic ketoacidosis | 1 (3.1) |

intervention to teach echocardiographic estimation of cardiac output to critical care fellows. After an average of 4.5 teaching sessions, fellows were able to obtain an LVOT VTI measurement in over 90% of patients, demonstrating the feasibility of this intervention within a busy clinical fellowship program.

Fellow measurements of VTI strongly correlated with cardiologist-reported values after the educational intervention. It is important to note that there was agreement in the clinically relevant interpretation of the measured VTI in 80% of cases, and fellow measurement was 91% sensitive to detect an abnormal VTI. Therefore, although there was a mean of 19.5% difference between fellow- and cardiologist-reported VTI and the interrater reliability was only fair to moderate, the clinical significance of these differences is uncertain, and fellow measurement may be sufficient to adequately differentiate shock states. As this is one of the most

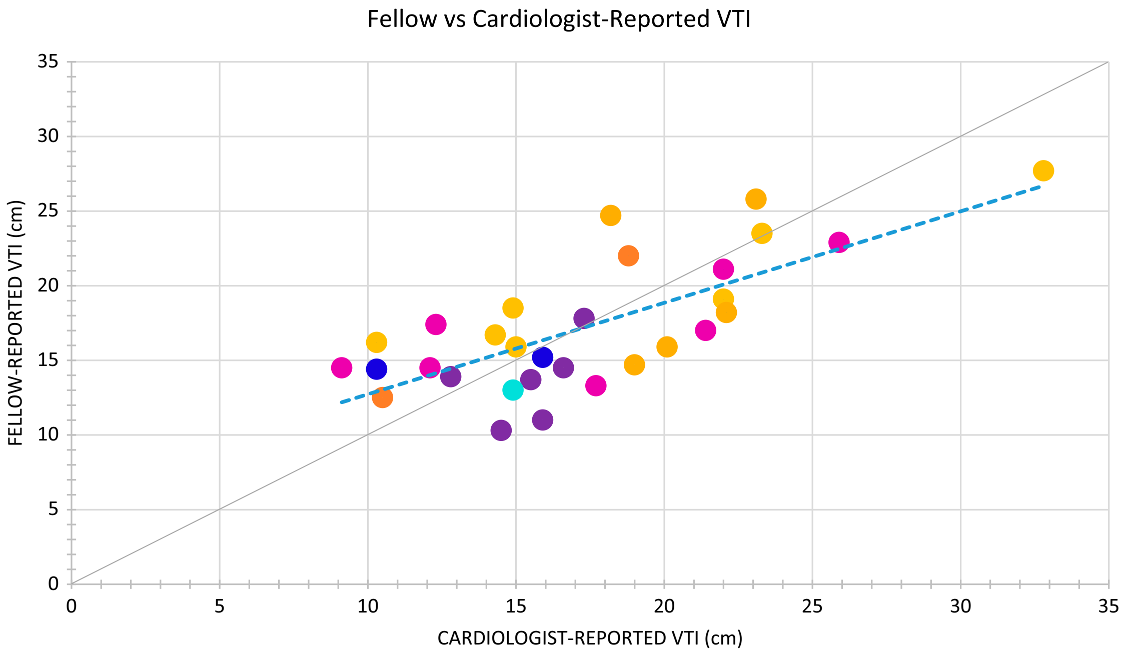


**Figure 1.** Fellow- versus cardiologist-reported VTI. Data from each participating fellow are indicated in unique colors, allowing the individual assessment of fellow performance. The gray line bisecting the graph represents a theoretical perfect agreement between raters. The blue dashed line represents the line of best fit. VTI = velocity time integral.

important applications of this technique, future studies should investigate this in large populations of patients with undifferentiated shock.

### Possible Sources of Fellow Error

Despite the questionable clinical significance, the differences in reported VTI values between fellows and cardiologists were larger than expected, and the specificity of fellow measurement was poor. When compared with the results reported previously by Dinh and colleagues, our percent difference, Cohen's kappa, and Pearson correlation were all slightly inferior (13). Data from this study provide some insight into specific sources of fellow error that could account for these differences. The error appears less likely attributable to the quality of echocardiographic view acquired, as there was no significant difference in quality for the PLAX and A5C views and only a small difference for the A3C view. Similarly, the error is less likely attributable to systemic bias, as Bland-Altman analysis does not suggest that either the cardiologists or the fellows consistently reported VTI values that were higher or lower than those reported by the other group. Rather, the error appears most likely attributable to Doppler measurement techniques, with analysis of sonographic images revealing multiple common Doppler pitfalls, including sample volume placement too close or too far from the aortic valve, inaccurate tracing of VTI spectral display, failure to measure multiple samples in atrial fibrillation, and Doppler angle error. These findings are not surprising, as quantitative Doppler techniques are not part of standard critical care training, and participating fellows had no prior experience with the use of pulsed-wave Doppler.

In considering why Doppler pitfalls may have been a larger contributor to trainee error in this study than in the prior

**Table 2.** Differences between measurements of LVOT VTI and LVOT diameter as reported by fellows and cardiologists

| Measurement ($N$ = 35) | Average | | % Difference | Bias | LOA (95% CI) | | Cohen's κ (95% CI) | Pearson $r$ (95% CI) |
|---|---|---|---|---|---|---|---|---|
| | Fellows | Cardiologists | | | Lower | Upper | | |
| LVOT VTI, cm | 17.0 ± 4.37 | 17.3 ± 5.19 | 19.5 ± 12.0 | −0.091 | −7.23 (−9.58, −4.88) | 7.05 (4.7, 9.4) | 0.379 (0.176, 0.582) | 0.731 (0.623, 0.839) |
| LVOT diameter, cm | 2.07 ± 0.23 | 2.08 ± 0.22 | 8.05 ± 7.0 | −0.010 | −0.4299 (−0.567, −0.291) | 0.409 (0.271, 0.547) | 0.384 (0.214, 0.554) | 0.507 (0.327, 0.687) |

*Definition of abbreviations*: CI = confidence interval; LVOT = left ventricular outflow tract; LOA = limits of agreement; VTI = velocity time integral.

research by Dinh and colleagues, one likely explanation is time spent in training. Our fellows required an average of 90 minutes of individualized hands-on bedside training before meeting the MPS during this study, whereas the attending physicians in the paper by Dinh and colleagues received 20 hours of instruction. Here, we begin to see the implications of expanding this kind of training to an entire fellowship program. Significant individualized training requires intensive effort and time commitment from faculty, a small percentage of whom might be qualified to provide this teaching. For example, if we were to offer 20 hours of training to all fellows at our institution, we would need 480 hours of hands-on instruction alone to teach just VTI and LVOT diameter. The need for time and expert faculty creates a challenge on a national scale, with lack of qualified faculty cited as a major barrier to fellows learning even basic echocardiography, let alone ACCE (16, 17). As it stands, most fellows attempt to learn ultrasound skills independently at the bedside with limited image review, despite fellows' and program directors' perception that supervised learning is more useful (17, 18). This being said, the ideal balance of ACCE training resources and fellow proficiency in these skills remains to be determined and requires further research.

### Variability in LVOT Diameter

Regarding interrater differences in LVOT diameter, the correlation between fellow- and cardiologist-reported values was moderate and notably weaker than that for LVOT VTI. Again, Bland-Altman analysis was not suggestive of systemic bias. On review of images, errors were found in caliper placement. These findings support the recommendations of the American Society of Echocardiography that LVOT

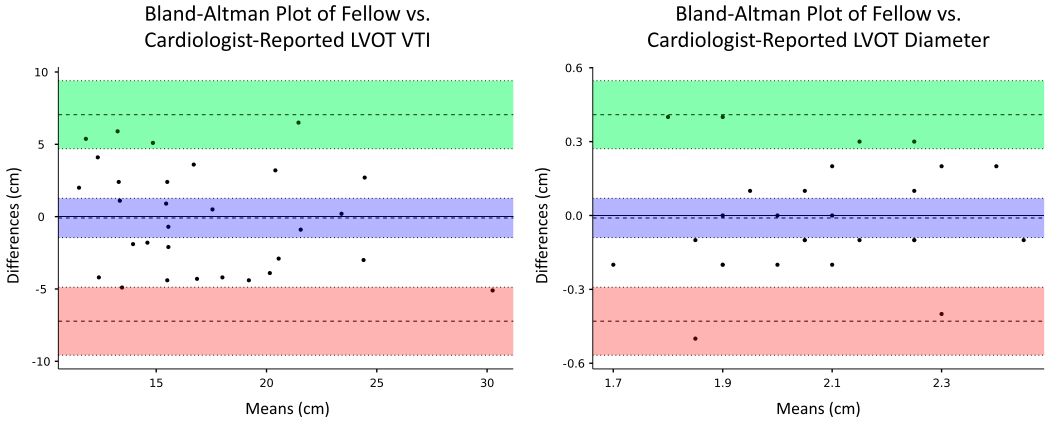


**Figure 2.** Bland-Altman plots for fellow- versus cardiologist-reported values. Bland-Altman plots are shown for fellow- versus cardiologist-reported VTI and fellow- versus cardiologist-reported LVOT diameter. Differences in measurements between the two raters are shown on the *y*-axis, with mean measurements on the *x*-axis. Even distribution above and below the *x*-axis suggests against systematic bias. LVOT = left ventricular ejection fraction; VTI = velocity time integral.

diameter often serves as an unnecessary source of variability when trending cardiac output, because it is squared in the calculation and does not vary significantly between exams.

### Variability between Fellows

Although quantitative analysis of each individual fellow's performance was beyond the scope of this study, our results suggest that there is some variability in accuracy between fellows. This can be seen in Figure 1, as measurements are color coded by individual fellows, and distance from the ideal correlation represents a visual qualification of error. We cannot explain this variation on the basis of our study results, and our sample size is too small to attempt definitive conclusions. Detailed review of fellow images facilitates hypotheses, including that there may be variability in Doppler skills and image quality between fellows. It is also possible that some individual fellows are spending more time at the bedside optimizing images and angles, although we did not measure time spent on image acquisition.

### Variability on Repeated Measurements

One interesting and unexpected finding was a weak positive correlation between fellow VTI error and number of previous exams performed during the study period. Although analyses of learning curves are beyond the scope of this study, one would

**Table 3.** Scoring of echocardiographic images obtained by fellows and professional echocardiography technicians

| Image Scored | Fellow Average | Tech Average | *P* Value |
|---|---|---|---|
| PLAX | 8.49 ± 2.94 | 8.54 ± 3.64 | 0.896 |
| A5C view | 5.37 ± 2.06 | 5.01 ± 2.04 | 0.337 |
| A3C view | 3.71 ± 3.02 | 5.49 ± 2.39 | 0.006 |

*Definition of abbreviations*: A3C = apical three-chamber; A5C = apical five-chamber; PLAX = parasternal long axis; Tech = technician.

expect the opposite direction of correlation if fellow accuracy were improving with subsequent exams. Notably, fellows in this study performed a maximum of seven echocardiograms, and this study was not designed to analyze learning effects. Additionally, we did not adjust our analyses for repeated measurements by the same fellow. Future studies should accumulate larger portfolios from each participating fellow to study the acquisition of mastery. It will be important that these studies utilize appropriate statistical methods to account for variations within each individual fellow's repeated assessments.

### Study Limitations

This study has several limitations, the most apparent being a small sample size. Enrollment was limited by fellows' clinical schedules, and 36% of fellows never reached the MPS to collect study exams, despite interest in participation. That being said, this single-center pilot educational study is, to our knowledge, the largest study to characterize ACCE accuracy of critical care fellows in the clinical setting. Furthermore, the sample size is larger than the compared population of a previous study with a similar design but a different learner group and clinical setting (13). Although the correlation and agreements reported in this study, therefore, may not apply to other training programs nationally, the insight regarding feasibility and the described educational intervention are likely to be widely generalizable.

Another limitation of this study is the acuity of illness, with only 8 (25%) patients examined on vasoactive medications. Although this may create some considerations for generalization to other patient populations, the clinical stability makes hemodynamic changes between the formal echocardiogram and fellow exam less likely. Additionally, appropriate correlation and clinical agreement may be harder to achieve within the range of "normal" values than at the obvious extremes of physiology. Therefore, this likely makes our results more conservative rather than overestimating fellow accuracy.

Finally, the use of images obtained by professional echocardiography technicians to estimate hemodynamic parameters is not a perfect gold standard. Although the sonographers at our center are well trained and have extensive experience, they are not immune to pitfalls that are associated with Doppler techniques. In fact, on examination of the professional images, we encountered three instances of Doppler angle error. That being said, we believe that this is the most sensible gold standard for our purposes and likely reflects the variability of real-world clinical echocardiography.

### Future Directions

This study demonstrates feasibility and gathers initial validity evidence for fellows' performance in the transthoracic echocardiographic measurement of cardiac output. However, there is a need for further research in this area. Future studies should focus on the ability of fellows to differentiate shock states and to predict volume responsiveness in sepsis, which are two of the most clinically useful applications of echocardiographic cardiac output measurement. Future studies are also necessary to further characterize the variability of accuracy between fellows, as well as the learning curve as fellows acquire mastery in these skills.

### Conclusions

After a brief mastery learning intervention, fellows were able to obtain measurements of LVOT VTI and LVOT diameter that demonstrated strong and moderate positive correlations, respectively, with the results of formal echocardiography. Although consistent with an acceptable clinical agreement, the interrater reliability and percent differences revealed areas for further improvement. As with any Doppler measurement, these techniques are prone to certain pitfalls and caveats. Therefore, results should always be interpreted in the context of both the two-dimensional images and the clinical context of any particular patient. Education in these advanced skills is resource intensive, and further research is needed to determine the most efficient and effective approach to training fellows on a larger scale.

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