How I Teach the Estimation of Right Ventricular Systolic Pressure Using Point-of-Care Ultrasound

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ABSTRACT

Point-of-care ultrasound (POCUS) is a powerful diagnostic tool that combines image acquisition with bedside interpretation, enabling physicians to make rapid diagnoses at the bedside (1). Over the last decade, the popularity of POCUS has surged because of its versatility and the immediate insights it provides in clinical decision making (1). However, basic POCUS does not provide important hemodynamic information, such as intracardiac pressures, stroke volume, or valvular regurgitation assessment. Critical care echocardiography (CCE) becomes indispensable as a specialized application of POCUS focused on using Doppler techniques to provide detailed hemodynamic assessments in critically ill patients (2). Teaching hemodynamic evaluation in CCE, such as estimating right ventricular systolic pressure (RVSP), is a challenging yet essential aspect of modern critical care education. RVSP is used to assess the presence of pathologic elevation in right ventricular afterload, which has significant clinical implications for critically ill patients. Deriving RVSP requires understanding ultrasound physics, fluid mechanics, and Doppler techniques and mastery of cardiac image acquisition (3–4). These complex skills are not just important but crucial for effectively managing critically ill patients in the intensive care unit (ICU). In this edition of "How I Teach," we introduce our methodology for instructing learners in our ICU on RVSP estimation using CCE. We use hands-on ultrasound training and e-learning strategies to optimize knowledge retention, ensure accurate interpretation, and promote practical application.

Keywords: RVSP; POCUS; critical care echo; e-learning

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Right ventricular systolic pressure (RVSP) is an estimation of the peak pressure within the right ventricle during systole, calculated based on Doppler measurements in echocardiography. The significance of RVSP is heightened in the intensive care unit (ICU) setting, where concerns such as ventilator-induced increases in transpulmonary pressure, pulmonary vascular resistance from hypoxic vasoconstriction, and elevated right ventricular (RV) afterload are prevalent (2, 3). These factors collectively serve as independent predictors of adverse outcomes (3–6). In the absence of pulmonic stenosis, RVSP is a close approximation of pulmonary artery systolic pressure, offering information about RV afterload. Catheter-measured pulmonary arterial pressures correlate strongly with Doppler-estimated RVSP, making bedside echocardiography an ideal tool for serial assessments (4–6). The ability to perform serial, noninvasive RVSP estimation at the bedside allows for real-time monitoring and timely adjustments to treatment strategies. We recognize that although calculating RVSP may seem challenging, it is a fundamental and important sonographic skill that can be effectively performed by any trained sonographer performing CCE. The process of RVSP estimation involves several detailed steps: identifying tricuspid regurgitation (TR) jet using color Doppler imaging while examining the tricuspid valve from multiple angles, measuring regurgitant jet peak velocity with spectral Doppler, estimating right atrial pressure, and applying the modified Bernoulli equation (7). Despite these perceived complexities, our experience has demonstrated that with specific, focused training, RVSP measurement can be effectively incorporated into the skill set of ICU trainees, enabling them to make more informed decisions in patient management (8–9).

WHO ARE THE LEARNERS?

In the medical ICU (MICU), our advanced ultrasound curriculum and critical care echocardiography training are primarily directed toward pulmonary and critical care medicine fellows, critical care medicine fellows, and critical care nurse practitioners.

WHAT IS THE SETTING?

Education primarily takes place in our MICU, where we emphasize daily POCUS for bedside image acquisition, interpretation, and immediate clinical integration for a variety of diagnostic and procedural purposes. We also extend our training to CCE, which is used in the MICU to address specific clinical questions regarding the hemodynamic status of critically ill patients.

WHAT IS THE APPROACH

The structured curriculum for POCUS education was designed to address the extensive volume and complexity of the material while accommodating the time constraints faced by learners. The program is divided into two tiers: a foundational curriculum for internal medicine residents and an advanced curriculum for pulmonary and critical care medicine fellows. The foundational curriculum, tailored for internal medicine residents, is delivered through weekly modules spanning 3 years, complemented by hands-on scanning sessions led by a team of emergency medicine, internal medicine, and critical care physician sonographers. This ongoing training ensures that residents build a solid foundation in point-of-care ultrasound.

In contrast, the advanced curriculum is specifically designed for fellows and combines e-learning modules with one-on-

one instruction from experienced physician sonographers who are board certified in critical care echocardiography by the National Board of Echocardiography. This advanced training emphasizes complex techniques, including hemodynamic assessment using color and spectral Doppler, which are essential prerequisites for RVSP estimation. By integrating e-learning with bedside instruction, the curriculum provides learners with a comprehensive and progressively structured approach to skill development throughout their training.

As part of this approach, learners are required to complete seven e-learning modules (Table 1), distributed via e-mail 1 week before their ICU rotation, before attending practical, hands-on scanning sessions. Each module, designed to take just 5 minutes to complete, provides the foundational knowledge necessary for accurate RVSP estimation. After completing the modules, learners advance to in-person sessions, where they further develop their skills through focused practice.

The e-learning platform allows for tracking module completion, ensuring accountability among learners. Completion of the e-learning modules is a mandatory prerequisite for participation in hands-on practice sessions. This structured progression ensures that learners arrive at in-person sessions with a solid foundational understanding, enabling them to refine their skills through focused and systematic practice.

Competency in RVSP estimation is not tied to a fixed number of training hours but is assessed through entrustable professional activities (EPAs), focusing on the learner's ability to independently perform the procedure. A full list of our EPAs can be found in the supplement to this article. This includes both accurate image acquisition and correct interpretation of the results. Fellows are deemed competent when they

Table 1. E-learning modules are delivered before hands-on educational sessions

E-Learning Module Topic	Relationship of RVSP Education
1. RV inflow https://forms.office.com/r/gdpnUL9cFJ	The first view used to assess the tricuspid valve and TR max velocity
2. PSAX base TV https://forms.office.com/r/T4hVPCC6tR	The second view used to assess the tricuspid valve and TR max velocity
3. Apical 4 https://forms.office.com/r/bER0mn7Js3	Builds an understanding of how to obtain the RV-focused view. TR max can be evaluated here
4. RV focused https://forms.office.com/r/gtYf40ZEhF	Third view used to assess the tricuspid valve and TR max velocity
5. Color Doppler https://forms.office.com/r/aMCMpcYd1V	Color Doppler determines the presence and location of tricuspid valve regurgitation
6. PW and CW https://forms.office.com/r/QHfZk3ifMf	CW is used to measure TR max velocity
7. RVSP https://forms.office.com/r/mKHBTUiF8q	Compiles the three echo views, color Doppler, CW Doppler, IVC measurement, and RAP pressure assigned and described the simplified Bernoulli equation

Definition of abbreviations: CW = continuous wave; IVC = inferior vena cava; PSAX = parasternal short axis; PW = pule-wave; RAP = right atrial pressure; RV = right ventricular; RVSP = right ventricular systolic pressure; TR = tricuspid regurgitation; TV = tricuspid valve.

demonstrate the capability to perform RVSP estimation independently, meeting the quality assurance standards required for inclusion in their imaging portfolio (10). To ensure consistency and thorough evaluation, we implement a structured EPA framework during bedside training, which allows us to systematically assess both image acquisition and interpretation skills. These assessments are based on a checklist of key competencies, including probe positioning, Doppler angle alignment, and accurate application of the modified Bernoulli equation. Once learners demonstrate competency on at least three consecutive cases, they are deemed independent in performing RVSP estimation (10).

WHAT IS THE CONTENT?

Our blended learning methodology adapts David Kolb's experiential learning theory by modifying its traditional structure to better align with our educational goals. Kolb's model typically follows four stages: concrete experience, reflective observation, abstract conceptualization, and active experimentation (10). However, instead of introducing new content during in-person sessions, as in a traditional classroom format, we begin with e-learning in a flipped classroom approach. Learners first engage in abstract conceptualization by building a theoretical foundation through e-learning, which is then applied during supervised, hands-on scanning sessions that provide concrete experience. This is followed by reflective observation, where learners enhance their understanding by observing others perform the techniques. To ensure comprehensive learning and competency, we integrate EPAs into the final phase. These EPAs guide learners through active experimentation, allowing them to progressively perform tasks independently, demonstrate proficiency in image acquisition and interpretation, and meet the required quality assurance standards (11).

Components of RVSP Measurement E-Learning Modules

In the first four modules (Table 1), we review transducer manipulation guided by the 2019 American Society of Echocardiography (ASE) guidelines to obtain the RV inflow view (Figure 1), parasternal short axis view (Figure 2), apical four-chamber view, and RV-focused view.

Modules five and six shift the focus to Doppler techniques necessary for identifying TR and measuring regurgitant jet velocity. These modules introduce color Doppler for mapping blood flow velocity and cover both pulsed-wave and continuous-wave Doppler, emphasizing that continuous-wave Doppler is required for RVSP calculations (Figures 2–4).

The final module integrates the knowledge from the previous six modules into a step-by-step approach for estimating RVSP. It reviews color Doppler assessment of the tricuspid valve, continuous-wave Doppler measurement of the tricuspid regurgitant jet, and estimation of right atrial pressure, including evaluation of the inferior vena cava and central venous pressure. The module concludes with a review of the modified Bernoulli equation and a summary video demonstrating RVSP measurement in a real patient.

Bedside Education

Learners are provided with opportunities to engage in deliberate practice with timely feedback during their ICU rotations by integrating RVSP estimation with POCUS into daily activities. Bedside education is conducted using the cart-based ultrasound machines available in the ICU, ensuring that learners practice in

Figure 1. E-learning module transducer movement (fanning) from the parasternal long axis to right ventricular inflow view.

a clinically relevant environment. Facilitators demonstrate the use of key functions such as zoom, cine-loop, color Doppler, spectral Doppler, and the appropriate cardiac packages for right heart function and tricuspid and pulmonic assessments (12).

To optimize retention and understanding, a structured approach is used: facilitators first demonstrate the sequence of control selections, followed by two guided practice attempts in which learners receive immediate feedback. Learners then complete two additional solo practice attempts, refining their skills independently. Finally, they solidify their learning by describing each step of the process to the instructor, ensuring comprehension and retention. This deliberate practice model allows learners to effectively build competency in POCUS techniques, even during the demands of their busy ICU rotations.

Step-by-Step RVSP Procedure

Step 1: Image acquisition.

Anatomy identification. Visualize the right atrium, tricuspid valve, and right ventricle, which can be achieved using

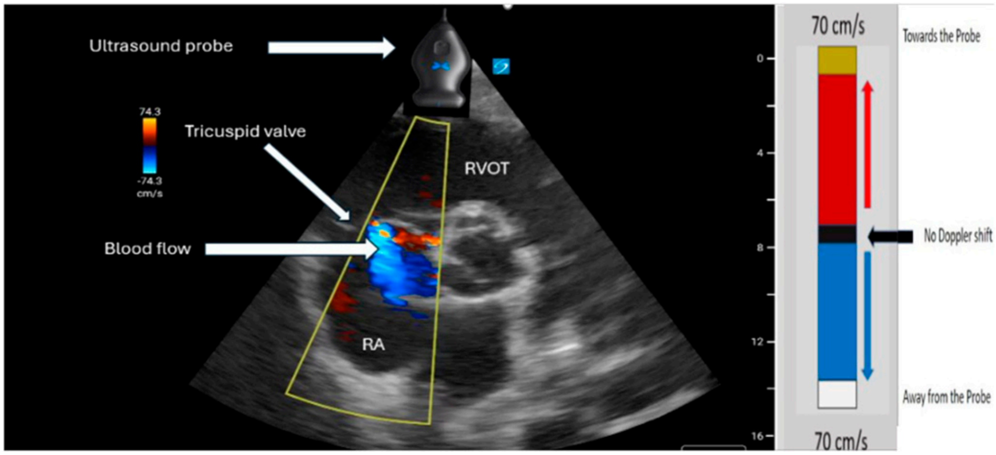

Figure 2. E-learning module 2 parasternal short axis base tricuspid valve view and color Doppler scale. RA = right atrium; RVOT = right ventricular outflow tract.

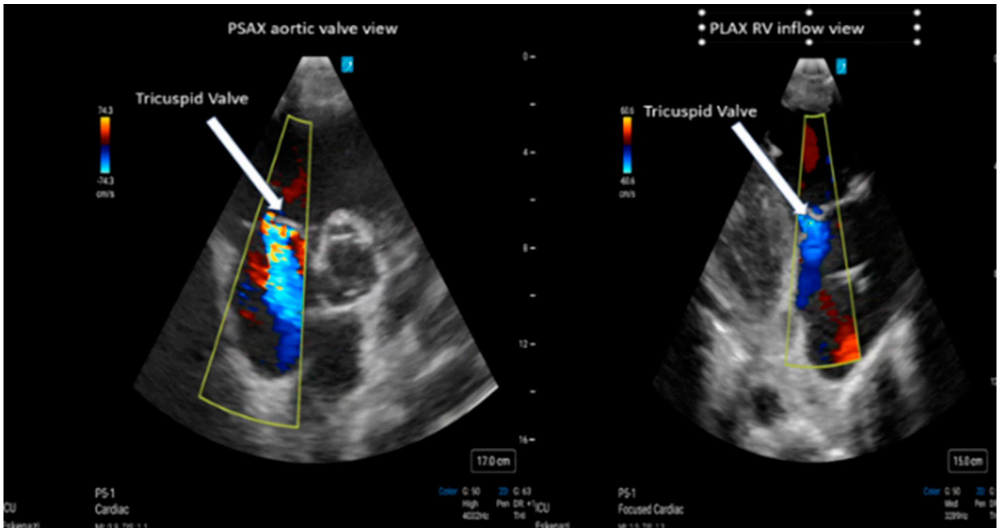

Figure 3. E-learning showing tricuspid regurgitation in the parasternal short axis view and right ventricular inflow view. PLAX = parasternal long axis; PSAX = parasternal short axis; RV = right ventricular.

the RV inflow view, parasternal short axis view, or RV-focused apical four-chamber view.

Transducer manipulation. Use rocking and fanning movements to align the tricuspid valve leaflets perpendicular to the ultrasound beam for optimal visualization of blood flow.

Once the correct image orientation is achieved, proceed to apply Doppler techniques for a detailed assessment of TR.

Step 2: Assess for TR.

Apply color Doppler. Place the color Doppler over the tricuspid valve and adjust the color box to capture the proximal right atrium. Ensure the color scale is set to at least 70 cm/s.

Interpret aliasing. Be aware of aliasing of the TR jet, which may appear as yellow or bright red hues near the regurgitant orifice, especially with fast-moving regurgitant jets.

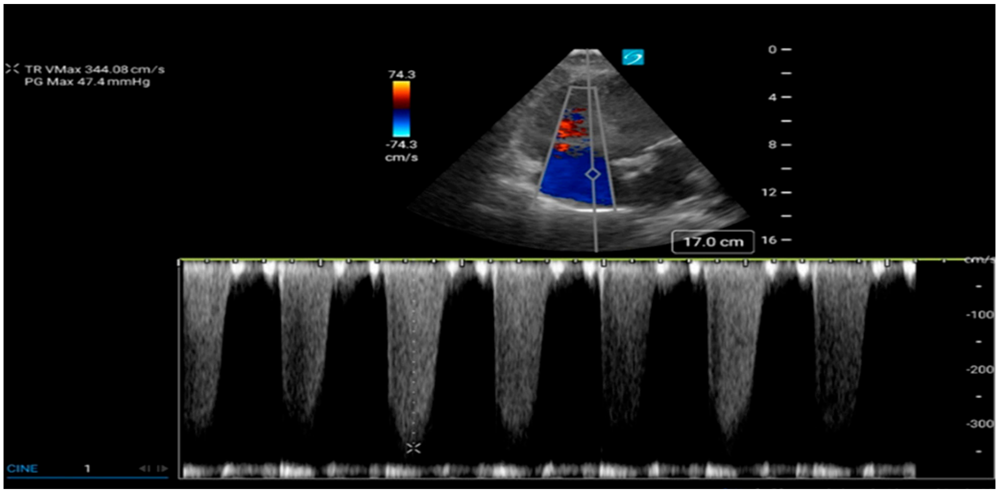

Figure 4. E-learning module 5 continuous-wave Doppler estimation of TR jet velocity. PG = pressure gradient; TR = tricuspid regurgitation.

Position continuous-wave Doppler. Align the continuous-wave Doppler over the highest velocity region of the jet, ensuring the interrogation angle is <20 degrees.

Once the Doppler signal is optimized, proceed to measure the tricuspid regurgitant velocity, which will assist in estimating the RVSP.

Step 3: Measure regurgitant jet velocity.

Adjust spectral Doppler settings. Adjust the baseline and scale to fully visualize the Doppler profile of the tricuspid regurgitant jet.

Record TR peak velocity. Measure and record the peak velocity (Vmax) of the TR jet in cm/s, ensuring the Doppler trace displays a well-defined, clear spectral envelope. This value will later be converted to m/s when used in the Bernoulli equation in Step 5.

With the peak velocity recorded, proceed to estimate the right atrial pressure (RAP).

Step 4: Inferior vena cava assessment and RAP estimation.

Transducer position. Place the transducer in the subxiphoid space with the indicator at the 12 o'clock position to visualize the inferior vena cava (IVC). Use M-mode to measure the IVC diameter during respiration, assessing its collapsibility with a sniff maneuver.

RAP estimation based on IVC indices. Based on ASE recommendations, the following method is used to estimate RAP by assessing the IVC diameter and its collapsibility during inspiration in nonintubated patients. An IVC diameter <2.1 cm with >50% collapse during inspiration corresponds to an RAP of approximately 3 mm Hg. An IVC diameter <2.1 cm with <50% collapse typically suggests an RAP of 8 mm Hg. Finally, an IVC diameter >2.1 cm with <50% collapse indicates an RAP > 15 mm Hg.

Alternative measurements for intubated patients. We use two noninvasive methods to estimate whether the RAP is greater than or less than 10 mm Hg in intubated patients.

E/Ea ratio. In intubated patients without a central venous catheter (CVC), the tricuspid E/Ea ratio can estimate RAP. This ratio compares early diastolic inflow velocity (E) with early diastolic relaxation velocity (Ea). A ratio >4.7 is predictive of a central venous pressure (CVP) > 10 mm Hg (14).

ICV diameter. In mechanically ventilated patients, the IVC diameter and its respiratory variation are less reliable because of positive pressure ventilation. However, according to the ASE guidelines for the echocardiographic assessment of the right heart, an IVC diameter of <1.2 cm in intubated patients can identify patients with RAP < 10 mm Hg (15).

Invasive measurements of RAP.

Using CVC to measure RAP. In mechanically ventilated patients with a CVC in place, RAP is directly measured as CVP from the distal port. To convert CVP from cm H_2O to mm Hg, use the conversion factor: 1 cm H_2O = 0.7 mm Hg.

With both the TR jet velocity and RAP estimated, you can now apply the modified Bernoulli equation to calculate the RVSP.

Step 5: Calculate RVSP.

Apply the modified Bernoulli equation. Use the formula $RVSP = 4 \times (TR\ Vmax)^2 + RAP$ to calculate the RVSP.

Verify that the TR Vmax is reported in m/s, and then add the RAP value to the pressure gradient calculated using the Bernoulli equation.

Document the result. Record the estimated RVSP and ensure that all images and measurements are accurately documented for future reference. Images are then acquired in the parasternal short axis and RV-focused apical views. For each subsequent view, steps two through four are repeated, and the highest RVSP is documented.

WHAT CAN BE CHALLENGING?

Arrhythmias

Arrhythmias, such as atrial fibrillation, pose significant challenges to accurate RVSP estimation, as the variability in cardiac cycle length can lead to inconsistencies in TR velocities.

Solution. To address this, learners should be taught to avoid using beats immediately after an extra systolic beat for RVSP estimation. They should focus on acquiring spectral Doppler signals over several cardiac cycles and average these measurements to improve accuracy. It is also important to identify and use the most stable cardiac cycles, typically during periods of regular rhythm (5, 13, 15).

Severe TR

In cases of severe TR, the use of the modified Bernoulli equation becomes unreliable because of large regurgitant volumes distorting the velocity measurements. Severe TR can mask the true peak regurgitant jet velocity, leading to underestimation of RVSP.

Solution. To mitigate this, learners should be trained to recognize the hemodynamic effects of severe TR during image acquisition. This includes identifying clues such as large color Doppler regurgitant jets and blunted spectral Doppler profiles. When severe TR is suspected, learners should be cautious in interpreting RVSP values and consider alternative diagnostic methods such as right heart catheterization for accurate pressure measurement (5–15).

Improper Alignment of the Doppler Signal

Doppler signal alignment is critical for accurate RVSP estimation, as misalignment can lead to underestimation of TR velocities. Achieving an optimal Doppler angle (<20 degrees) can be difficult, especially in patients with challenging anatomy or suboptimal acoustic windows.

Solution. To improve alignment, learners should be trained to acquire multiple views (e.g., parasternal long-axis, apical, subcostal) to find the best alignment between the ultrasound beam and TR jet. Hands-on practice with live patients and ultrasound phantoms can help learners develop a feel for subtle transducer adjustments that optimize Doppler alignment.

Absence of TR

The absence of TR presents a significant limitation for RVSP estimation, as Doppler echocardiography relies on the TR jet to calculate pressures. When TR is minimal or absent, noninvasive estimation using the modified Bernoulli equation becomes impossible.

Solution. Learners should be taught to recognize when the absence of TR indicates an underlying pathological condition rather than normal hemodynamics. In such cases, indirect markers, such as RV size, pulmonary artery dilation, and septal flattening, should be assessed for signs of elevated pulmonary pressures (5, 12, 15). When TR is absent, the injection of saline can enhance the Doppler signal by increasing the echogenicity of blood and improving the signal-to-noise ratio. This technique facilitates the detection and quantification of subtle regurgitation that may otherwise be overlooked during standard echocardiography (16).

RV Failure

RV failure can lead to both underestimation and overestimation of pulmonary pressures. Here, we describe these contrasting phenomena.

Underestimation of Pulmonary Pressures

In cases of RV failure, the TR jet velocity may be deceptively low because of a diminished pressure gradient between the RV and the right atrium. This reduction reflects the compromised ability of the RV to generate adequate pressure, resulting in a lower RVSP. Importantly, a low TR jet velocity gradient does not necessarily equate to any level of pulmonary hypertension, as the gradient is influenced by both RVSP and right atrial pressure. In severe RV failure, elevated right atrial pressure further narrows the gradient, masking the presence of elevated pulmonary artery pressure. This highlights the need to interpret TR jet velocity in the broader context of RV function and overall hemodynamic status to avoid underestimating the severity of pulmonary hypertension.

Solution. To avoid overestimation of pulmonary pressures in cases of TR caused by structural changes, additional echocardiographic measurements can help distinguish between mechanical and pressure-driven regurgitation:

- RV basal diameter: A diameter >42 mm at the base suggests RV dilation.
- RV Midcavity diameter: A midlevel diameter >35 mm indicates RV enlargement (16).

Overestimation of Pulmonary Pressures

A dilated RV and tricuspid annulus can lead to TR even in the absence of elevated pulmonary pressures, driven by mechanical alterations in the tricuspid valve apparatus. As the RV dilates, the tricuspid annulus enlarges, preventing the tricuspid valve leaflets from achieving proper coaptation during systole.
This structural dysfunction results in regurgitation that is not reflective of elevated pulmonary pressures but rather of the anatomical changes within the right heart. Recognizing this mechanism is critical to avoiding overestimation of pulmonary pressures based solely on the presence of TR.

Limited Views

In patients with conditions such as chronic obstructive pulmonary disease, where standard echocardiographic views, including the parasternal long axis, parasternal short axis, and apical views, are challenging to obtain, RVSP estimation can be difficult.

Solution. In such cases, learners should be familiar with the subcostal short axis view, which provides access to the tricuspid valve and allows evaluation of the TR jet velocity. This view is obtained by positioning the transducer in the subxiphoid area at the 12 o'clock position, then rocking the tail toward the pelvis while fanning slightly to the left until the base of the heart is visualized, using the liver as an acoustic window (Figure 5).

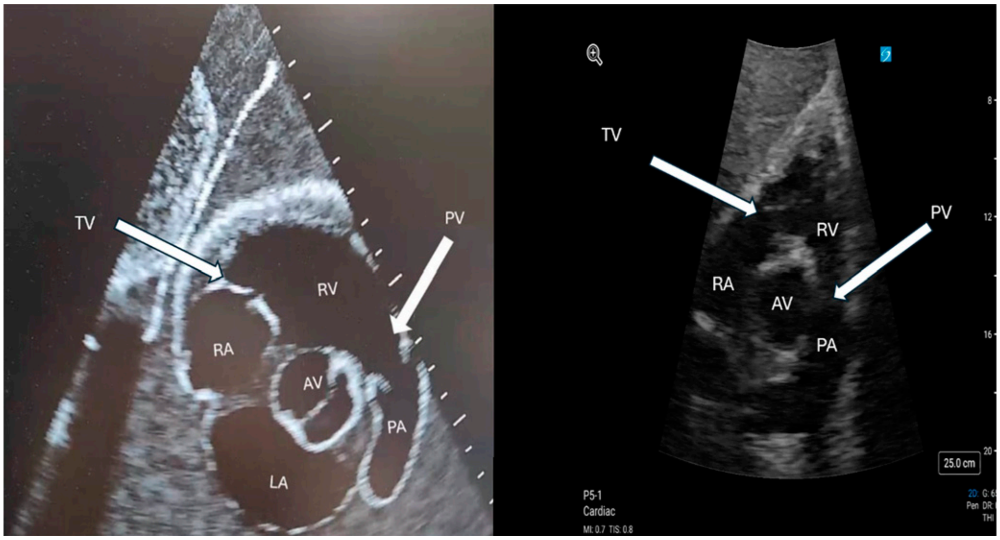

Figure 5. Subcostal short axis view. The image on the left is a simulated view, and the image on the right is an actual patient view. AV = aortic valve; LA = left atrium; PV = pulmonic valve; RA = right atrium; RV = right ventricle; TV = tricuspid valve.

Acquiring Highest Jet Velocity

Anatomical variability can sometimes make it difficult to align the continuous-wave Doppler tracing parallel to the regurgitant jet, potentially leading to an underestimation of RVSP.

Solution. To mitigate this issue, multiple RV views should be used, and expertise in probe manipulation and image acquisition should be developed. Furthermore, the spectral tracing should be measured at the clear, sharp, and well-defined TR jet signal, commonly referred to as the "chin," rather than the fuzzy, less-defined portion of the signal, known as the "beard," which is less accurate (13–15).

WHY THIS APPROACH

This approach is designed with both practicality and efficacy in mind, ensuring that learners can confidently acquire the complex skills necessary for RVSP estimation in critically ill patients. By integrating e-learning modules with hands-on instruction, we provide a structured yet flexible learning environment that allows trainees to build foundational knowledge at their own pace before applying it in real-world, high-stakes clinical scenarios. The repeated practice of ultrasound techniques, reinforced by immediate feedback, ensures learners achieve proficiency in both image acquisition and interpretation. Moreover, the step-by-step teaching of RVSP estimation, grounded in Doppler physics and anatomy, enables learners to navigate the nuanced challenges posed by different patient anatomies and conditions. Ultimately, this approach fosters not only technical competence but also critical thinking, empowering trainees to make informed, timely decisions that directly impact patient outcomes in the ICU.

This educational methodology can be adapted for other advanced sonographic practices and holds great promise for enhancing both patient care and bedside education.

Author disclosures are available with the text of this article at www.atsjournals.org.

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