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The Evolution of Ultrasound in Critical Care:

From Procedural Guidance to Hemodynamic Monitor

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Point-of-care ultrasound (POCUS) has become a standard of care in the contemporary medical intensive care unit (ICU). A cursory chronologic survey of POCUS in the medical ICU over the past 3 decades is summarized by sequential expansion of its roles (Figure 1). We believe this illustrates a transition from POCUS as a procedural assistance tool to that of a diagnostic asset couched within an extended physical examination. However, with recent developments in machine learning and the sophistication of POCUS technologies, we propose that POCUS is further evolving into a hemodynamic monitoring tool, affording clinicians cross-sectional measurements that are trended and used during ICU management similar to traditional vital data.

Chronologic Survey

With the development of smaller, faster, and more-portable real-time ultrasound (US) devices during the last 2 decades of the 20th century, emergency medicine adopted POCUS early in routine care, embracing it as a quicker and, potentially, more accurate management tool in trauma and shock. Thereafter, the use of POCUS in the medical ICU grew but initially for procedural guidance.¹ However, as evidence of POCUS use in shock and trauma in emergency medicine solidified, medical intensivists also adopted bedside US as a diagnostic tool in shock, with the goal of quickly capturing life-threatening abnormalities.² This relatively qualitative approach gave rise to protocolized US assessments summarized by mnemonics such as RUSH (rapid ultrasound in shock,) FAST (fast assessment in shock and trauma), and ACES (abdominal and cardiac evaluation with US in shock).³ As these

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protocols improved the efficiency and expediency of recognizing patients with life-threatening conditions (eg, differentiating shock etiology), the popularity of POCUS as a clinical decision support tool in acute care settings has grown. For example, POCUS training is now widely encouraged in both internal and critical care medicine training programs.⁴

Broad use of thoracic, abdominal, and vascular US over time has given intensivists confidence when using POCUS for the diagnosis of nuanced conditions. Intensive care unit trainees are now empowered to distinguish between etiologies of acute respiratory failure (eg, pneumonia versus pulmonary edema). Indeed, the Apprentissage de l'Echographie Pulmonaire Study Group found that 25 supervised examinations are required for competence in lung US,⁵ and lung US has excellent accuracy for differentiating basic causes of respiratory failure.⁶ Additionally, whole-body US protocols have been published for the evaluation of hemodynamic instability, hypoxemia, encephalopathy, and oligoanuria among other conditions.⁷ Although the diagnostic accuracy of each of these protocols is beyond the scope of this brief, narrative review, POCUS is providing decision support to clinicians.^{8,9}

Consequently, used as a comprehensive, multi-organ assessment tool offering repetitive US assessments during the extended course of a patient's ICU stay, POCUS is undergoing a paradigm shift, moving its focus from a qualitative toward a quantitative assessment of pathologic processes. Iterative POCUS in resuscitation has become particularly relevant, with recognition of the detrimental effects of excessive fluid resuscitation and identification of functional hemodynamic parameters as keys to successful intravenous fluid management in shock.¹⁰ Functional hemodynamic monitoring is underpinned by the concept of the preload challenge and typically demands recurrent bedside evaluations for diagnostic decisions. In other words, functional hemodynamic monitoring is predicated on accurate measurement of the stroke volume—or some surrogate—in response to an altered cardiac preload. Unsurprisingly, POCUS has been recognized as an important tool in guiding shock management,¹¹ especially given its ability to quickly and repeatedly provide semiquantitative hemodynamic information such as a change in the left ventricular (LV) ejection fraction, right ventricular size and function, estimation of central venous pressures, and information about third spacing of fluids. Furthermore, the proficiency with which POCUS provides dynamic parameters of fluid responsiveness such as cardiac output, the LV outflow tract velocity time integral (VTI), inferior vena cava distensibility, and corrected flow time variability has revealed a promising fund of predictive metrics.^{12,13}

Point-of-Care US as a Monitoring Tool

The transition to precise and fully quantitative US has been slowed by high interoperator variability, which can affect the interpretation of US-derived data¹⁴; for example, capturing and interpreting US images is heavily influenced by training and experience.⁵ Although much effort has been invested in standardizing training and defining POCUS competency, diagnostic and management errors may be reduced by technological advances, giving birth to the concept: “train every physician to use US, but train US to tolerate every physician.”¹⁵ Accordingly, early methods of artificial intelligence (AI) in POCUS such as autocapture of the LV outflow tract VTI,¹⁶ inferior vena cava distensibility,¹⁷ and pulmonary B-lines¹⁸ have been deployed (Figure 2, A–C). Ostensibly, acquiring, retaining, and sharing US data that

are augmented by AI will mitigate interoperator variability and afford safer clinical practice. Although there are many proposed AI applications for both pulmonary and cardiac POCUS (falling under such broad headings as intelligence augmentation, automated image labelling and quality, decision support, and data mining¹⁹), these avenues are still emerging. Moreover, building AI requires large databases of US images with both normal and pathologic findings,¹⁹ and finally, AI advancements are not infallible. For instance, VTI measurements can be flawed secondary to image quality or specific pathologic conditions (eg, pulsus bisferiens in the LV outflow tract); similarly, vena cava variation may be affected by the patient's condition (eg, respiratory variation, breathing pattern, or intra-abdominal hypertension), leading to erroneous conclusions.²⁰ In addition to AI, the development of smaller, attachable US transducers,^{21–23} capable of monitoring hemodynamics across time, heralds a new and exciting era whereby POCUS is used as a monitoring device among other applications (Figure 2D). As with machine learning and AI, adherent US monitors may limit subjectivity and measurement variability.²²

Conclusions

Ultrasound in the ICU will continue to expand and evolve. Although new technology often begins with great excitement, some of this initial enthusiasm must be tempered. Point-of-care US as a decision-making tool during shock resuscitation is still nascent—further research and experience will shape its future and reveal its reliability and limitations. Crucially, POCUS must remain a tool that enhances management based firmly on Bayesian principles. The onus is on the operators to remember that POCUS remains an “extended stethoscope” and, potentially, a supplemental monitor with which the clinician triangulates all available data.

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Abbreviations

AI	artificial intelligence
ICU	intensive care unit
LV	left ventricular
POCUS	point-of-care ultrasound
US	ultrasound
VTI	velocity time integral

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THE EVOLUTION OF ULTRASOUND IN THE ICU

Figure 1.
Evolution of POCUS in the medical ICU.

Figure 2.

Novel automatization approaches still to be clinically validated: **A**, Auto recognition of inferior vena cava distensibility. **B**, Left ventricular outflow tract VTI autocapture with trending over time. **C**, Autorecognition of pulmonary B-lines. **D**, “Patch” transducer continuous carotid VTI/carotid corrected flow time monitoring. These examples reflect the use of POCUS in iterative cross-sectional evaluations and real-time hemodynamic monitoring (used with permission from GE Healthcare, Pasadena, CA [A–C] and Flosonics Medical [D]).