The Future
ICU

PLUS

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The Future of Critical Care Ultrasound

Critical Care Ultrasound (CCUS) has progressed by leaps and bounds, and will continue to push boundaries, with techniques being modified to suit evolving clinical needs and new applications.

Introduction

With roots traceable to sonar technology developed for underwater listening and submarine detection, the era of medical ultrasound began during the Second World War; the first research paper on brain ultrasonic transmissions was published by Dr. Karl Theodore Dussik in 1942. The 1950s saw the development of echocardiography and obstetric ultrasound, followed by pulsed Doppler and 3D ultrasound a few decades later, establishing the diverse applicability of ultrasound in medicine (ultrasoundschoolsguide.com/history-of-ultrasound/).

Thereafter came the technological advances in electronics, computing and transducer engineering which radically improved image quality and processing. The introduction of microbubble contrast agents enabled functional assessment of tissue beds at a microvascular level.

During this time, emergency ultrasonography had been gaining momentum; the Focused Assessment with Sonography for Trauma (FAST) examination is considered the first and most significant widespread application of ultrasound outside the radiology department, performed by emergency physicians at the point of care in trauma patients (Richards and McGahan 2017).

Critical Care Ultrasound (CCUS) has also become more commonplace, beginning with the extension of echocardiography beyond the remit of cardiologists. Increasingly considered a valuable tool for diagnosis, monitoring and guidance of practical procedures in critically ill patients, its applications continue to evolve. In recognition of the need for consistency and quality in practice, there now exist formal routes to CCUS accreditation (Galarza et al. 2017).

Given the rate at which ultrasonography has progressed in this short time, what can we expect next? We will consider two aspects likely to have the greatest impact in CCUS: the machine and the modalities.

The Machine

The ideal ultrasound machine is light, smart, affordable and accessible. Early prototypes took the form of large water-filled drums with a transducer passing along the circumference to capture images of the patient immersed within **(Figure 1)**. These days, having done away with water baths, the average ICU machine is the size of a large computer and can be wheeled to the patient's bedside **(Figure 2)**.

Pocket-Sized Portability

A huge leap in technology within the past few years has led to the development of handheld ultrasound devices with the processing power of a smartphone **(Figure 3)**. Despite miniaturisation and some limitation of functions compared to full-sized machines, these devices retain an impressive array of capabilities with image quality that is continually improving. Initially restricted to 2D or B-mode imaging, handheld devices now integrate more advanced functions such as Colour Doppler, with some running on artificial intelligence-powered software, though none of these incorporate spectral Doppler at present (Blood and Mangion 2019).

A fairly recent paradigm shift in the processes within critical care medicine has given rise to the concept of ICU without walls, an aspirational model of care intended

Figure 1. Early prototype ultrasound machine. Source: Medical Diagnostic Ultrasound: A retrospective on its 40th anniversary (1998) Kodak Eastman with National Museum of American History.

Figure 3. Handheld ultrasound devices. Source: becominghuman.ai.

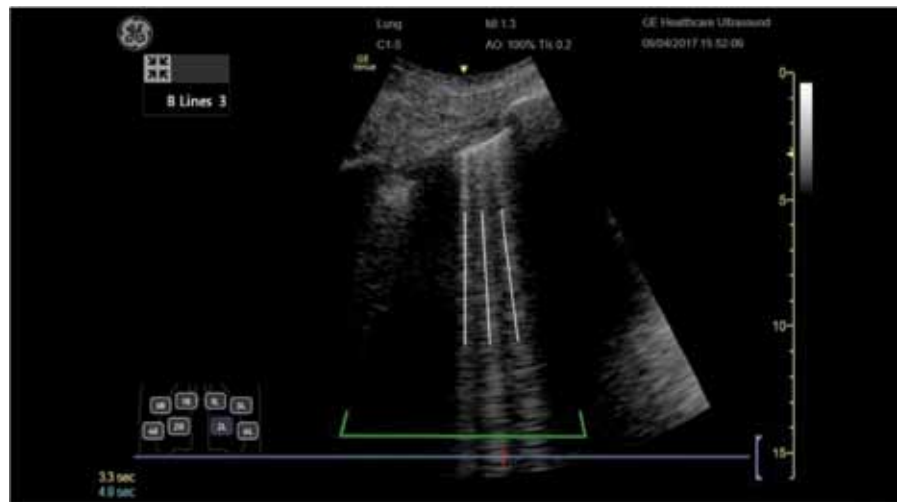**Figure 2.** Modern bedside ultrasound machine. Source: iusimaging.com.

Figure 4. B lines detected during ultrasound examination of lung parenchyma, as delineated by white lines. The number of B lines in each examined zone can be recorded, allowing a comparison between zones. Source. gehealthcare.nl

to recognise and respond to critical illness early and rapidly. This concept proposes that the ICU is defined not by physical location but by a set of healthcare professionals with relevant expertise to care for the at-risk/ critically ill patient even if they are located outside of the ICU. A handheld ultrasound device can be readily taken to the wards or indeed anywhere in the hospital by the intensivist for these purposes, aligning it neatly to the concept of ICU without walls.

Augmented Intelligence and Machine Learning

The use of artificial intelligence is expand-ing within critical care, an important example of which is a sepsis prediction tool that processes a large volume of patient-related data within an algorithm and alerts healthcare professionals to those at risk of developing sepsis (Desautels et al. 2016). The term 'artificial intelligence' in this instance alludes to the fact that machine has completely replaced mankind in the algorithmic prediction of sepsis. Where ultrasound is concerned however, the operator as yet cannot be replaced despite sophisticated software engineering, and therefore the term 'augmented intelligence' might be more accurate, reflecting an enhancement rather than replacement of the operator's ability. The ways in which augmented intelligence has revolutionised CCUS is two-fold: image optimisation and image analysis.

As machines become smaller, it is their computational ability that allows advanced image processing in order to minimise operator variability and compensate for limitations in image quality control. Through augmented intelligence, images can be automatically adjusted for noise while purposefully recognising relevant artefacts to provide the best quality of information to the practitioner, with little need for

manual adjustment or indeed in-depth knowledge of the controls.

With the addition of image analysis software packages, once the probe has been appropriately positioned for a specific view, the machine will detect and highlight structures/artefacts e.g. identifying left ventricular outflow tract in the apical 4 chamber view or B-lines on lung ultrasound **(Figure 4)**. Automatic calculation of indices is also possible e.g. estimation of ejection fraction.

Augmented intelligence does have its limitations and in its current iteration at least, machine learning does not replace clinical acumen; ultrasound findings still need to be integrated into the clinical context (arguably the most challenging aspect of CCUS). However, this technology can save valuable time during the scanning process, accommodates variability due to operator/patient/environmental factors and can increase diagnostic confidence of the clinician by providing a 'second read' on the image particularly if the practitioner is relatively inexperienced or unable to seek a second opinion. Remarkably, despite augmented intelligence being in its early stages, it has already been shown that machine algorithms are more reliable in detecting cancer compared to human operators (Ardila et al. 2019).

Cloud-Based Technology

The process of obtaining a second opinion has been revolutionised by cloud-based technology; long gone are the days of sending hard copy images by courier to a specialist centre or transmitting studies via the internet from a specified workstation. Through wireless capabilities, ultrasound machines, including handheld devices, are able to instantaneously upload ultrasound studies to the Cloud with unlimited storage capacity, enabling swift sharing of images and more convenient access to expert opinion. Individual manufacturers have proprietary platforms allowing remote review and discussion of images.

Akin to the concept of ICU without walls, cloud-based technology and the ability to remotely access large volumes of patient data appear to be a significant evolutionary step in telemedicine, taking patient care beyond the constraints of hospital walls. An excellent example of this is presented by the Emory Healthcare group whereby collaboration between ICU teams in Atlanta USA and Australia across a 12 hour time zone positively impacted upon patient care including health spending and 60-day readmissions (Trombley et al. 2017). The eICU platform allows distant monitoring, diagnosis and management with consultant-led reciprocal care for the partner group during overnight periods where senior-level staffing typically decreases; Cloud-based imaging data can be vital to clinical decision making in these settings.

Key issues such as patient confidentiality, consent, data protection across digital networks and ownership of data become of prime importance at this level of technological innovation and need to be addressed with care and transparency

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(Lui 2018). A detailed discussion of these issues is beyond the scope of this article.

Ultrasound as a Replacement for the Stethoscope?

Given its safety profile and real-time applicability, the potential of the ultrasound machine to replace the stethoscope has already been debated in educational and

clinical circles.

A handheld device is as portable as a stethoscope while providing far more detailed diagnostic information in most clinical scenarios. It would not be far-fetched to predict the handheld ultrasound device may soon supersede the stethoscope in healthcare settings without budgetary constraints, although the practical considerations e.g. appropriate training, image documentation and governance should not be underestimated.

The Modalities
Standardising Training and Improving Access
International expert and consensus statements from nearly a decade ago had already made the case for ultrasound competency in intensivists, defining a core skill set and more advanced ones (Mayo et al. 2009).

It is generally agreed that the core CCUS skill set includes the ability to scan the heart, lungs, abdomen and vascular system, but the definition of these competencies permits flexibility of interpretation and therefore variations are common in skill sets of practitioners accredited in CCUS from different countries/regions/training centres (Malbrain et al. 2017). There also remain barriers to implementation of training programmes, with a recent international survey highlighting a shortage of trainers and mentors in many countries (Galarza et al. 2017).

To address the accessibility issues for novices seeking training in CCUS, there are now online learning platforms providing video-based lectures and demonstrations covering basic techniques, image acquisition and a range of common pathology as an alternative to a hands-on course in locations with limited access. Augmented reality will take this one step further, in the form of simulation training programmes.

In the future, we anticipate an improvement in the non-uniform distribution of CCUS trainers and mentors as increasing numbers of clinicians gain accreditation and become trainers within their regions. As more practitioners (including non-doctors)

gain 'core' competencies, we expect to see a push to explore beyond the boundaries of CCUS practice.

Whilst on the topic of CCUS training, we would be remiss not to mention the introduction of ultrasound training into the undergraduate curriculum in some institutions, although its value to (and hence inclusion in) undergraduate medical education is currently not supported by a sufficient base of empirical research (Feilchenfeld et al. 2017). As proponents of point-of-care ultrasound however, we believe that this skill is invaluable in many aspects of patient care and would welcome any measures that promote early exposure to foster interest in ultrasonography.

New Techniques
A previously underexplored territory in CCUS is the central nervous system— this is changing. Besides its obvious value in neuro-ICU, it may also have a role in the general ICU setting. Using optic nerve sheath measurements as a surrogate marker of intracranial pressure could translate to more timely detection of significant intracranial abnormalities (Robba et al. 2019), without the inherent risks and reliance on specialist expertise and equipment associated with invasive monitoring. Transferring patients to CT or MRI, which is time- and resource-consuming could be reserved for complex cases or where CCUS has not provided sufficient information.

More novel ultrasound techniques will find their relevance in CCUS. Within radiology, contrast-enhanced ultrasound is commonly used to characterise lesions and their vascularity. Within critical care, contrast-enhanced ultrasound utilisation currently focuses on assessment of organ perfusion, including the liver, heart, kidney and brain (Blomley et al. 2001; Harrois et al. 2018). A study investigating its value in the assessment of renal perfusion in shock is underway (Watchorn et al. 2019).

Early work assessing the value of VEXUS (venous excess ultrasound score) suggests that doppler analysis of the venous vasculature of specific organs may be useful in detecting and quantifying venous congestion (Haycock and Spiegel 2019).

Ultrasound-guided tonometry (based on an ultrasound probe connected to a pressure-transducing system which takes into account the physical pressure applied to the abdomen by the practitioner) may become a valuable noninvasive tool in the estimation of intra-abdominal pressure (Bloch et al. 2018).

It should be remembered that CCUS applications tend to evolve in parallel to developments in other specialties, an example of which is speckle tracking for strain analysis in echocardiography. As a highly sensitive measure of myocardial performance, it is sometimes used in cardiology to time invasive interventions. This technique could be similarly applied to detect myocardial strain in the context of critical illness (Orde et al. 2016).

Conclusion
CCUS has progressed by leaps and bounds in the last two decades. We believe what lies in the future is not a reinvention of the wheel, but rather a gradual pushing of boundaries as this skill continues to mature, with techniques being modified to suit our evolving clinical needs and new applications founded on the basis of current ones. We are certain that CCUS will become an indispensable part of critical care practice.

Ultimately, assessment and management of the critically unwell patient must remain holistic, with CCUS providing an additional dimension to diagnosis and monitoring. An excellent intensivist will be able to integrate the appropriate ultrasound techniques into the examination and interpret the images in the clinical context to provide the best care for the patient. ■

Key Points

- Critical Care Ultrasound (CCUS) is a valuable tool for diagnosis, monitoring and guidance of practical procedures in critically ill patients, and its applications continue to evolve.
- Two aspects are likely to have the greatest impact in CCUS: the machine and the modalities.
- A handheld ultrasound device can be readily taken to the wards or indeed anywhere in the hospital by the intensivist, aligning it neatly to the concept of ICU without walls.
- Through wireless capabilities, ultrasound machines, including handheld devices, are able to instantaneously upload ultrasound studies to the Cloud with unlimited storage capacity, enabling swift sharing of images and more convenient access to expert opinion.
- The potential of the ultrasound machine to replace the stethoscope has already been debated in educational and clinical circles.

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