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Point-of-Care Ultrasound: New Concepts and Future Trends

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Abstract: Ultrasound (US) technology, with major advances and new developments, has become an essential and first-line imaging modality for clinical diagnosis and interventional treatment. US imaging has evolved from one-dimensional, two-dimensional to three-dimensional display, and from static to real-time imaging, as well as from structural to functional imaging. Based on its portability and advanced digital imaging technique, US was first adopted by emergency medicine in the 1980s and gradually gained popularity among other specialists for clinical diagnosis and interventional treatment. Point-of-Care Ultrasound (POCUS) was then proposed as a new concept and developed for new uses, which greatly extended clinical US applications. Nowadays, artificial intelligence (AI), cloud computing, 5G network, robotics, and remote technologies are starting to be integrated into US equipment. US systems have gradually evolved to an intelligent terminal platform with powerful imaging and communication tools. In addition, specialized US machines tend to be more suitable and important to meet increasing demands and requirements by various clinical specialties and departments. In this article, we review current US technology and POCUS as new concepts and its future trends, as well as related technological developments and clinical applications.

Key words: Ultrasound; Point-of-care ultrasound; Specialty ultrasound; Artificial intelligence; 5G network; Application

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Modern medical ultrasound (US) technology has made tremendous advancements over the years with many breakthroughs. These revolutionary milestones include developing digital high resolution grayscale US for anatomic structure imaging display, establishing color and power Doppler flow imaging for cardiovascular functional evaluation, creating quantitative elastographic imaging for tissue stiffness measurement, and inventing contrast-enhanced US technology for the integration of structural and functional imaging [1]. With technological advancements and miniaturization of US systems, portable US emerged and has developed since the 1980s, first used by emergency medicine physicians [2] and then extended to other clinical specialists. Clinicians in various disciplines have gradually applied US technology to the diagnosis and treatment of their respective specialties, using the imaging advantages of US technology to implement focused, purposeful, and rapid US examinations to provide clinical information for making diagnoses and treatment decisions, namely Point-of-Care Ultrasound (POCUS) [2]. With the evolvement of artificial intelligence (AI), cloud computing, 5G network, robototics, and remote technology, as well as increasing

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demands by clinical specialties requiring more refined clinical diagnosis and treatment brought by precision medicine, the miniaturized, intelligent, and specialized US has become a trend for future development [3].

This article will review traditional US and POCUS as new concepts with a focus on related current US technology and its future trends for clinical application. The value of modern technology in promoting technology improvement and expanding clinical application will be discussed.

Traditional Medical Ultrasound

Medical US is a safe, simple, real-time, easily operated, low cost, and widely used imaging modality in medicine besides CT and MRI [4]. Since the 1940s, medical US technology has evolved from A-mode, M-mode, B-mode (2D gray scale) to Doppler-mode imaging. B-mode US developed in the 1950s could display the soft tissue structures, which laid the foundation of modern US diagnosis [5]. Subsequently, M-mode US imaging was formed with integration of tissue movement information (such as cardiac motion) [6]. In the mid to late 1980s, color Doppler US was developed based on the principle of Doppler frequency shift and auto correlation is used to obtain blood flow information, which is coded in different colors. Doppler spectrum analysis can measure the velocity of blood flow and obtain the hemodynamic information over time, which is a spectral Doppler technique. The establishment of Doppler US technology has created a new field for non-invasive testing of cardiovascular and organ blood flow and hemodynamic research [7,8]. Up to now, the above several imaging methods are still the mainstream technologies in medical US. With improvement of computer processing power, Baum and Greenwood proposed the original concept of three-dimensional US in 1961[9]. Subsequently, the development of 3D US underwent three stages, which are early static 3D imaging (static 2D image reconstruction), dynamic 3D imaging (adding time parameters) and real-time 3D imaging (with no time delay) [10]. 3D US has been widely used in cardiology, obstetrics, gynecology, oncology, interventional radiology, peripheral vascular, and other fields because of its intuitive, accurate and real-time features [11]. Since the 1990s, new US technologies, including contrast-enhanced US (CEUS) [12], tissue Doppler [13], and elastography [14], have further improved US capabilities and diagnostic accuracy (Fig. 1). In particular, development of microbubble contrast agents for contrast US imaging is a revolutionary breakthrough technique, which played a substantial role in the field of medical imaging. Quantitative analysis of CEUS can be carried out to evaluate the micro-circulation perfusion of organs or tissues, which transits the ultrasonic imaging from structure to function [15]. In addition, enhanced US imaging through non-vascular approaches (bile duct, urinary tract, oral administration, etc.) has gradually been applied in clinical practice as well [16-18]. Through the fusion of US technology with other imaging technologies (such as CT and MRI), the ability of lesion detection has also been improved significantly, which improves the lesion localization and interventional operation [19,20].

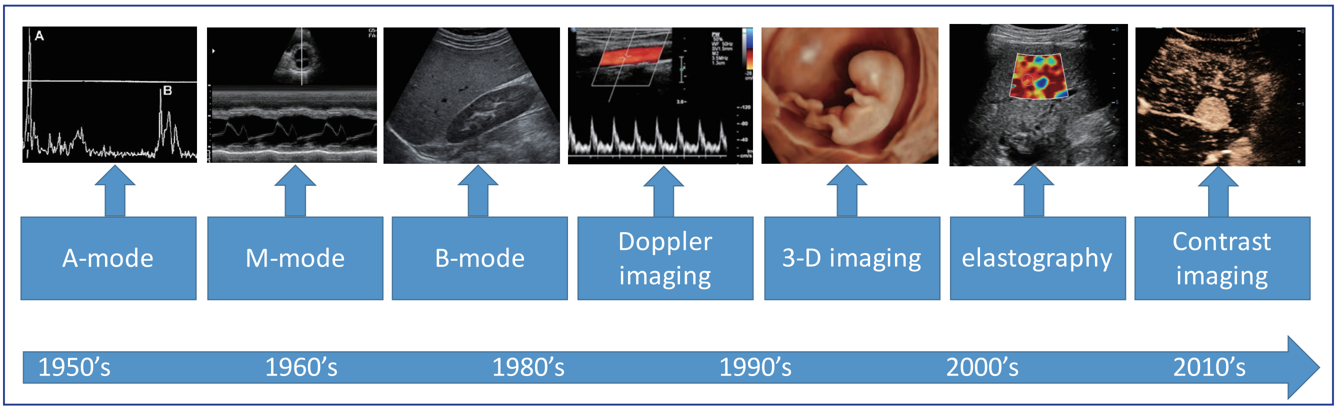

Figure 1 Schematic diagram of US technology developments

After decades of development, medical US has achieved rapid development in terms of imaging technology, imaging modes, software, and hardware. However, traditional US has great challenges in meeting the clinical demand for diagnosis and treatment because of the large size of the equipment, the configuration of the probe, and the imaging features. Although continuous upgrades have been made in probe materials, imaging analysis software, and overall machine design, traditional US technique is relatively mature and has become an established modality. At the same time, due to the lack of equipment/personnel and heavy workload in US departments as well as increasing use US by clinical physicians, continuous advancement of US applications has led to the rapid development of POCUS with clinicians/specialties as the main body of users.

Point-of-Care Ultrasound

Portable B-mode US devices provide the possibility for clinicians to perform bedside real-time US diagnoses. In the 1970s, diagnostic US was first used in the evaluation of trauma patients in Europe. Since 1988, Germany has required surgeons to master US skills. The United States began to promote US assessment of trauma in the mid-1980s, replacing diagnostic abdominal lavage in most trauma centers. Since the 1990s, US has been widely used in acute and critical patients worldwide. Because bedside US emphasizes timeliness and accuracy, the concept of POCUS is proposed in clinical practice [2,21,22].

In 2011, the New England Journal of Medicine described POCUS as "US performed by a clinician at the bedside," emphasizing the "instant" operation by clinicians rather than by professional US physicians [23]. The specific meaning of POCUS is that the clinician is the one who makes the decision to perform bedside US, adjusts the diagnosis, and monitors the treatment accordingly. Based on the advantages of US technology, as well as increasing miniaturization of US instruments and continuous improvement of their functions, POCUS can better meet the clinical needs for different applications. At the same time, with continuous improvement of clinicians' ability to use US, the scope of POCUS application has been greatly expanded, including in the areas of acute and critical care, anesthesia, rehabilitation, rheumatology, obstetrics and gynecology, pain management, sports medicine, and orthopedics, etc. [24,25]. In addition, POCUS has played an important role in the fight against the COVID-19 during the pandemic. It can not only make the diagnosis, assess severity, and provide dynamic monitoring of lung lesions, but also provide important information of multi-organ injury (such as heart, kidney, blood vessel, gastrointestinal, etc.). POCUS has helped in classifying cases based on severity and directing patients to appropriate treatment, which greatly improved the therapeutic efficiency [26,27].

The expansion in applications of POCUS are the result of a convergence of advancement of US technology and clinical needs. Because of its advantages in imaging visualization, it is also called the "visual stethoscope" [28,29]. The scope of POCUS has increasingly expanded and includes the following applications and scenarios.

Acute and critical care applications

POCUS can be used in special medical scenarios such as battlefields, first aid, traffic accidents, and disaster scenes. Through rapid assessment of organ damage, it can guide the risk of classification, triage, and treatment measures [30]. Focused assessment with sonography for trauma (FAST) protocol is a bedside examination method for rapid assessment of internal bleeding in trauma patients, with specificity of 94-98%, sensitivity of 73-99%, and accuracy of 90-98%. Also, POCUS is superior to traditional chest radiographs in the diagnosis of pneumothorax [23,31]. The application of POCUS in acute and critical cases pays more attention to volume management and hemodynamics monitoring through streamlined US workflows, such as focused echocardiographic evaluation in life support (FEEL) protocol, bedside lung US in emergency (BLUE) protocol, and rapid US in shock (RUSH) protocol, etc., which can quickly and effectively integrate and interpret critical pathophysiology with US findings, and then guide clinical diagnosis and treatment [32-34].

US-guided visual procedure applications

When US-guided nerve block (such as subarachnoid space, axillary brachial plexus, sciatic nerve, etc.), the nerve structure and peripheral blood vessels, muscles, bones, and internal organs can be clearly displayed, and the puncture process and drug diffusion can be monitored in real time. Under US-guidance, the blindness of the interventional procedures can be avoided, the success rate of anesthesia can be improved, and the complications and the amount of local anesthesia can be reduced. The integration of systemic US imaging into the clinical practice of anesthesia is a new concept and research direction in the field of POCUS. In addition, US is very useful to guide the establishment of vascular access during a variety of procedures. In the case of patients with poor vascular conditions (such as drug abuse, burns, vascular congenital variability, children, and severe obesity), the advantages of US visualization can improve the precision of venous catheterization and reduce the failure of procedures [35-37].

Musculoskeletal and others applications

POCUS can be used in rheumatology, rehabilitation, physiotherapy, sports medicine, and orthopedics for dynamic assessment of joint and tendon abnormalities, monitoring of inflammatory lesions, and diagnosis and localization of the cause of pain [38,39]. In terms of basic obstetric POCUS examination, through standardized training, POCUS can be used by relevant medical staff in underdeveloped countries or remote areas of the world to perform basic examinations of fetal anatomy, umbilical blood flow status, and fetal position, gestational age, and fetus growth and maternal labor process which could effectively reduce maternal and fetal mortality [38,40].

In order to meet the above-mentioned clinical applications, equipment manufacturers are also constantly modifying the US instruments to provide better systems for POCUS needs, such as: (1) Removing non-essential function and parameter control buttons, or customizing function keys, simplify operating steps and making the operation faster and more user-friendly; (2) Shortening the switching speed of the ultrasonic instrument, improving the operation response, increasing probe switching and storage speed to meet the needs of emergency scanning; (3) Making more compact equipment with portable designs accustomed to the limited work space in the emergency room, anesthesia suite and intensive care unit as well as other small space environments [41,42].

POCUS is a one-step forward examination method compared to routine clinical US. In the POCUS inspection process, important information such as organ anatomy, functional status, and systemic hemodynamics can be obtained in-situ and in a timely fashion, helping clinicians to make more accurate assessments for immediate and subsequent treatment. POCUS can provide reliable essential information, and participate in the entire clinical diagnosis and treatment process (i.e., preliminary diagnosis, initial treatment, efficacy evaluation, and adjustment of therapy plan). Thus, the application of POCUS for multi-disciplinary, multi-system, and multi-organ assessment is a future direction and a key link in various clinical disciplines with broad clinical application prospects [43,44].

POCUS with New Concept and Techniques

In recent years, POCUS has been applied in many clinical departments and achieved encouraging results. However, in most hospitals at present, portal US is still performed by US doctors/radiologists with bedside consultations. In addition to being somehow unfamiliar with the purpose of clinical specialist's requests, it is also impossible to achieve continuous follow-up observation for special patients, such as FAST examination for trauma patients [45] and cardiopulmonary US for patients with ECMO treatment [46,47]. Some clinical departments in large-scale hospitals have been equipped with portable US and carry out POCUS examinations. However, the lack of effective operating standardization, high scanning skill, and interpretation experience leads to ambiguous diagnosis results, which diminishes the clinical application value of POCUS [48].

Although portable US equipment has achieved technical integration (i.e., multiple imaging functions in a single unit) and miniaturization (such as handheld US device), there are still challenges for development of US devices and applications to move forward into a subspecialty of clinical disciplines. For example, in anesthesiologic uses, clearly showing the boundary of normal tissue structure is more important than the diagnosis of pathological structures. A touch screen that is easier to sterilize is better than the traditional operating keyboard [49]. Therefore, a specially-designed US machine with new concepts is needed in developing specialty-oriented instruments.

With the rapid integration of modern technologies such as artificial intelligence (AI), cloud computing, 5G networks, robots, and tele-remote technology with US modality, the development of a specialized POCUS system will be further facilitated as an intelligence terminal platform, improving the application of POCUS and leading to a new pathway for medical US advancement (Fig. 2). New generations of POCUS systems will represent a development trend of medical US. In addition to using a variety of new technologies to improve the accuracy of US diagnosis, specially-designed POCUS will be combined with advanced technology to better meet the needs of various specialists which may differ from the traditional US systems.

5G-based tele-remote POCUS

Tele-remote US refers to using modern computer, network communication, and multimedia technology to digitally reconstruct US images to remotely achieve image acquisition, storage, transmission, analysis, and processing. This allows for remote real-time diagnosis and interventional procedures through high-precision synchronization via video, audio, text and other multi-channel communications. Expert doctors can use remote technology to guide patient-side doctors to perform US examinations to improve their diagnostic experience, and reduce diagnostic errors by overcoming operator-dependent barrier. The remote robotic US system enables expert doctors to use their own skill to remotely control the robot to perform US scans, and perform medical diagnosis based on real-time US imaging generated by the robotic scanning [50]. In recent years, emerging 5G technology has met the long-distance, real-time, high-bandwidth, high-resolution, and low-latency requirements for remote US consultation and US robotic operation, allowing for high-quality transmission of US imaging and sharing as a valuable medical resource, which provides the opportunity for broad application of tele-remote US technology. The 5G-based remote US has shown important value during the COVID-19 pandemic for remote assessment of patients' lung lesions and guidance during interventional procedures, saving expert resources and minimizing cross-infection [50,51]. However, remote US is not conducted for large-scale clinical application, and it can only be used as a basic screening tool for special situations at present due to the lack of unified standards for image acquisition, quality control, data transmission, and security [52,53].

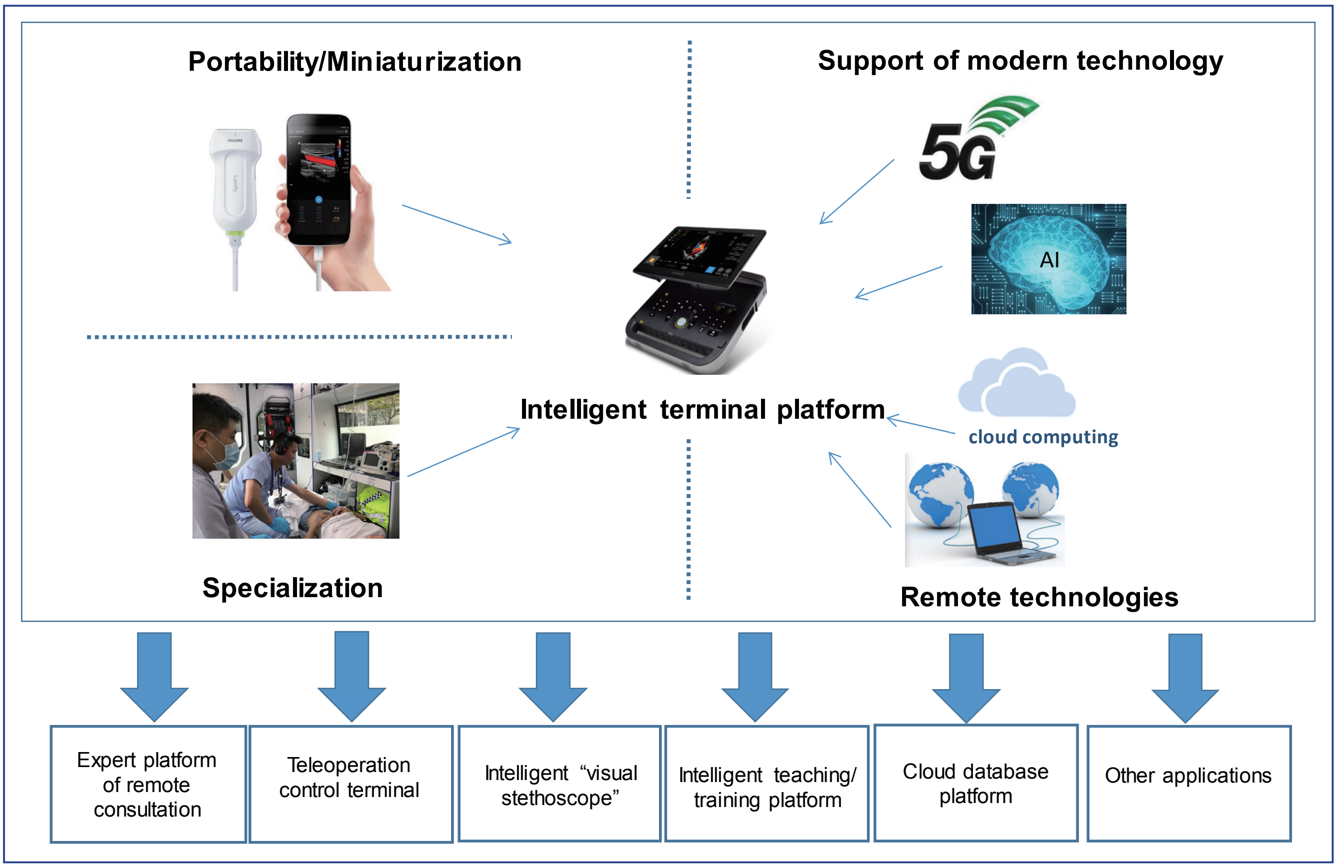

Figure 2 Conception of ultrasound intelligent terminal platform

POCUS with AI technology

Sonologists/radiologists who independently perform US diagnoses often require years of training and experience accumulation. Currently, diagnostic US is the first choice for clinical imaging examination, and as a result, the demand for diagnostic US scans can be overwhelmed by a heavy workload with limited staffing. With AI technology being gradually implemented in the medical field, AI-assisted diagnosis systems could help alleviate this situation although applying AI in diagnostic US is a relatively new concept in the field of digital imaging. Advantages of AI include fast imaging processing, uniform standards, continuous workflow, and excellent repeatability, which can handle large amounts of data and quickly obtain diagnostic images and even dig out the raw data and patterns to improve diagnostic efficiency and accuracy. In addition, through the continuous optimization or iterative update of AI algorithms, US imaging processing and analysis can be simultaneously improved, and ultimately realize intelligent disease prediction, risk assessment, clinical diagnosis, and treatment [54,55].

Deep learning methods are commonly used in AI technologies, in which convolutional neural network (CNN) is the most popular, and has made great progress in various research areas such as image classification, lesion detection, and target segmentation [56,57]. Buda et al. [58] used CNN to develop an intelligent recommendation algorithm for whether thyroid lesions need biopsy, with a sensitivity of 87% and a specificity of 52%. CNN is composed of many convolutional layers which have the powerful ability to independently learn a large amount of imported image training data, and automatically parse and extract the best characteristics in a specific layer, and finally, realize the classification of the image. This process is much better with more detailed information than human eye observation which is the biggest advantage of CNN compared with traditional machine learning methods. Traditional machine learning uses artificially defined characteristics, such as whether the edges of the nodules are regular and the echogenicity, based on the doctor's subjective judgment criteria [59].

US equipment has also made great progress with AI technology, such as the built-in intelligent evaluation features, intelligent optimization of imaging quality and intelligent screening, acquisition, analysis, and data processing, etc., helping US operators to bypass the complicated image optimization and measurement work, and instead focus on clinical diagnosis and treatment. At present, US with AI technology has been applied in clinical practice such as minimally invasive intervention, thyroid, breast, musculoskeletal, pediatrics, and cardiac examinations, improving the accuracy of clinical US diagnosis [60-65]. For example, the coincidence rate by AI-based US systems in the interpretation of benign and malignant thyroid nodules has increased from 64% to 84% [66]. However, there are still many challenges in AI US applications. First, the huge quantity of data generated in the short term puts higher requirements on algorithms and computing power. Second, the computing power limitation needs to be solved to ensure that the AI model can be effectively used on tablets or mobile phone platforms [67]. Finally, it is necessary to establish supervision systems and regulations and improve the scheme to evaluate the stability and accuracy and overcome the difficulty of defining medical liability for AI US applications.

Cloud-based POCUS

The rapid development of the Internet brings up cloud computing applications. In 2006, Amazon in the United States launched the world's first cloud computing system—Amazon Web Services (AWS), and cloud computing began to gain rapid promotion globally. Cloud computing is a new type of computing platform that has the advantages of low cost, high reusability, high performance, and easy expansion. Through the internet, it accelerates the integration of a large number of algorithm formulas and storage resources, and then provides and distributes to specific users accordingly. Currently, the definition given by the National Institute of Standards and Technology (NIST) in the United States is more authoritative for implantation. The main goal of cloud computing is to form a pool of resources for network, storage, application, service, and other resources, and strengthen flexible allocation and integration, as well as optimize network resources. Through these approaches, cloud computing can enhance its reliability, versatility, and expansibility to maximize the utilization of network information resources [68].

US technology has been widely used in the diagnosis and treatment of diseases in almost all fields of medicine. Thus, a large volume of imaging data is generated due to the characteristics of real-time imaging. Using cloud computing technology to build a cloud platform for medical image service will make data processing simple and convenient. Recently, with the application of mobile terminal devices such as mobile phones or tablet computers, cloud computing technology has brought new changes for US diagnosis. The US system on the patient side is responsible for collecting image data, while the mobile device on the doctor side displays the image data. Through 5G technology and cloud platforms, the real-time transmission of image data between the two locations and the implementation of remote consultation can be realized [69]. The cloud service platform can also endow users with huge storage capacity and high reliability. After US equipment is integrated into a cloud computing system, it could effectively increase the processing speed, optimize the allocation of resources, realize the interconnection and intercommunication between various terminal devices, and become a veritable "cloud US", enabling instant sharing of medical information, resources, and services [70]. Since "cloud US" is a new concept, it is necessary to further develop industry standards and technology for its potential applications.

Specialty-oriented POCUS

The configuration of transducers (such as shape and frequency) and machines for whole-body high-end US systems often have a universal design and lack of specific consideration for clinical specialty uses. The key diagnostic information of the heart, hemodynamics, and lungs has to be obtained through complex operations or measurements by experienced sonologists. Specialty clinicians without an in-depth understanding of US principles and operating training may not be able to operate sophisticated US devices for their point-of-care applications. Thus, development of the specially-configurated US instruments is clearly necessary for clinical specialties to be used [71,72]. For example, the anesthesiologist requires US scanner to have a more refined ability to recognize superficial nerve structures and to have the function of puncture navigation, while the emergency and critical care physician needs US system to be rapidly activated and intuitive operation; a musculoskeletal specialist needs US unit to have better imaging resolution for visualization of superficial tissues (Fig. 3).

With POCUS development, specialized US products that meet various specialty needs for clinical application have been developed by many US companies such as portable US machines by GE (Venue^{TM}), Mindray (M9^{TM}), Sonoscape (S9^{TM}), Wisonic (Navi^{TM}), and hand-hold US scanners by Philips (Lumify^{TM}), Butterfly (iQ+^{TM}), Chison (SonoEye V5^{TM}), Stork (S35^{TM}), SonoStar (Bprobe^{TM}) and so on (Fig. 4). For example, GE Venue^{TM} is specifically developed for use by clinicians in the field of emergency and critical care, and is dedicated for specialty needs, including intelligent functional design (such as the intelligent BLUE and RUSH protocols based on deep learning technology and VTI intelligent

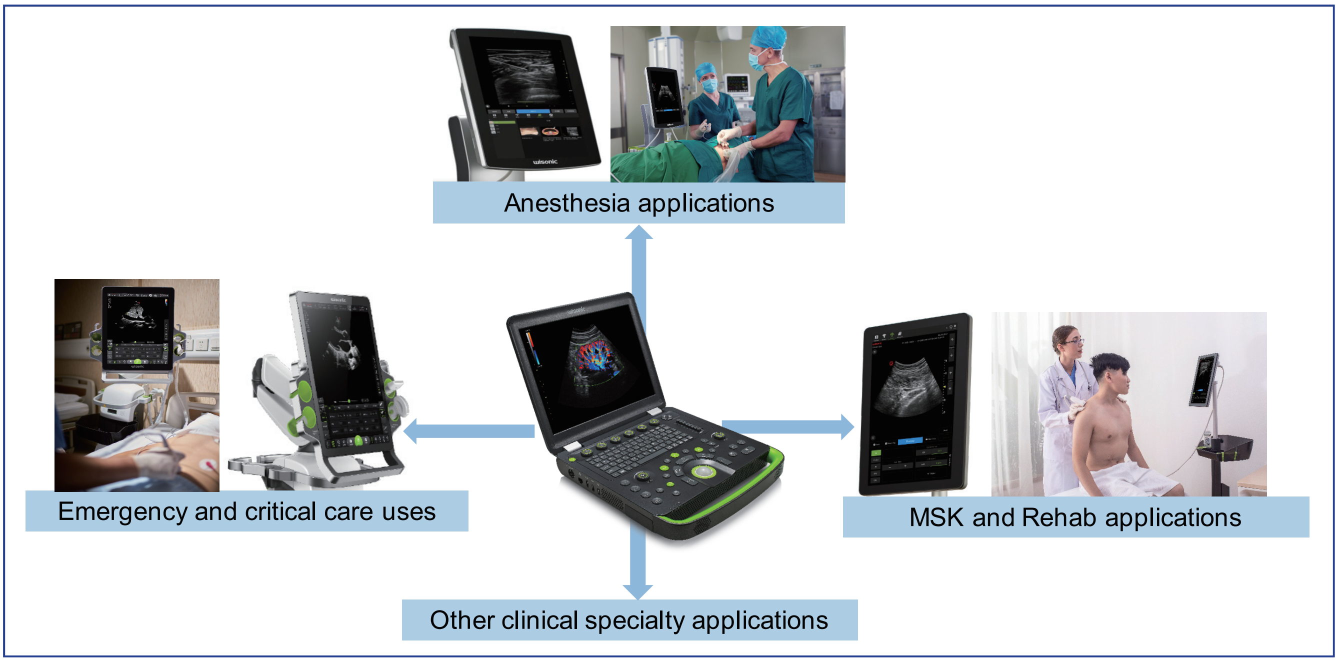

Figure 3 Illustration of portable US systems for clinical specialty applications

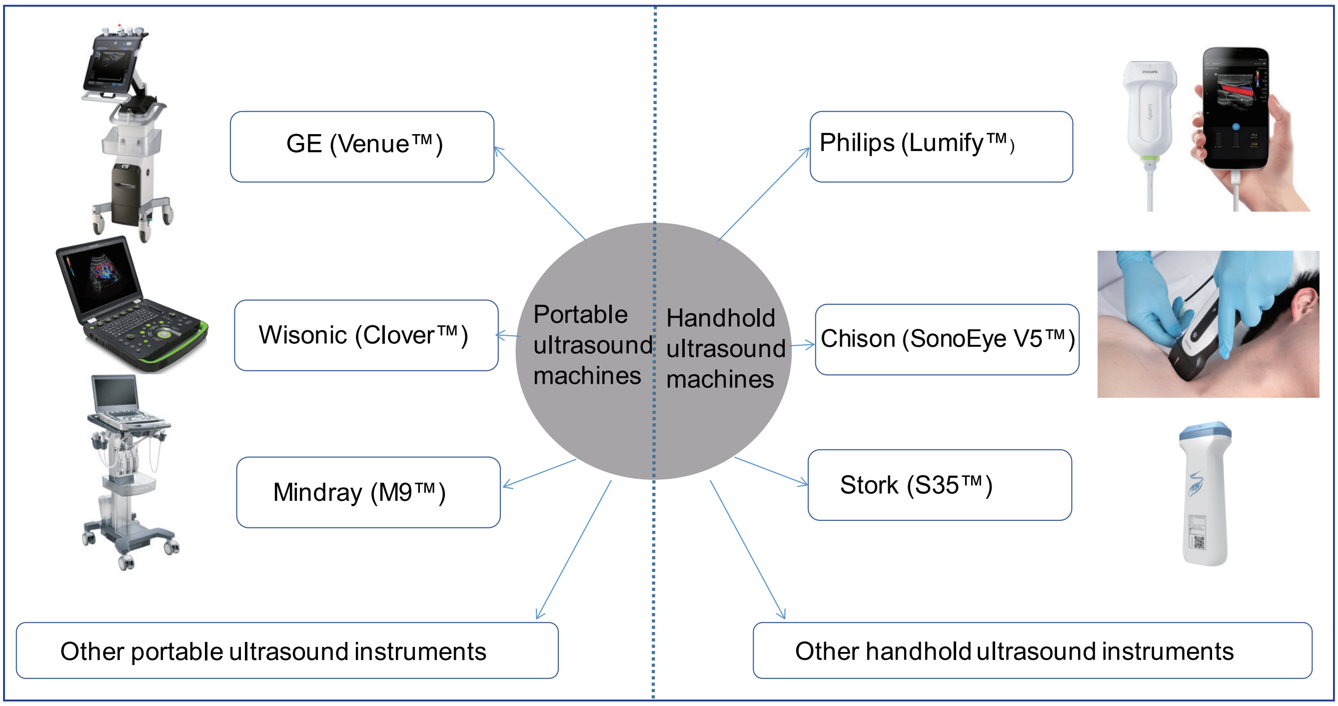

Figure 4 Examples of portable and handheld ultrasonic instruments

measurement) with simple and efficient operation process [72,73]. Wisonic Navi™ is an all-in-one machine specifically designed for anesthesiologic applications and equipped with a large touch screen for far-distance observation and easy disinfection. Customizable functional buttons are built on the probe for Doppler control and parameter adjustment as well as mode switching and needle enhancement control. Thus, POCUS devices must fit with specific applications and requirements by specialty clinicians, which is expected to become a key development area of US systems in the future. In the meantime, multiple specialized US techniques can also be used in the same clinical scenario to carry out multi-organ or multi-modal US evaluation [33].

Conclusion

POCUS, endowed with new concepts and prospects, will greatly extend clinical US applications. Currently, AI, cloud computing, 5G network, robotics, and remote technologies started to integrate into US equipment. US systems have gradually evolved to an intelligent terminal platform with powerful imaging functions. In addition, customized US machines tend to be more suitable and are important to meeting the increasing requirements by various clinical specialties and departments. POCUS not only represents a modern technology revolution but also expands scenarios of US applications.

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Conflicts of interest

The authors declare no conflicts of interest.

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