Point-of-Care Ultrasound in Austere Environments

A Complete Review of Its Utilization, Pitfalls, and Technique for Common Applications in Austere Settings

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KEYWORDS

- Point of care • Ultrasound • Austere • High altitude • Resource limited • Disaster • Battlefield • Military

KEY POINTS

- Ultrasound systems must be handheld, battery operated, durable, and able to withstand extremes of temperature and altitude, while additional equipment may be necessary to help prevent battery degradation and equipment damage.
- Point-of-care ultrasound is portable and lightweight, and can be used to screen for a wide variety of pathology and injury common to austere environments, disaster situations, and resource-limited settings.
- Common point-of-care ultrasound applications used in austere environments include the Extended Focused Assessment with Sonography in Trauma, musculoskeletal and soft tissue injury, high-altitude pulmonary edema, high-altitude cerebral edema, pneumonia, volume status, and various procedural guidance applications.
- The various point-of-care applications used in austere environments for procedural guidance include peripheral vascular access, nerve blocks for pain control, foreign body removal, and abscess drainage.
- Point-of-care ultrasound is a reliable tool to assist in triage, resource allocation decisions, and screening for conditions common in austere environments.

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INTRODUCTION: POINT-OF-CARE ULTRASOUND AND HANDHELD SYSTEMS

Ultrasound technology continues to advance and has come a long way from large wall-mounted systems with poor image quality to small handheld devices with good image quality. Ultrasound systems were optimized for medical military use in the 1980s. Due to its successful utilization at the point-of-care, its lack of ionizing radiation, and the expansion of computer technology, point-of-care ultrasound (POCUS) rapidly spread to trauma, emergency department, and "out-of-hospital" settings, including in austere environments where other imaging modalities cannot be carried.[1,2]

There are various handheld systems that can fit into a large coat pocket, and the power supply and case can fit into any backpack. Their power timing and image quality is less than that of laptop-based systems, but their portability and ability to transfer images wirelessly to electronic mailing or via text messaging make these systems unique. The GE (Chicago, IL) VScan was one of the first handheld devices to come to market with a "flip-open" and touch-sensor style, now with a dual probe for both high-frequency and low-frequency imaging. The SonoSite (Bothell, WA) iViz is one of the newest devices on the market with a larger screen, good image quality, and touch-screen capability. The Philips (Andover, MA) Lumify is another new system that currently requires a subscription. Other devices, including handheld devices by Clarius (Burnaby, Canada) and Signostics (Bothell, WA) provide a probe and require a smart phone for scanning.

POINT-OF-CARE ULTRASOUND IN AUSTERE ENVIRONMENTS: UTILITY AND PITFALLS

The first portable ultrasound machine weighed just over 5 pounds, was the first battery-operated ultrasound machine, and was durable enough to withstand unpredictable battlefield environments.[3] Austere environments continue to pose special challenges to ultrasound equipment, including battery degradation, hard-drive failure, and physical abuse. Advances in equipment design and environment-specific care have allowed successful use of ultrasound in these extreme situations.

MILITARY AND COMBAT ENVIRONMENTS

Ultrasound on the Battlefield

The battlefield is an unforgiving environment for ultrasound machines. In Iraq and Afghanistan, ambient temperatures fluctuate greatly, resulting in battery degradation.[4,5] The environment is also sandy and dusty, contributing to overheating. Ultrasound machines are often treated roughly out of necessity. There are space limitations in medical treatment facilities, so equipment may inadvertently be jostled or knocked to the ground during a mass casualty incident (MCI). Medics may carry small portable ultrasound machines in their packs to the point of injury. Therefore, machines must be handheld, use cooling fans, and have extra batteries available.

Because most battlefield deaths are caused by hemorrhage, the most common role for ultrasound in this environment is the focused assessment with sonography in trauma (FAST) examination, which parallels the civilian MCI experience in which triage of casualties is the priority.[6] Computed tomography (CT) may not be available, and physicians in war zones found ultrasound to be invaluable during triage.[7] The FAST examination can identify occult blood loss in young, highly conditioned patients whose physiologic reserve undermines the reliability of vital signs until late stages of shock.[8]

Pneumothorax assessment of the extended FAST (eFAST) is also useful, especially when planning medical evacuations, because even small pneumothoraces, which might otherwise be considered insignificant, can benefit from thoracostomy to prevent in-flight decompensation.

A variety of other emergency-related ultrasound applications, including fracture assessment and its reduction, inferior vena cava (IVC) collapsibility for resuscitative decision in nontraumatic shock states, optic nerve sheath diameter (ONSD) for intracranial pressure assessment when CT or neurosurgical consultation is unavailable, and procedural guidance for venous access, regional anesthesia, pericardiocentesis, cricothyrotomy, and foreign body detection and removal, have all been found useful.[2,9–13]

Ultrasound in Flight

Because of noise and space limitations in the field with limited physical examination performance ability, POCUS in flight is highly valuable to care for patients in transit to higher levels of care, as they may deteriorate due to their tenuous physiology and stressors of flight (hypoxia, hypobaria, constant movement, noise, and hypothermia or hyperthermia). Ultrasound equipment in flight must be lightweight, take up little space, and be able to tolerate vibrations and large fluctuations in temperature and elevation. Ultrasound has not been found interfere with aircraft avionics and can be used on multiple rotary and fixed-wing airframes.[9,14–16]

Helicopters are often used to transport trauma patients from the field or from a smaller hospital to a larger trauma center. Both small and large fixed-wing aircraft have been used to transport medical patients over longer distances or to areas outside disaster zones. These aircraft are often staffed by medical personnel who can use ultrasound to determine the etiology of undifferentiated hypotension or hypoxia (eFAST, cardiac echo, IVC) and perform ultrasound-guided procedures.[16–20]

DISASTER AND MASS CASUALTY INCIDENTS

During MCIs the volume and severity of casualties overwhelms the capabilities and resources of the response effort. POCUS is ideally suited for MCI conditions when other imaging is often not available due to the remoteness of the mission, destruction of previously available equipment, or interruption of the region's ability to produce electricity. Early in disaster missions, ultrasound is often used as a triage tool. Later, it is more frequently used to diagnose common conditions like pneumothoraces, long bone fractures, and dehydration. Portability becomes an even greater priority when the disaster-relief team has to hand-carry their equipment over a long distance.

Natural Disasters

Several reports from various earthquakes, including the 1988 magnitude 6.9 earthquake in Armenia (one of the first studies to quantify POCUS use during a natural disaster), concluded that POCUS is invaluable since medical care often takes place outdoors for safety reasons, CT scanners may be reserved for head trauma cases, ultrasound provides procedural guidance, and ultrasound has been used to decipher which patients needed dialysis and their likelihood of recovery from crush-related acute renal failure. Furthermore, there were low false-negative rates of the FAST examination for traumatic injuries requiring surgical intervention, with most being due to retroperitoneal or solid organ injuries, a known limitation of the FAST scan.[21–26]

After several more studies from mudslides, cyclones, and earthquakes, a wider range of ultrasound applications was found to be useful, including pelvic, right upper quadrant, renal, orthopedic, cardiac, deep venous thrombosis, and lung scans.[27,28] Decisions regarding patient management and transport were made, and clinical management was changed in a large percentage of patients following POCUS.[9,28]

Man-Made Disasters

The utility of the FAST examination after the bombings in Madrid, London, Lebanon, and Boston have been reported.[29–34] The report from the Boston Marathon bombing describes how the volume of critically wounded and unregistered patients overwhelmed standard radiography processes, causing an emergency physician to go “bed to bed,” performing eFAST exams on each patient and leaving the hand-written results taped to the gurneys; 24% of these ultrasound-triaged patients received immediate operative intervention. This report also noted that an older ultrasound machine was limited in utility due to a lack of battery backup and long boot time. This report concluded there should be a battery-operated ultrasound machine in each clinical area, and alternative image documentation protocols should be used during MCIs.

Tropical Environments

Portable ultrasound has been carried on multiple humanitarian missions to remote tropical locations (**Fig. 1**). Portability and battery power are needed, and solar electrical chargers are ideal while attempting to prevent battery degradation. Tropical environments pose the added challenge of prolonged humidity and/or frank wetting, which can destroy batteries and other electrical equipment. A report from the Amazon jungle noted that 7 of the 25 examinations performed (1 FAST, 6 hepatobiliary, 5 transabdominal, and 7 endovaginal pelvic, 3 renal, 3 aorta) changed management; 4 patients avoided a potentially dangerous 2-day evacuation, and 3 were referred for rapid surgical intervention.[27]

Fig. 1. A battery-operated portable ultrasound device was used to locate and remove the foreign body from a nonambulatory patient in a facility without electricity in the Suriname jungle. (*Courtesy of* K.L. Anderson, MD.)

THE INTERNATIONAL SPACE STATION AND REMOTE TELEMONITORED ULTRASOUND

Ultrasound has been used in some remote areas where it is not feasible to have a clinician or even a technician with specialized training present. The International Space Station (ISS) is probably the epitome of remote locations, and the National Aeronautics and Space Administration pioneered remote telemonitored ultrasound (RTUS), which uses live video streaming of ultrasound examinations performed by nonmedical personnel and reviewed by clinicians in real-time on Earth.[35] This technology has subsequently proven feasible in other remote locations, including high-elevation mountains and inside flying aircraft.[36–39] The number of ultrasound applications possible is limited only by the expert's ability to verbally instruct the operator.

HIGH ALTITUDE

Ultrasound has been most commonly used as a research tool in 2 environments at high altitude (above 1500 m): ski resort health clinics, and base camp clinics for climbers. At ski resort clinics, other radiologic options such as radiograph, CT, or

Fig. 2. Electronic devices used on a solar-powered, high-altitude ultrasound research expedition to Mt Kilimanjaro. (*A*) These rigid solar arrays weigh less than 5 kg and provide more than 50 W of power under equatorial sun on Mt Kilimanjaro. This power is controlled by an electronic voltage regulator using a lead-acid battery storage system, housed in the waterproof case in the foreground. (*B*) From left to right: (1) the ultrasound unit (Sonosite 180-plus; Sonosite, Bothell, WA), (2) laptop data storage (Dell Inspiron 910; Dell, Round Rock, TX), (3) 300 W DC-to-AC converter (box in foreground, Go Power!; Carmanah, Victoria, British Columbia, Canada), and (4) electronic voltage regulator with lead-acid battery storage (CT Solar LLC, Palm City, FL). Total weight of all electronic and power storage equipment is less than 18 kg. (*Reprinted from* Fagenholz PJ, Murray AF, Noble VE, et al. Ultrasound for high altitude research. Ultrasound Med Biol 2012;38:5; with permission from Elsevier.)

MRI also may be available. However, at very high altitude (3500 m to 5500 m) or extreme altitude (above 5500 m) the clinics are usually remote, with the only imaging modality being ultrasound that was carried there by foot. Spinning hard drives may cause machine failure, likely due to the cold and decreased barometric pressures; solid state memory devices are recommended, as they do not have any moving parts. Sleeping with cold batteries or soaking transducers in warm water to keep them functioning reliably have been described. Light, portable solar arrays can be used to recharge batteries[40] (**Fig. 2**). Ultrasound applications can be performed within minutes, limiting patient exposure to the cold environment. Additionally, RTUS techniques can be used, demonstrating that an experienced sonographer does not need to be physically present (**Fig. 3**).

Fig. 3. A nonexpert operator is performing a thoracic ultrasound examination on a fellow climber in a tent at Advanced Base Camp on Mount Everest. The remote expert is seen on the computer screen in the background directing the examination. (*From* Otto C, Hamilton DR, Levine BD, et al. Into thin air: extreme ultrasound at Mt Everest. Wilderness Environmental Med 2009;20:285; with permission from Elsevier.)

COMMON CLINICAL APPLICATIONS OF POINT-OF-CARE ULTRASOUND IN AUSTERE ENVIRONMENTS: TECHNIQUE AND PATHOLOGY

Trauma and Injury Assessment: Extended Focused Assessment with Sonography in Trauma Scan and Musculoskeletal Ultrasound

Extended focused assessment with sonography in trauma

The eFAST examination is a screening tool for intraperitoneal, intrathoracic, and pericardial fluid plus an assessment for pneumothorax. It includes 6 views and does not evaluate the retroperitoneal space. Supine patient positioning is required.[41,42]

- Right upper quadrant (RUQ) (**Figs. 4** and **5**, Videos 1 and 2)
  - Pathology: This is the most sensitive view for free fluid (FF) detection, best seen in the paracolic gutter and Morison pouch. FF is black (anechoic), but can be gray (echogenic) if there are clots (**Fig. 6**, Video 3). Pleural fluid is seen as an anechoic area above the diaphragm causing the spine to be visible, as opposed to normal mirror image of the liver seen above the diaphragm (**Fig. 7**).
- Left upper quadrant (LUQ) (**Fig. 8**, Videos 4 and 5)
  - Pathology: Fluid is best seen in the subdiaphragmatic region. A left pleural effusion can be seen as described previously (**Figs. 9** and **10**, Video 6).
- Suprapubic (SP) (**Figs. 11** and **12**, Videos 7–9)

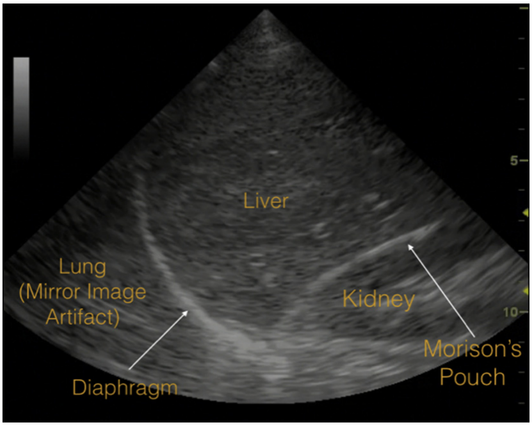

Fig. 4. Normal RUQ view showing above and below the diaphragm, and Morison's pouch.

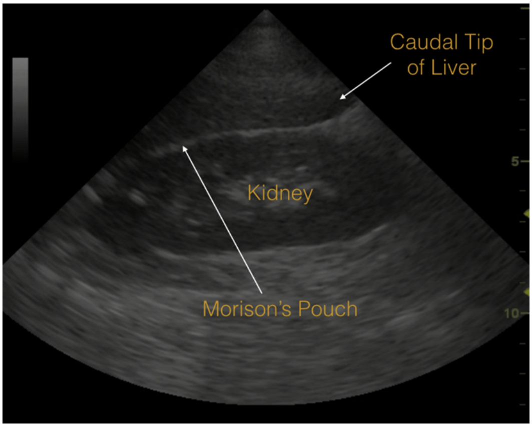

Fig. 5. Normal RUQ view showing Morison's pouch and the caudal tip of the liver.

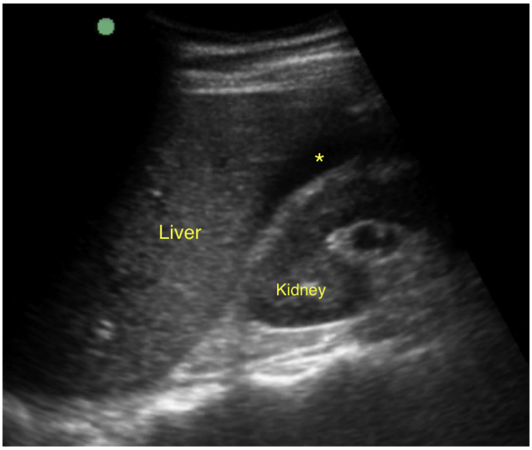

Fig. 6. Positive RUQ view showing black (anechoic) free fluid (*asterisk*) in Morison pouch and around caudal tip of liver.

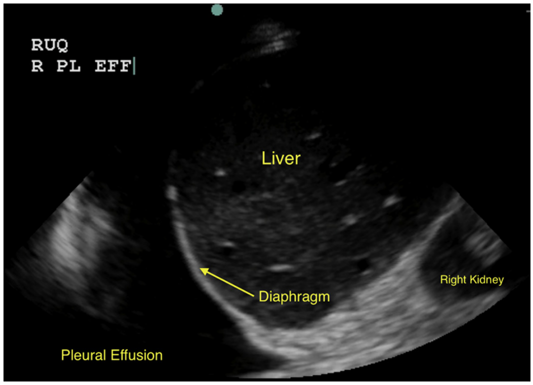

Fig. 7. Positive right thoracic view showing pleural effusion.

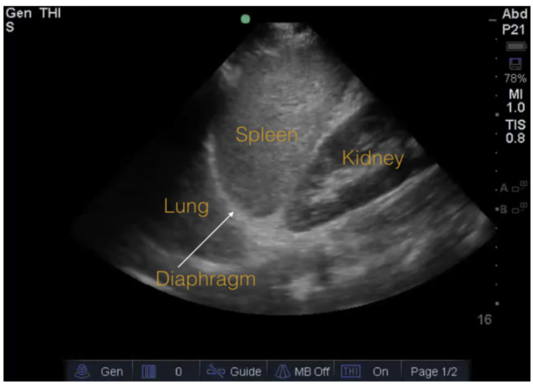

Fig. 8. Normal LUQ anatomy above and below diaphragm and splenorenal space.

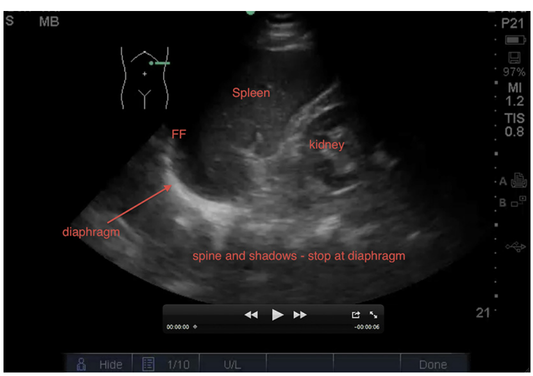

Fig. 9. Positive LUQ black (anechoic) FF in the subdiaphragm region.

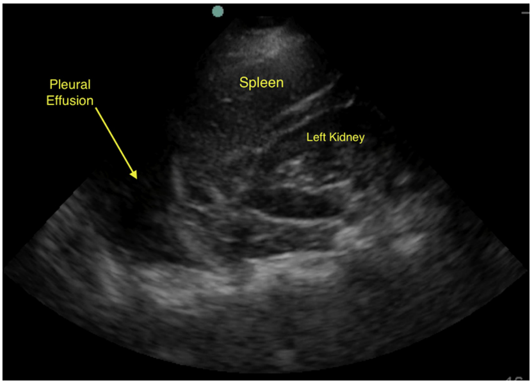

Fig. 10. Positive left thoracic view showing pleural effusion.

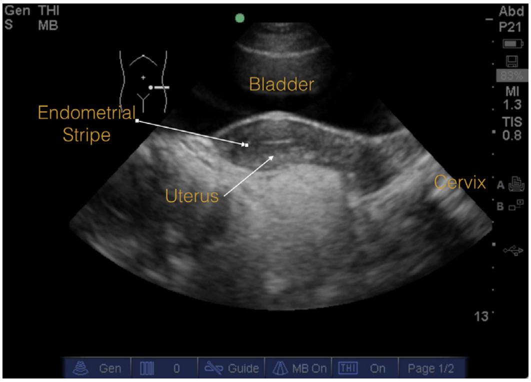

Fig. 11. Normal female sagittal suprapubic anatomy with full bladder.

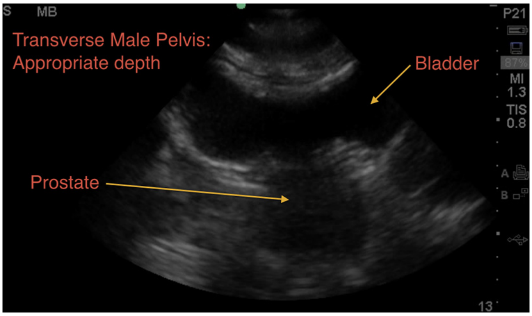

Fig. 12. Normal male suprapubic transverse anatomy showing appropriate depth and prostate.

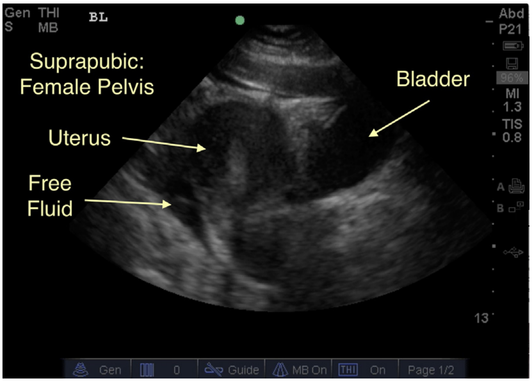

Fig. 13. Positive suprapubic sagittal view of female pelvis.

- Pathology: FF is most likely to be present posterior to the bladder (male individuals) and in the cul-de-sac (Pouch of Douglas in female individuals) (**Figs. 13** and **14**; Videos 10 and 11).

- Subxiphoid (**Fig. 15**, Videos 12 and 13):
  - Pathology: Pericardial effusion (PCE) appears as an anechoic band inferior to the right ventricle (RV, **Fig. 16**). If a suboptimal view, a parasternal long view is used in which PCE is visualized posterior to the heart above the hyperechoic pericardium, which can help differentiate PCE from epicardial fat that will be seen only anteriorly (**Fig. 17**; Video 14). An assessment of left ventricular (LV) contractility and RV strain can be added if the eFAST is used for patients with unexplained shock. Normal is 40% to 50% contraction and an RV:LV ratio of 0.7:1.0.
- Thoracic view for pneumothorax (**Fig. 18**, Videos 15 and 16):
  - Pathology: With 2 ribs in view, each a hyperechoic curve with posterior shadowing, the pleural line is a bright horizontal line between and below the ribs. With normal lung sliding, it "shimmers" as the parietal and visceral pleura move against each other. With pneumothorax, air disrupts ultrasound waves: no movement is seen at the pleural line (Video 17). In motion (M)-mode, lung sliding shows up as a "seashore sign" (**Fig. 19**), whereas pneumothorax has a "barcode sign": only straight horizontal lines demonstrating the lack of

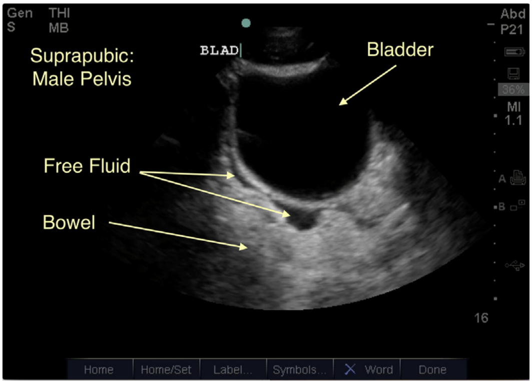

Fig. 14. Positive suprapubic transverse view of male pelvis.

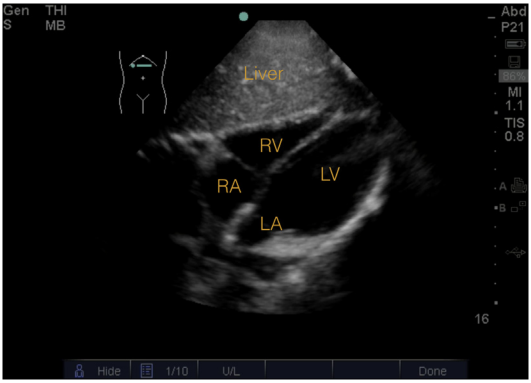

Fig. 15. Normal subxiphoid anatomy showing the 4-chamber heart with liver as an acoustic window.

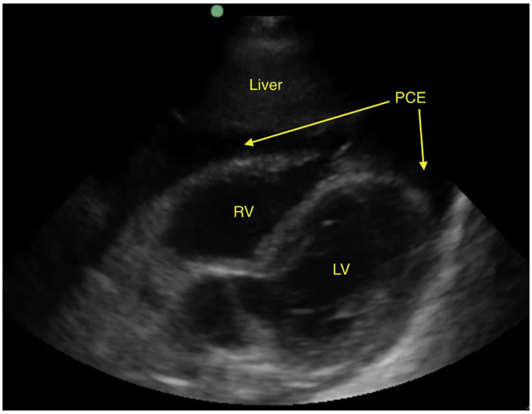

Fig. 16. Positive subxiphoid view showing pericardial effusion inferior to the right ventricle (RV).

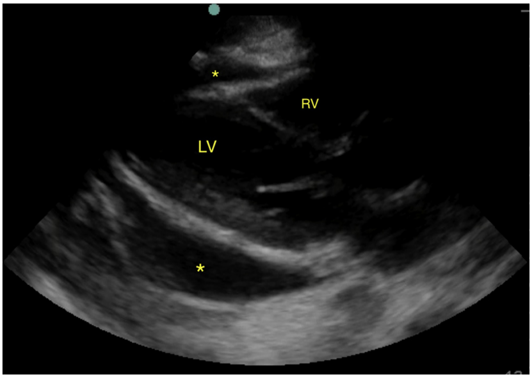

Fig. 17. Positive parasternal long view showing pericardial fluid (*asterisks*) anterior and posterior to the left ventricle (LV).

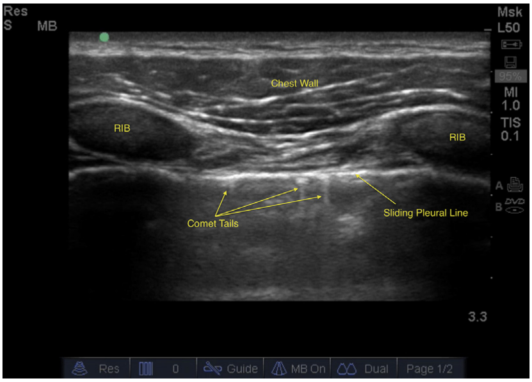

Fig. 18. Normal chest showing comet tail artifact of pleural line from lung sliding between 2 rib shadows.

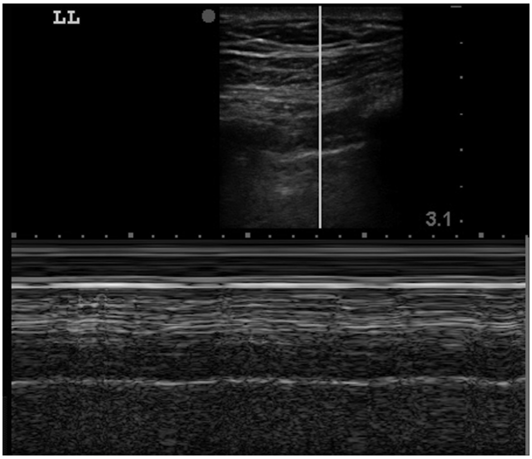

Fig. 19. Normal M-mode pattern appearing like a seashore.

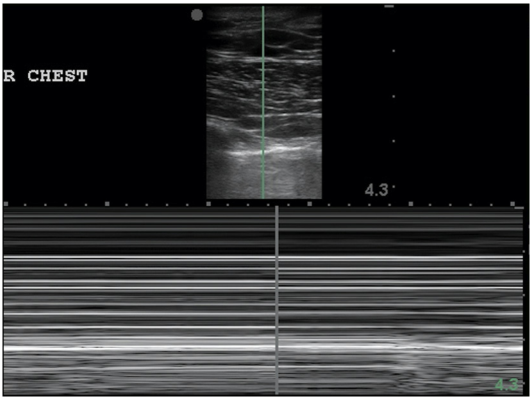

Fig. 20. Abnormal M-mode pattern of pneumothorax appearing like a barcode.

movement (**Fig. 20**). The “lung point” is the junction in which the pneumothorax ends and sliding is again seen, pathognomonic for pneumothorax (Video 18).

The eFAST scan can change differential diagnoses and patient management in a significant number of patients in remote settings.[43] Deciding on evacuations, patients saved from thoracostomy, and identification of emergent conditions masked by normal vital signs have all proved eFAST to be invaluable.[43–45]

Musculoskeletal injury

Austere environments can have treacherous terrain, placing people at risk for musculoskeletal injury. The high-frequency linear probe is often used because most injuries do not require increased depth.

- Subcutaneous or deep tissue hematoma
  - Pathology: Normal skin is echogenic with varying levels of brightness with linear arrays separating various fascial planes (Video 19). Hematomas tend to be initially hypoechoic with mixed echogenicity as the clotting process progresses[46,47] (Video 20). Use color Doppler to differentiate it from a solid mass, as hematomas will lack vascularity. Compression cause the internal echoes of a hematoma to move.
- Fractures/Effusions: POCUS is useful for occult fractures and more sensitive than radiograph for scaphoid, hip, long bone, and sternal fractures, as well as joint effusions.[48–52]
  - Pathology: Fractures are seen as a cortical discontinuity. Another suggestive sign is an adjacent hematoma (**Fig. 21**). The nearby joint space can be assessed for associated joint effusions, seen as a larger anechoic joint space fluid compared with the contralateral side[7] (Video 21).
  - Fracture reduction and hematoma blocks: Ultrasound can be used to identify the location for hematoma blocks for pain control, as well as assess alignment of the bone after reduction attempts.[53]
- Dislocation: POCUS has been studied in shoulder and hip dislocations with high sensitivities.[54,55]
  - Technique and pathology: By placing the probe in longitudinal orientation to the humerus or femur at the joint space, a dislocation can be seen as a

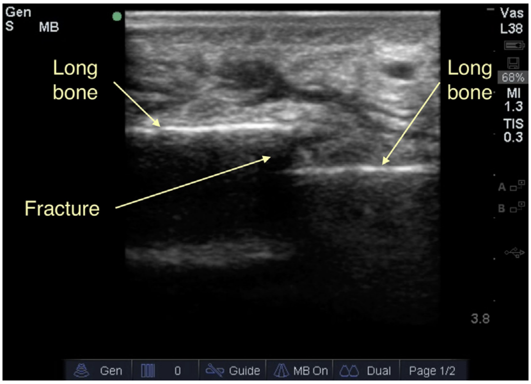

Fig. 21. Fracture seen as a cortical disruption.

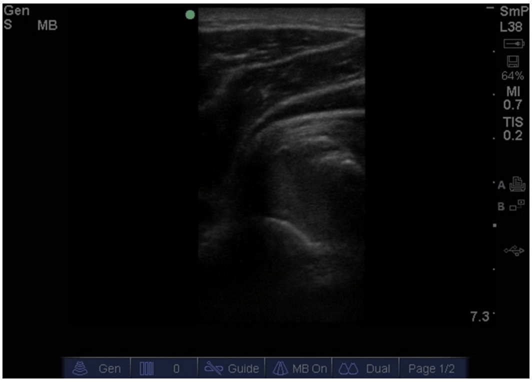

Fig. 22. Anterior shoulder dislocation showing humeral head lateral and inferior to glenoid.

separation of bones. Ultrasound can provide confirmation after dislocation reduction (**Fig. 22**).

- Tendon tear: Tendon tears, especially those of large muscle groups, such as the triceps, quadriceps/patella, and biceps, is accurately diagnosed with POCUS.[56] Tendons appear differently depending on the angle and tilt of the ultrasound transducer relative to the tendon. When oblique against tendon fibers, a hypoechoic artifact is observed, leading to a false-positive interpretation.[56]
  - Pathology: Normal tendon has a linear striped fibrillar appearance and is more echogenic than muscle. Findings suggestive of a tendon tear include local swelling around the tendon fibers, fiber discontinuation, irregularity of the tendon, and hypoechogenicities within the tendon bed itself[56] (**Fig. 23**). Accurate diagnosis is reached by comparing to the contralateral side.[57] Ranging the patient's joints throughout the examination will show the 2 severed ends in a tendon tear separating from one another[58] (**Fig. 24**).

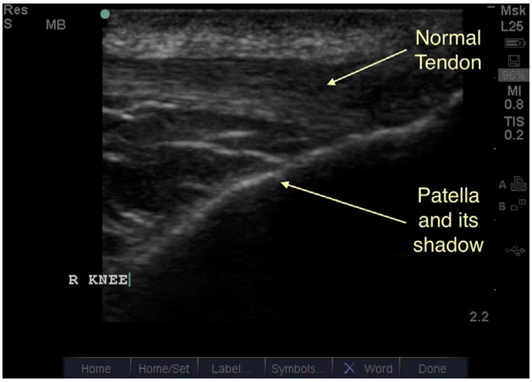

Fig. 23. Normal tendon showing linear fibrous tendon without adjacent fluid of soft tissue edema.

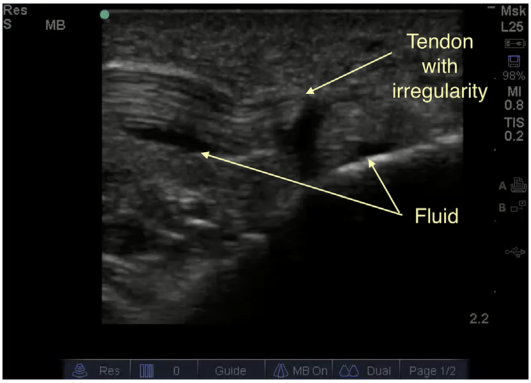

Fig. 24. Partial patella tendon tear seen as disruption of normal tendon linearity with adjacent fluid.

High-Altitude Pulmonary Edema

Lung and cardiac ultrasound can identify individuals with high-altitude pulmonary edema (HAPE) susceptibility and distinguish HAPE from other causes of dyspnea. Cardiac ultrasound has replaced pulmonary artery catheterization for assessing the increased pulmonary artery pressures, allows detection of a patent foramen ovale, and allows assessment of LV and RV myocardial performance to hypoxia because they may contribute to or are associated with HAPE.[59–62] Sonographic B-lines, diagnostic of interstitial fluid, are linear vertical rays arising from the pleural line and extending to the end of the screen, with the number of B-lines correlating with degree of hypoxia and symptom severity in patients with known HAPE.[63] The number increases with each ascend and improves with either the descend or treatment for HAPE.[64] Also, B-lines can appear in all lung zones within minutes of arrival at high altitude, suggesting hypobaria alone could lead to interstitial fluid accumulation before symptoms (subclinical HAPE).[65] Additionally, findings on ultrasound that suggest etiologies of dyspnea, such as pneumothorax, pneumonia, heart failure, pulmonary embolus, or

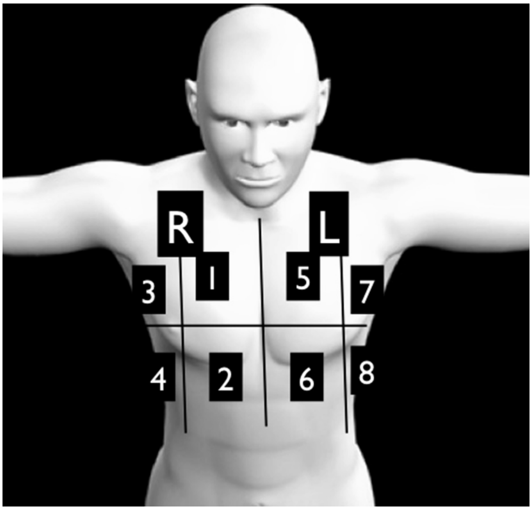

Fig. 25. 8-zone technique of assessment for B-Lines.

myocardial infarction, require immediate evacuation, whereas patients with HAPE may descend until symptoms resolve.

- An 8-zone technique is used, avoiding the need for patients to undress in the cold (Fig. 25). The anterior chest wall is delineated from the sternum to the anterior axillary line and subdivided into upper and lower halves (the clavicle to the third intercostal space, and from the third intercostal space to the diaphragm). The lateral zone is delineated from the anterior to the posterior axillary line and subdivided into upper and lower halves. One scan is obtained from each area.
- Pathology: Normal lung will show linear horizontal reverberation artifact, called A-lines (Fig. 26). B-lines are defined as discrete laser-like vertical hyperechoic reverberation artifacts that arise from the pleural line, extend to the bottom of the screen without fading, and move synchronously with lung sliding (Fig. 27). They

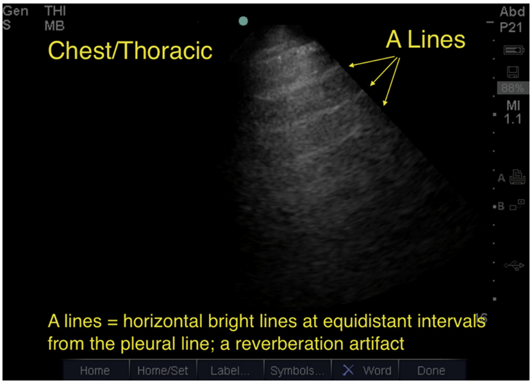

Fig. 26. Sonographic A-lines of normal chest.

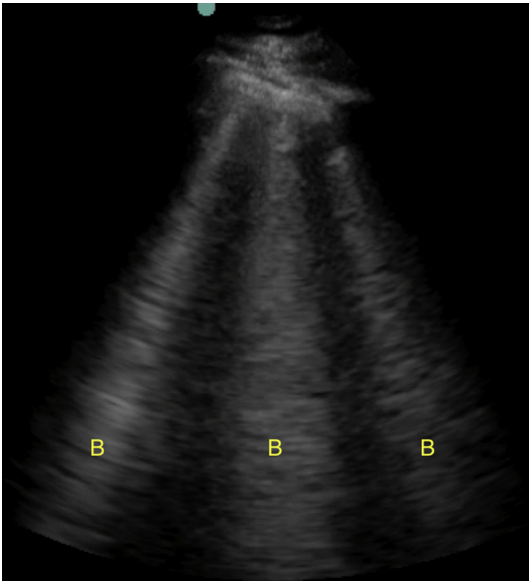

Fig. 27. Sonographic B-lines showing pulmonary edema.

arise from the pleural line, move with lung sliding, spread to the edge of the screen without fading, and erase A-lines. Interstitial syndrome (including pulmonary edema) has been defined as more than 2 B-lines in more than 2 zones, bilaterally. Also, the total sum of all B-lines yields a B-line score which is another indicator of the extent of extravascular lung water.[40,66–68] It is currently unclear if the number of B-lines is able to predict or assess the extent of pulmonary edema at altitude.

Acute Mountain Sickness and High-Altitude Cerebral Edema

Increasing ONSD measurements have been associated with severity of acute mountain sickness (AMS).[69,70] This finding supports the theory that AMS is due to increased intracranial pressure (ICP); however, significant individual variations, at baseline and at altitude, as well as interobserver variation exists with this technique.[71,72] ONSD increases with altitude alone in subjects both with and without AMS, but to a higher degree in the former.[69,70,73] In those who do have AMS, ONSD has a positive correlation with the severity of symptoms, including the Lake Louise score, oxygen saturation, and resting heart rate.[70] However, more recent research failed to demonstrate any association between ONSD and headache, which is often considered the most significant AMS symptom.[74] Other pathologies can be seen with ocular ultrasound, including retinal detachment, vitreous hemorrhage, retrobulbar hematoma, and orbital rupture. The high-frequency linear probe is used (Video 22).

- Pathology: The optic nerve will be visualized in the axial plane as a linear hypoechoic structure extending posteriorly from the anechoic circular globe, surrounded by echogenic retrobulbar fat. ONSD measurement is taken 3 mm behind the papilla, the location with the highest distensibility with increased ICP (**Fig. 28**). Each eye is scanned both sagittally and transversely, and the ONSD is compared with the unaffected eye. The normal cutoff for adults is 5 mm, whereas younger children can be higher.[75,76]

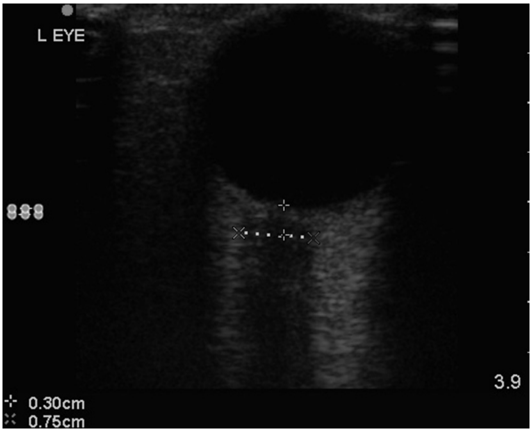

Fig. 28. Abnormal ONSD measured 3 mm from posterior orbit.

Pneumonia

Lung ultrasound is shown to be superior to radiography, and comparable to CT for the diagnosis of pneumonia.[77–79] Compared with traditional imaging used to identify pneumonia, sonography is the preferred method in children.[80–82] Researchers regard POCUS as the reference standard for lung consolidation and concluded that the World Health Organization case management algorithm is inferior in comparison.[81] Considering that pulmonary infection is quite common in patients infected with the human immunodeficiency virus (HIV), ultrasound is especially valuable in countries with high HIV prevalence.[82] The low-frequency phased array or curvilinear probe is used.

- Pathology: Consolidation is seen as a hypoechoic area with tissuelike heterogeneous texture, oftentimes described as "hepatization." It usually has irregular or blurred borders and hyperechoic dendritic or punctate structures representing air bronchograms (Figs. 29 and 30). B-lines also can be seen extending from the consolidation (Fig. 31). If the consolidation reaches the pleura, the pleural line will have decreased or absent lung sliding. There also may be a parapneumonic pleural effusion in the dependent thorax. It can appear anechoic, or echogenic in the case of empyema, hemorrhage, or clots[77–83] (Fig. 32).

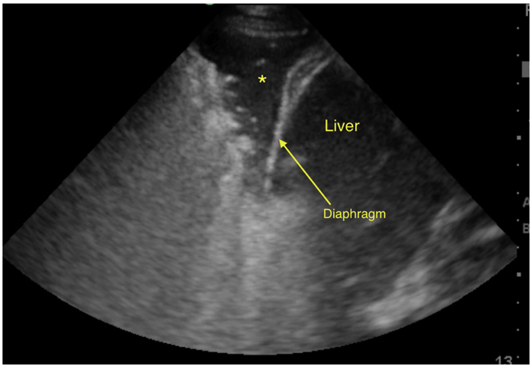

Fig. 29. Right lower lobe pneumonia seen as a hypoechoic triangular region (*asterisk*) with hepatization and hyperechoic borders.

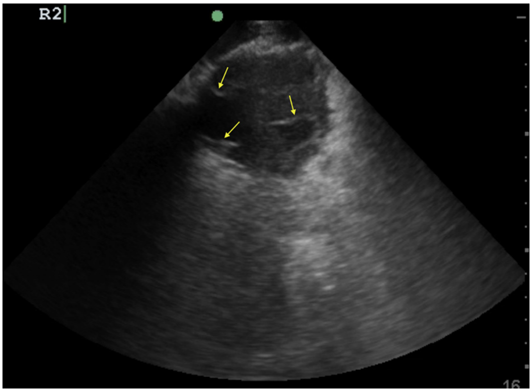

Fig. 30. Air bronchograms (*arrows*) seen within consolidation consistent with pneumonia.

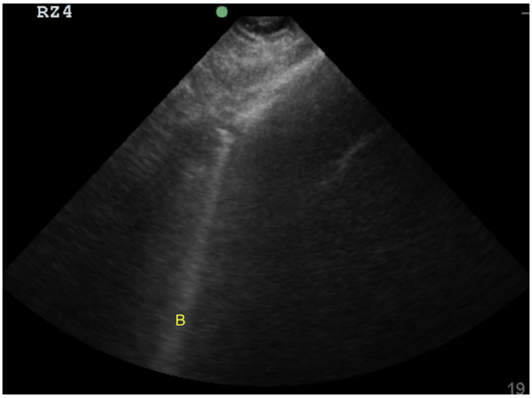

Fig. 31. Small area of pneumonia with resultant B-line extending from the consolidation.

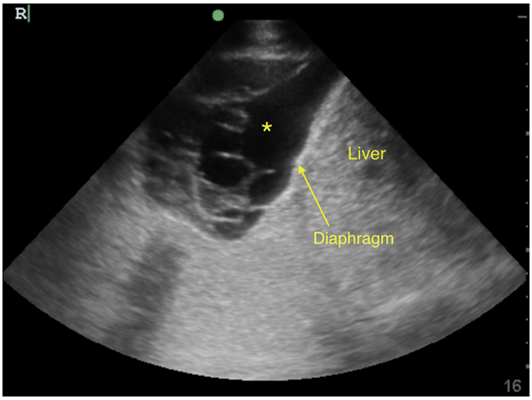

Fig. 32. Loculated parapneumonic pleural effusion (*asterisk*) adjacent to consolidation.

Volume/Hydration Status

Intravascular volume and fluid tolerance is assessed by ultrasound by an evaluation of either the internal jugular (IJ) vein or IVC. Extremes of volume status are correlated to IVC respiratory variation.[28,84–86] Patients with undifferentiated hypotension will benefit from POCUS to assess hydration status, as intravenous fluids may not be widely available.[28] The aorta-to-IVC ratio is associated with volume status in children, even though reports diverge on whether ultrasound alone accurately identifies dehydration in resource-limited settings.[84,85]

- IJ assessment
  - Probe and technique: a high-frequency linear probe is placed on the mid to lower anterior neck, perpendicular to the skin in transverse plane of the vein with the patient supine or semi-upright to 30°. Only gentle pressure should be applied. Under M-mode, the maximum (Dmax) and minimum (Dmin) diameter of the vein can be measured to obtain the collapsibility index (CI)[87–89]: $CI = [(D_{max} - D_{min})/D_{max}] \times 100\%$.
- IVC assessment
  - The IVC will be seen entering the right atrium, with measurements of respiratory variation taken 2 cm caudal to the right atrial inlet. Similar to the IJ,

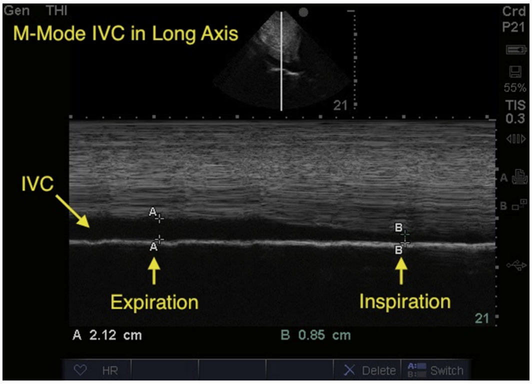

Fig. 33. IVC evaluation using M-mode.

M-mode is used for the recording and determination of the CI (Fig. 33). If the maximum diameter of the IVC is less than 2 cm with greater than 50% respiratory variation, the patient may be hypovolemic; if the maximum diameter of the IVC is greater than 2 cm with less than 50% respiratory variation, the patient may be hypervolemic[90,91] (Videos 23 and 24).

COMMON PROCEDURAL ULTRASOUND IN AUSTERE ENVIRONMENTS

Nerve Blocks/Regional Anesthesia

In the wilderness, traumatic injuries to the upper or lower extremities account for approximately 65% of all musculoskeletal/soft tissue injuries, with most of these being lacerations, traumatic pain, sprains or strains, abrasions, fractures, or dislocations. Pain medications are frequently unavailable and can pose medical problems, making nerve blocks an excellent choice for pain control.[92,93] These blocks have demonstrated effectiveness in the combat setting, because patients with significant injuries can be treated in the field while awaiting evacuation.[94] Complications from inadequate pain control include impaired sleep, impaired immune function, increased risk of developing chronic pain, and increased time to recovery.[94,95] The primary challenges include an inability to clearly identify the nerve, intraneural penetration, and intravascular injection. In the wilderness environment, additional challenges include nonsterility and inability to monitor for signs of local anesthetics systemic toxicity, a rare condition causing neurologic and/or cardiovascular excitation (agitation, seizure, tachycardia, and hypertension) then depression (respiratory depression, coma, bradycardia, asystole).[93,96]

- Probe: High-frequency linear probe for superficial nerves; low-frequency curvilinear probe for deeper nerves.
- Technique: Nerves have a "honeycomb" appearance on ultrasound due to hypoechoic (dark) areas embedded within the hyperechoic (bright) nerve sections (Fig. 34). Place the probe in transverse orientation to the nerve, at a safe distance from the vascular bundle to avoid inadvertent vascular injection. Using a longitudinal approach in relation to the needle, penetrate the skin, visualizing the needle on the screen at all times as it gets closer to the nerve, being careful to never penetrate the nerve (Fig. 35). Draw back on the syringe to avoid injecting within a vascular structure, then slowly inject the anesthetic, creating a "halo" appearance of fluid surrounding nerve (Fig. 36).

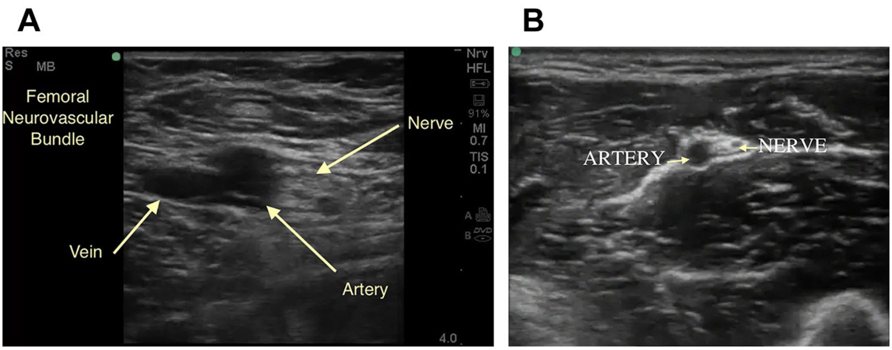

Fig. 34. (*A*) Femoral nerve with its "honeycomb" appearance next to the femoral vessels. (*B*) Ulnar nerve with its characteristic honeycomb appearance next to the ulnar artery.

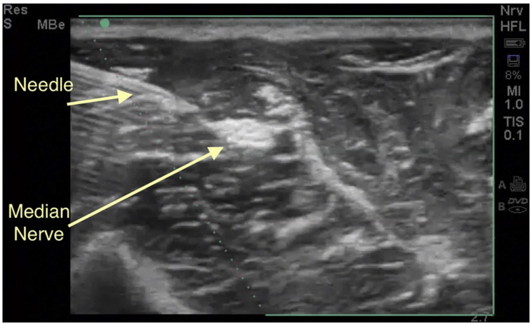

Fig. 35. The length of the needle is seen due to the probe oriented in-plane to the needle. Its tip is seen approaching the median nerve.

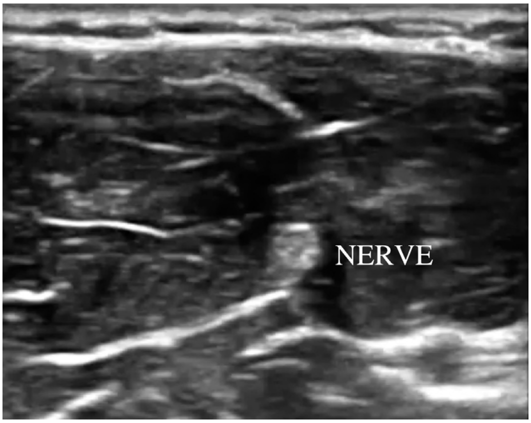

Fig. 36. A "halo" of black fluid is seen surrounding the median nerve.

Approximately 5 to 20 mL of anesthetic is used depending on the anesthetic and nerve size (smaller nerves need only 5 mL, whereas larger nerves require up to 20 mL). Retract if patient notes significant pain with injection, as intraneural penetration may have occurred. Intralipids can be used if toxicity occurs. Contraindications to nerve blocks include coagulopathy or allergy to anesthetic.

- Nerve function: The nerve's motor and sensory functions must be assessed before and after the procedure (**Table 1**).

Table 1
Commonly used ultrasound-guided nerve blocks

Nerve	Motor	Sensory	Injuries Treated
Radial	Wrist extension	Dorsal aspect of hand from thumb to radial half of ring finger	Hand injuries to affected area
Median	Wrist and finger flexion	Volar aspect of hand from thumb to radial half of ring finger	Hand injuries to affected area
Ulnar	Intrinsic muscles of hand	Sensation to 5th digit, and ulnar half of ring finger	Hand injuries to affected area
Interscalene brachial plexus	Superior and middle trunks of the brachial plexus (C5–C7), shoulder and upper arm	Superior and middle trunks of the brachial plexus (C5–C7), shoulder and upper arm	Shoulder, humerus, and elbow injuries; does not reliably block forearm or hand injuries
Sciatic (popliteal)	All movements of foot and toes (via tibial and peroneal nerves)	Foot and most of leg, excludes most medial aspect (innervated by saphenous)	Injuries to lower leg, ankle, and foot
Femoral	Flexion at hip and extension at knee	Medial aspect of distal thigh and leg	Hip fractures, proximal femur, and knee injuries

Peripheral Vascular Access

Vascular access in the hypovolemic patient can be difficult to achieve. Using ultrasound to guide peripheral vascular access has provided success rates from 91% to 97% after prior failed attempts, and initially perceived difficult peripheral access cases are often deemed easier when ultrasound is used.[97–100] In the austere environment, when transfer to the nearest medical facility may be delayed, beginning resuscitative efforts in the field is important. Ultrasound-guided vascular access is easy to learn, with novice users trained to proficiency after minimal training.[101] Complications are the same as those associated with traditional methods: local infiltration, cellulitis, thrombophlebitis, and hematoma formation.[102]

- Technique: The most common area for ultrasound-guided vascular access is the antecubital fossa, although any visible vein can be used. A tourniquet is placed proximally. A longer 1.5-inch catheter may be needed for deeper veins. After cleaning the skin with an alcohol swab, the nondominant hand holds the probe with its indicator toward the sonographer's left in transverse orientation to the vein, a short-axis technique.[101] Then, centering the vein on the screen by sliding the probe and adjusting the screen depth, compressing it with the probe to distinguish it from an artery, and noting the vein's depth from the skin, all will optimize successful cannulation. The dominant hand holds the catheter and places it at the center of the probe and penetrates the skin (**Fig. 37**, Video 25). The needle tip must be seen as it advances toward the vein. This requires the probe to also slide in the direction of needle advancement. You may notice a tenting of the anterior wall of the vein. Once the needle punctures the vessel wall, blood return will be seen, and you can place the probe down, advance the catheter over the needle, and secure the line using standard methods (**Fig. 38**).

Fig. 37. Short-axis single-operator technique. The nondominant hand holds the probe while the dominant hand holds the catheter.

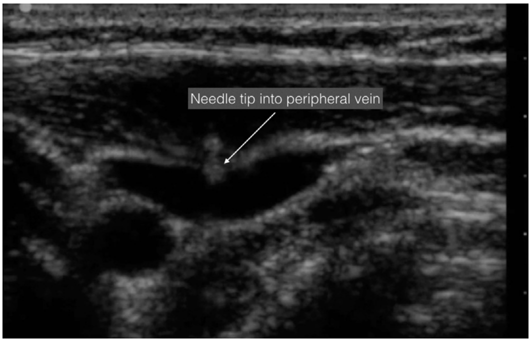

Fig. 38. Needle tip seen tenting the anterior wall of the vein.

Foreign Body (Identification and Removal)

In the wilderness, foreign objects are estimated to account for 2% of all soft tissue injuries.[92] Delay in identification or removal of foreign bodies has been shown to increase associated pain, infection, and inflammation. Ultrasonography is a reliable diagnostic mode for foreign bodies assessment, as well as for guiding their removal.[103,104] It has proven to be superior to plain film radiography, detecting both radiopaque and radiolucent objects with sensitivities of 94% to 98%.[105,106] Unsuspecting fragments and adjacent musculoskeletal and neurovascular structures also can be seen, and once detected, ultrasound can be used to guide the removal of the foreign body with reliability and less complication.[106] During foreign body removal, you are able to accurately identify the location and its measurements, as it may not be in the area of the puncture site, so you are able to make your incision length more precise.[107]

- Technique: The probe is placed over the injury, or the assumed entrance site if visible, and a wide margin is evaluated. Once the hyperechoic foreign body is identified, evaluate it in both its longitudinal and transverse axis, and measure its length and width respectively, which allows the assessment of its position, orientation, and any potential fragments alongside it (**Figs. 39** and **40**). After appreciating the regional structures, identify the closest distance of the object in longitudinal axis from the skin's surface and mark the skin; this will be your entry point for removal. After wiping the area with an alcohol wipe, and injecting local anesthetic if available or performing a nerve block, use a number 11 scalpel and make a small incision as wide as the width of the foreign body. Applying gel and the probe over the skin adjacent to the incision site allows for direct visualization while blunt dissection is done by forceps through the incision and advancing toward the foreign body for its capture and removal. Irrigate the wound again, and allow it to heal by secondary intention.
- Water bath technique: If a foreign body is suspected in the hand or foot, placing the region in a bucket of water and inserting the probe in the water without applying pressure on the region can prevent further pain elicitation and improved foreign body removal technique[108] (**Fig. 41**, Video 26).

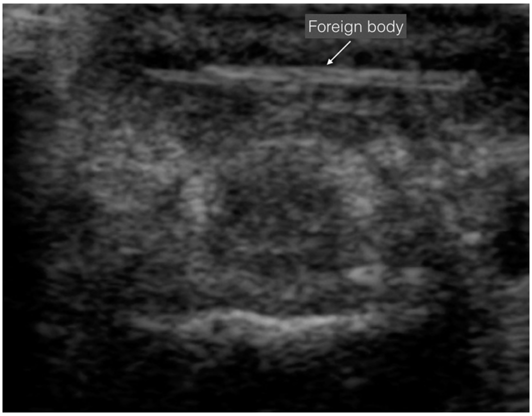

Fig. 39. Ultrasound of foreign body in longitudinal axis.

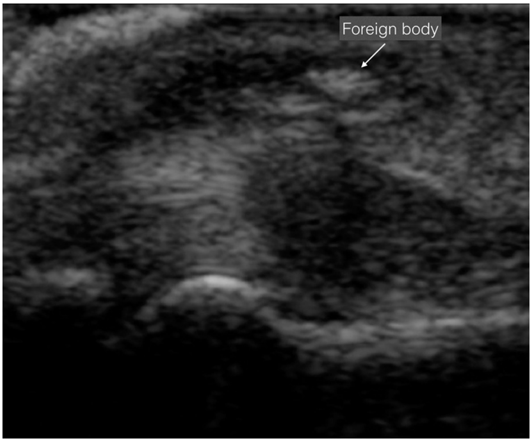

Fig. 40. Ultrasound of foreign body in transverse axis.

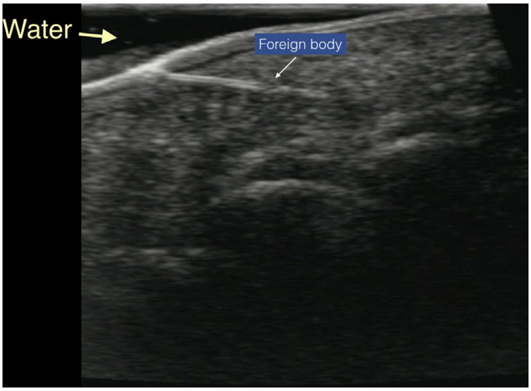

Fig. 41. Ultrasound of foreign body using water bath.

Abscess (Diagnosis)

Differentiating abscess versus cellulitis can be difficult with physical examination alone. Using POCUS will improve accuracy of diagnosis from 86% for physical examination alone to 98% with POCUS.[109] This improvement will save certain patients from unnecessary invasive procedures if cellulitis or an abscess smaller than 1 cm is seen, and reserve an incision and drainage for those who really need it.[110] In addition, abscesses may be deeper than previously anticipated, or may be communicating with deeper infective pockets that require surgical drainage,[111] allowing appropriate management decisions on evacuation need in austere environments.

- Pathology: Normal soft tissue will have well-delineated tissue planes (**Fig. 42**). Cellulitis is seen as anechoic layers of fluid within the soft tissue causing a characteristic "cobblestone" appearance, or in some cases you may only see a loss of well-demarcated tissue planes caused by tissue thickening and inflammation (**Figs. 43** and **44**). Abscesses are seen as anechoic or hypoechoic irregularly bordered structures, often with echogenic purulent material (**Fig. 45**). When the

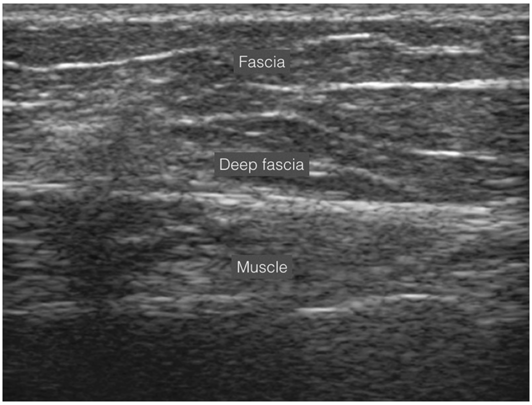

Fig. 42. Normal soft tissue with well-delineated tissue planes.

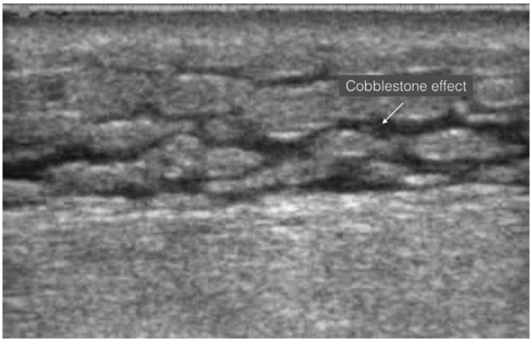

Fig. 43. “Cobblestone” effect suggestive of cellulitis.

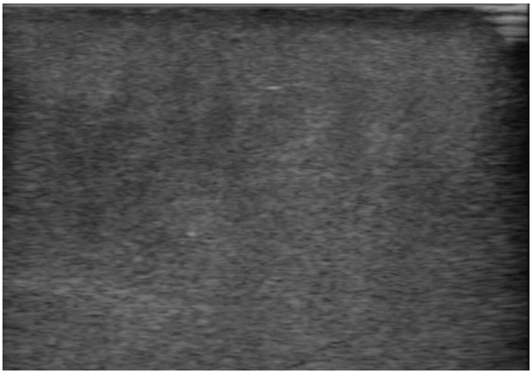

Fig. 44. Cellulitis with loss of well-delineated tissue planes.

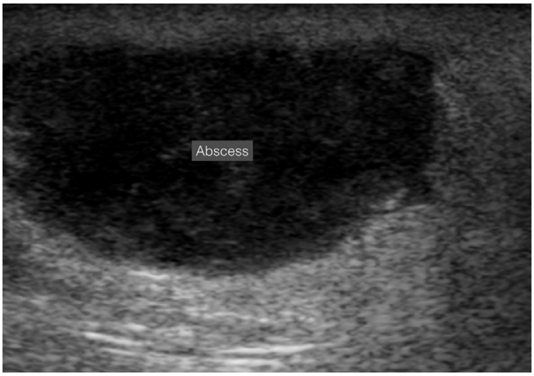

Fig. 45. Hypoechoic fluid-filled structure consistent with an abscess.

probe is directly over the abscess, and gentle pressure is applied, the purulent material will move within the abscess (Video 27). Take note of any adjacent structures, such as nerve bundles, vascular structures, muscle, or tendons, and their relative location to the abscess to assist in incision and drainage.

SUMMARY

Ultrasound systems must be handheld, battery operated, durable, and able to withstand extremes of temperature and altitude, and additional equipment may be necessary to help prevent battery degradation and equipment damage. POCUS is portable and lightweight, and can be used to screen for a wide variety of pathologies common to austere environments, disaster situations, and resource-limited settings. Common POCUS applications used in austere environments include the eFAST scan, musculoskeletal and soft tissue applications, an assessment for HAPE, high-altitude cerebral edema, pneumonia, volume status, and various procedural guidance applications. The various POCUS applications used in austere environments for procedural guidance include peripheral vascular access, nerve blocks for pain control, foreign body identification and removal, and abscess identification and drainage. POCUS is a reliable tool to assist in triage, resource allocation decisions, screening for conditions, and management of patients with pathology common in austere environments.

SUPPLEMENTARY DATA

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.emc.2016.12.007.

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