Ultrasound in Disasters and Austere Environments

9

Jay Doucet

9.1 Introduction

Natural disasters and some man-made mass casualty events can produce enough injured patients to overwhelm local health care systems and create loss of healthcare infrastructure, including imaging resources. They may also require healthcare to be provided in austere, resource-limited environments. Current healthcare in high-income nations is extensively based on advanced medical imaging. Organisation for Economic Co-operation and Development (OECD) 2018 data indicates that from 100 to 271 CT scans per 1000 inhabitants were performed in US and EU countries [1]. In the surge of patients occurring during loss of utilities and nonavailability of advanced medical imaging, there may be a critical lack of image-based clinical decision-making support. This will be a severe challenge for trauma care providers. A method to screen and diagnose trauma and non-trauma conditions that is rapid enough to deal with a large patient surge is ultrasound.

The characteristics of recently released ultrasound devices—lightweight, battery powered, handheld devices that use wireless, cloud-based image storage, can have considerable utility in disasters and austere environments. However, adequate preparation and training are required for successful deployment.

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9.2 POCUS Training

Bedside ultrasonography by a non-fulltime sonographer clinician, also called Point of Care Ultrasonography (POCUS) has become a common part of the practice of trauma and acute care surgery [2]. Ultrasound facilitates diagnosis and increases the safety of procedures. Medical students in the US are now being taught ultrasonography skills in their junior years of medical school. Residencies and fellowships are increasingly adopting ultrasound curricula. The quality of ultrasound equipment and images are improving, ease of use is better and cost of equipment has decreased. Some newer devices are provided with integrated training modules for physicians.

The operator-dependent nature of the FAST exam and need for experience has led to a recognition that formal ultrasound curricula must be offered in medical school, residencies and fellowships. Facility with ultrasound is now required by Residency Review Committees' Milestones requirements for several specialties in the US. In 2017, new guidelines, including didactic education and a specified number of proctored examinations were provided in the US by the Surgical Critical Care Program Directors Society (SCCPDS), who train trauma surgeons and surgical intensivists in the US [3].

Training and credentialing in POCUS is available to all physicians. The American Medical Association has asserted that ultrasound imaging is not the exclusive property of any specialty, but that hospital medical staffs should determine requirements for privileging. These requirements should be based upon the physician's training for the use of ultrasound technology and strongly recommends that these criteria are in accordance with recommended training and education standards developed by each physician's respective specialty [4].

There is no single prescribed credential in POCUS that is universally accepted. Indeed, there is controversy whether external agencies should play a role versus using hospital-based training, required postgraduate training or continuing medical education (CME) courses alone. While an external credential for a specific clinical skill might demonstrate commitment to excellence and validation of training, there is no evidence that an external POCUS credential enhances patient safety. Indeed, in low and middle-income nations and in resource-limited environments, a requirement for an external credential could actually be a barrier to wider adoption of a critical patient care skill.

For those physicians who did not receive sufficient training in residency to be skilled in ultrasound, excellent resources are available on-line from sites such as pocus.org, sdms.org, aseuniversity.org and other sites. Finding a mentor who can observe your technique and review your examinations is also very helpful. There are also live CME-type POCUS ultrasound courses held in many countries, but these can be very expensive, and can only provide an introduction. If a physician is using POCUS to enhance decision-making or procedures, they should participate in a quality assurance (QA) program to allow ultrasound-facile peers to review complications and outcomes associated with POCUS use. Logs should be kept of POCUS exams to maintain privileges and enable QA processes.

9.3 POCUS Equipment

A revolution in wireless technology and microprocessors has also affected ultrasound devices. It is now possible to purchase a US FDA-approved ultrasound machine that performs most typical imaging modes, uses a robust semiconductor chip sound emitter, has digital image processing, connects to "cloud" storage via the provider's mobile phone and costs less than US$2000, not including annual subscriptions (~US$400) (Fig. 9.1). Pocket-sized ultrasound machines are decreasing in cost and will be carried by increasing numbers of providers. Ignoring the capabilities of this imaging modality will soon be impossible for trauma and acute care surgeons.

The small size of the newest handheld probes such as the Butterfly iQ, General Electric (GE) VScan or Philips Lumify simplifies their use in austere environments, they literally can be kept in a pocket. In the case of the Butterfly iQ, an Apple iOS device such as an iPhone or iPad is needed for visualization, while the Lumify needs an Android-based tablet. These devices could be easily taken on board aircraft or vehicles and brought to the billions of the world's population who lack good access to medical imaging. Battery life of these devices is typically 120 min, meaning some thought must be made for how these devices will be recharged between uses in resource-limited devices. Additional power sources, such as battery banks or solar chargers that provide mains power or USB power to charge the device and any visualization devices such as tablets should be also be acquired for use in disasters.

The current devices use Wi-Fi wireless connections to upload stored images. In the case of the GE VScan or Phillips Lumify, these can provide DICOM standard images for archiving in a hospital PACS system. The Butterfly iQ requires a separately-charged subscription to upload images to a cloud-based server system via Wi-Fi. If many images are to be stored and Wi-Fi with an internet connection is not available, images may be stored temporarily on the Android tablet or iOS device. In the case of

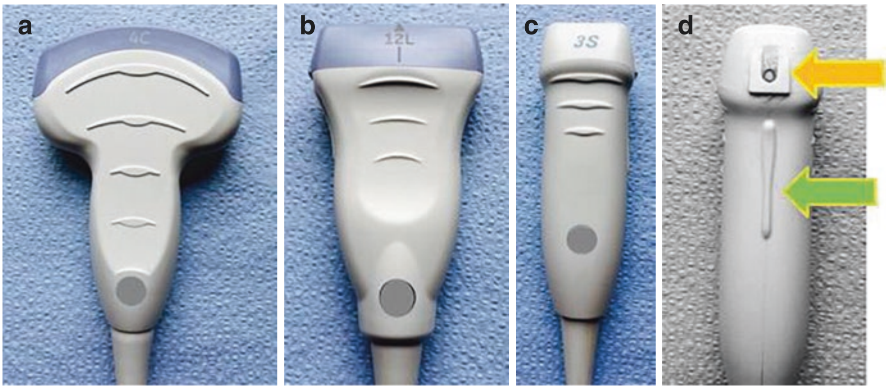


Fig. 9.1 Typical ultrasound probes. (**a**) Convex low frequency transducer—used in abdominal exams, (**b**) linear high frequency transducer—used in vascular and pleural exams, (**c**) phased array low frequency transducer specifically designed for cardiac imaging/echocardiography, (**d**) showing the transducer orientation index marker. Note the ridge on the probe housing and the LED

the Butterfly iQ being used in low resource environments, individual images taken are typically between 500 KB and 1 MB, and videos are 1–2 MB per second of recording. 16 GB of free space on a typical Apple iPhone or iPad would hold thousands of images and videos prior to internet connection. The Butterfly iQ does have to connect to the internet every 30 days for firmware updates and to check for recalls [5].

9.4 Conventional POCUS Studies

9.4.1 FAST

In 1996, "Focused *Abdominal* Sonography for Trauma" or FAST was described by Rozycki et al. The exam was "focused"—looking for free fluid only—to simplify the test and to make it faster [6]. However, within a year in the name of the exam had already changed to the "Focused *Assessment* with Sonography for Trauma" due to the realization that thoracic structures such as the heart, pericardium and pleura could also be evaluated [7]. FAST is useful not just in trauma patients, but can be adapted for the assessment of other acute surgical patients as well.

The purpose of the FAST examination is to determine the presence of pathologic intra-abdominal, intrapleural, or intraperitoneal free fluid, which has a distinctive hypoechoic or anechoic (that is, black) appearance on the screen [8]. About the only absolute contraindication to doing the FAST exam is when it delays performing a definitive operative procedure.

Ultrasound offers several advantages in the evaluation of the acute surgical patient. It is rapid and can be done at the bedside. It is noninvasive and does not require the use of radiation. It can be performed quickly, including in the middle of a trauma or shock resuscitation or even during CPR. The test can be repeated as often as desired. This makes it very suitable for the acute patient in shock, where the American College of Surgeons Advanced Trauma Life Support (ATLS) "Primary Survey Adjuncts" of FAST, Chest X-ray, and Pelvis X-ray can quickly locate the site of a large intracavitary hemorrhage and hematoma [9].

FAST ultrasound of the abdomen does have some significant limitations, the most significant is its lack of sensitivity, typically less than 75%. There are other tests that are more sensitive such as the CT scan of the abdomen, which is very sensitive and specific, or the diagnostic peritoneal lavage, which is exquisitely sensitive and not very specific. Sensitivities as low as 42% have been reported with FAST. However, that may not matter when FAST is employed by surgeons using an appropriate trauma or ICU algorithm. The low sensitivity of FAST is complemented by a good selectivity which means that a positive test is likely true and the negative test simply means more evaluation is necessary.

The FAST exam has been continually improved since the original four quadrant exam. The eFAST (enhanced FAST) means the addition of pleural views, which can detect a pneumothorax more rapidly and with greater sensitivity than a chest X-ray [10, 11] The thoracic views improve the utility of eFAST, even though it shares the relative lack of sensitivity of the traditional FAST abdominal exam compared to the CT scanner.

In patients in whom there is a doubt regarding the presence of pericardial effusion or tamponade, the FAST exam of the pericardium is invaluable and can be life-saving.

Some centers have improved the sensitivity of trauma ultrasonography by actually doing extra views and examining the organs, instead of just looking for fluid as done in FAST. At our Level I Trauma Center, we have previously demonstrated that a combination of a comprehensive negative screening ultrasonography (US) and negative clinical observation for 12–24 h, in the setting of blunt abdominal trauma, virtually excludes missed abdominal injury [12]. We call this complete examination CUST—Complete Ultrasonography for Trauma. Other advantages of CUST are the significant reduction in hospital charges as well as a large reduction in radiation exposure in trauma patients. Surgeon-selected blunt abdominal trauma screening with the CUST protocol appears to have similar outcomes as CTAP. While the initial CUST sensitivity was 76% in 19,128 patients, when combined with serial examination and selective CT scanning, the false negative rate was 0.29% with a NPV of 99% [13].

There are conditions in which a negative FAST cannot be accepted as definitive and a CT Scan should be performed.

A negative FAST examination should not be accepted as definitive if:

- it is of poor quality,
- it is a case of seat belt mark injury,
- it is a case of penetrating torso trauma,
- the patient is very obese,
- there is hematuria,
- the patient has significant abdominal pain without other operative indications, or,
- spinal and/or pelvic fractures are suspected.

In such cases, the patient should undergo CT scanning if available, or undergo serial examinations with a high suspicion for need for operative intervention.

Immediate laparotomy or thoracotomy without performing a FAST exam might be considered in penetrating trauma, or in blunt trauma with conditions such as peritonitis or evisceration. However, this means that there will be no evaluation of the pleura or pericardium prior to the procedure. The exact trajectory of penetrating trauma might not be immediately known at laparotomy. The presence of an occult pneumothorax might be missed and manifest only after intubation and anesthesia. Missed tamponade can be a lethal error, and can occur in both penetrating and blunt trauma.

Serial abdominal examination without FAST means that the opportunity to conduct repeat FAST exams is lost. Repeat FAST examinations increase the test's sensitivity and can indicate the need for CT or operation before peritonitis or abdominal pain manifests [14].

A limitation of FAST is that results are operator-dependent. Less experienced operators are less sensitive to detecting fluid—in one study about 10% of residents and attendings could detect 400 ml of intraperitoneal fluid, 85% could detect 850 ml and 97% could detect 1000 ml (Figs. 9.2 and 9.3) [15].

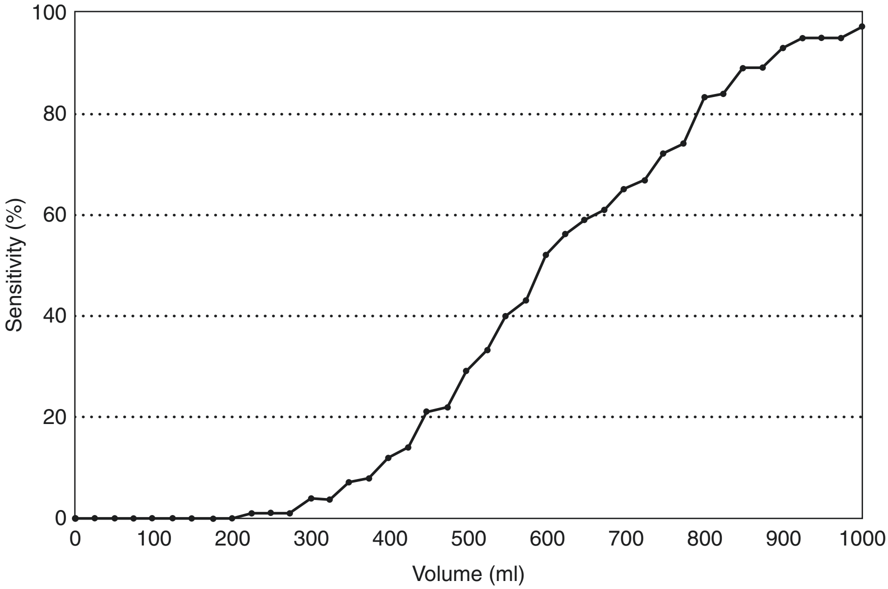


Fig. 9.2 Sensitivity of FAST to intraperitoneal fluid volume—EM attendings and residents

Fig. 9.3 Hand held, multimode, semiconductor chip ultrasound transducer, connects to iOS mobile phone, uses cloud storage, costs less than US$2000

The principal probe positions for the FAST examination are shown at Fig. 9.4 along with typically appearances of hemoperitoneum and pericardial fluid (Fig. 9.5). eFAST adds pleural and parasternal windows as well.

9.4.2 Specific Abdominal Organs

The acute care surgeon, after mastering the FAST examination can expand their skills into an ultrasound repertoire that could include abdominal aortic aneurysm (AAA), gallbladder/hepatobiliary, spleen and appendix/intestinal examinations. Each new area requires additional training and a sufficient caseload to maintain proficiency. Most of these exams are not extremely time critical, with the possible exception of the AAA examination in a hypotensive patient. In most medical centers a skilled sonographic technician routinely performs these examinations. However these are also within the ability of an interested acute surgeon-sonographer.

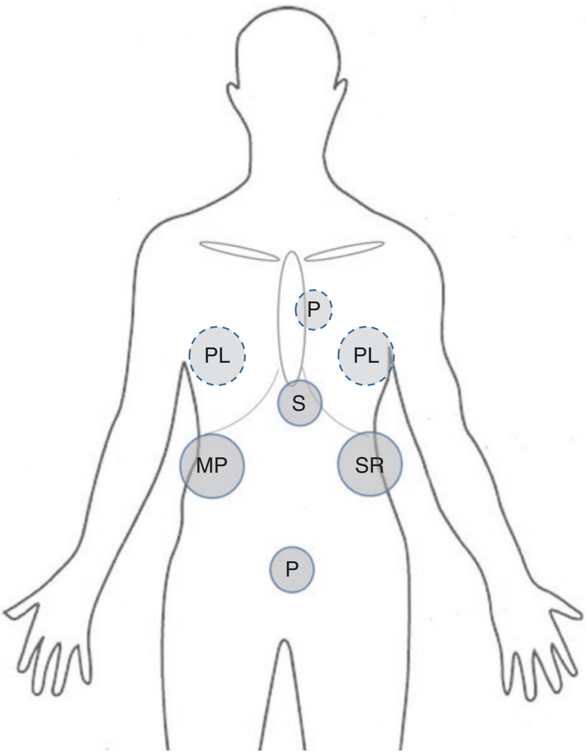


Fig. 9.4 Solid ovals are probe locations for FAST abdominal ultrasound—Morrison's pouch (hepatorenal fossa), the splenorenal fossa (SR), the subcostal area (S), and the pelvis (P). Dashed circles are typical additional windows for eFAST—pleura (PL) and parasternal (P)

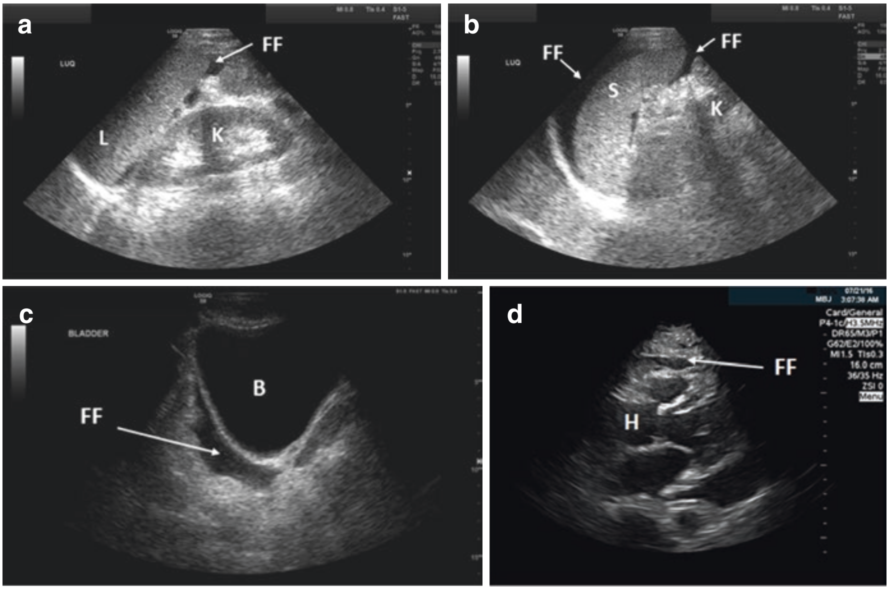


Fig. 9.5 (**a**–**c**) Example FAST images with hemoperitoneum—(**a**) Morrison's pouch (hepatorenal fossa), (**b**) splenorenal fossa, (**c**) pelvis with bladder, (**d**) FAST Subcostal SLAX view with large pericardial effusion. FF marks areas of free fluid. *L* liver, *S* spleen, *K* kidney, *B* bladder, *H* heart

9.5 Cardiac Ultrasound

The differential diagnosis and management of shock states are frequent challenges to the acute surgeon. Clinical examination is notoriously unreliable. Invasive monitoring techniques such as central venous pressure and pulmonary artery pressure catheters have fallen out of favor in many cases due to concerns for increased complications and difficulty of interpretation. These will also be difficult or impossible to manage in resource-limited settings. The latest addition to the FAST examination is the use of ultrasound to guide resuscitation of the acute surgical patient with shock. The intravascular volume status of the trauma patient has been estimated by the inferior vena cava (IVC) diameter and collapsibility as well as by ventricular filling [16]. More than 20 studies have been published describing the use of cardiac ultrasonography for resuscitation [2].

Bedside limited echocardiography has the advantages of being noninvasive, rapid, and being performed by the acute surgeons who will make immediate decisions on definitive management. Right and left ventricular function, intravascular volume and tamponade physiology can be rapidly identified. The Focus Assessed Transthoracic Echocardiography (FATE) examination was first described in 1989 in Denmark as a rapid way to assess shock states in critical care patients [17]. Similarly, the Focused Cardiac UltraSonography (FoCUS) examination was recommended by the American Society of Echocardiography (ASE) in 2014 for non-cardiologist clinicians to obtain rapid cardiac assessments [18]. The purpose of these exams is not to replace formal echocardiography, which can detect subtle and sophisticated findings such in as chronic valvular disease, but instead to make a shortened echocardiographic assessment of the current physiologic state, rule in or out critical diagnoses and guide resuscitative efforts.

Limited echocardiography is a step up in training complexity from the FAST examination. The target is moving, the useable sonographic windows are smaller and there is a greater demand on psychomotor skills to place the probe in the exact position to obtain the desired view. In trauma patients, typically less than 50% of the cardiac echocardiographic windows are useable due to subcutaneous air, pneumothoraces, edema, wounds, dressings, spinal precautions, and difficulty in positioning the patient [19]. Another training issue is that ultrasound machines switching from abdominal to cardiac modes by convention usually reverse the image, causing the index mark on the screen to shift from top left to top right. However, acute surgeons and trainees have routinely mastered these skills and are rewarded by the ability to make rapid assessments of cardiac physiology and intravascular volume status in the shock state.

9.5.1 Performing a Limited Echocardiography

There are three typical probe locations on the thorax for limited cardiac echo—the subcostal area (S), the left parasternal area (P) and the apical area (A) (Fig. 9.6).

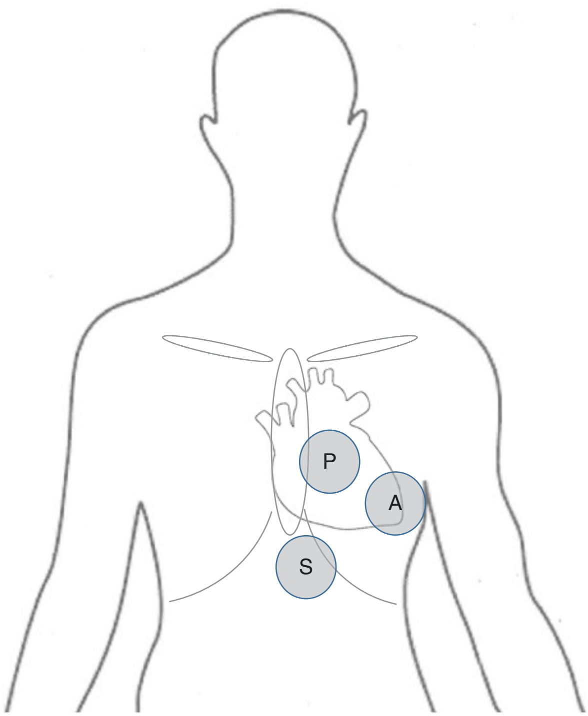


Fig. 9.6 Probe locations for point-of-care echocardiography—the subcostal area (S), the left parasternal area (P) and the apical area (A)

The subcostal location is included in the FAST examination and has two probe positions—subcostal long axis (SLAX) and subcostal short axis (SSAX) which give long axis and short axis views of the ventricles. A view of the inferior vena cava can also be obtained here (SIVC). The SLAX view requires placing probe below the xiphisternum, pointing the probe at the left acromion and rotating the probe on its long axis so that the index mark points away from the right shoulder, giving a long view of the ventricles (Fig. 9.7). The SLAX allows assessment of the left ventricle's performance. The SSAX view can then be obtained by continuing to point the probe at the left acromion while rotating the probe so that the index mark to pointing toward the patient's feet, giving a view across the ventricles (Fig. 9.8). This allows

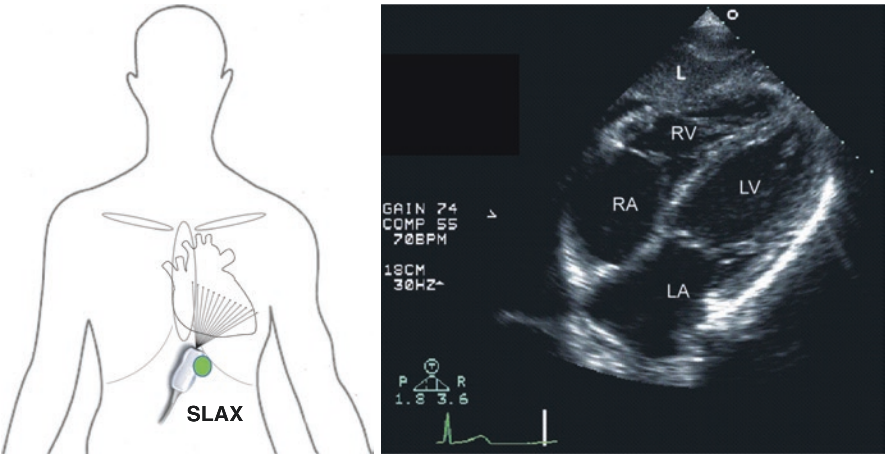


Fig. 9.7 The Subcostal Long Axis (SLAX) view—the index mark is to the patients left. *RV* right ventricle, *LV* left ventricle, *L* Liver. (From Adams D., Forsberg E. (2009) Conducting a cardiac ultrasound examination. In: Nihoyannopoulos P., Kisslo J. (eds) Echocardiography. Springer, London)

Fig. 9.8 The Subcostal Short Axis (SSAX) view—the index mark is to the patients feet. *RV* right ventricle, *LV* left ventricle, *L* Liver. (From Adams D., Forsberg E. (2009) Conducting a cardiac ultrasound examination. In: Nihoyannopoulos P., Kisslo J. (eds) Echocardiography. Springer, London)

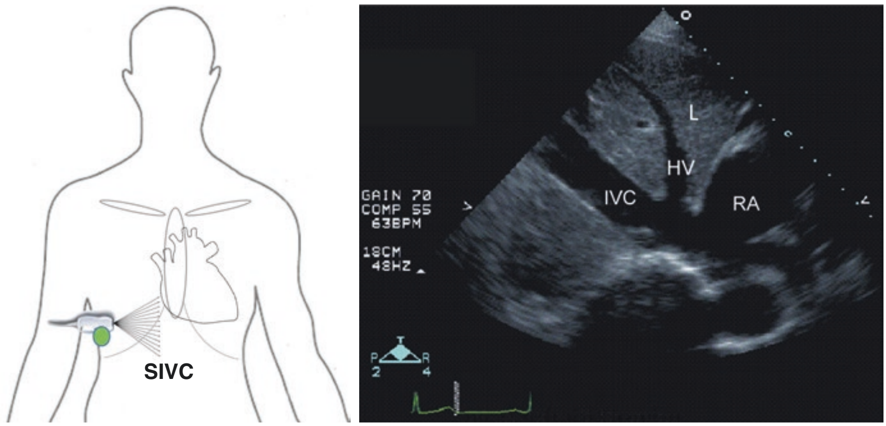
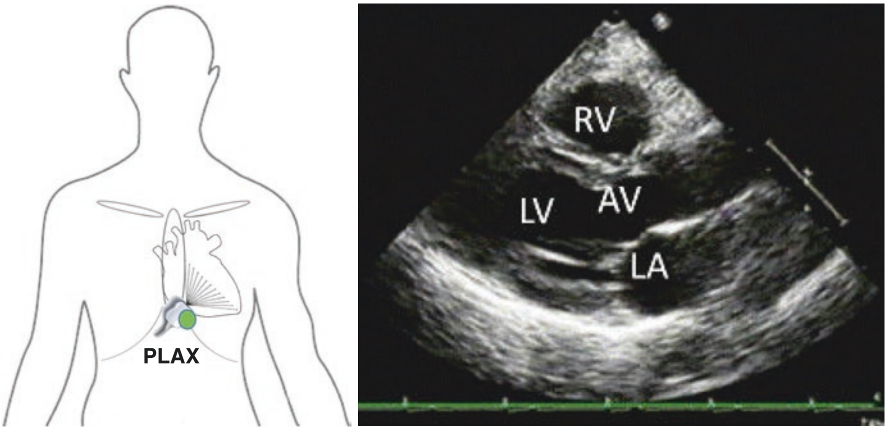


Fig. 9.9 The Subcostal IVC (SIVC) view—the index mark is towards the patients feet. *HV* hepatic vein, *IVC* inferior vena Cava, *RA* right atrium, *L* liver. (From Adams D., Forsberg E. (2009) Conducting a cardiac ultrasound examination. In: Nihoyannopoulos P., Kisslo J. (eds) Echocardiography. Springer, London)

assessment of the relative size of the left and right ventricle and comparison of performance of various areas of the left ventricle, as well as qualitative assessment of ejection fraction. The SIVC view is then obtained by pointing the probe in the subcostal area more medially to see the entry of the IVC into the inferior right atrium (Fig. 9.9). The SIVC allows assessment of intravascular volume status by IVC diameter.

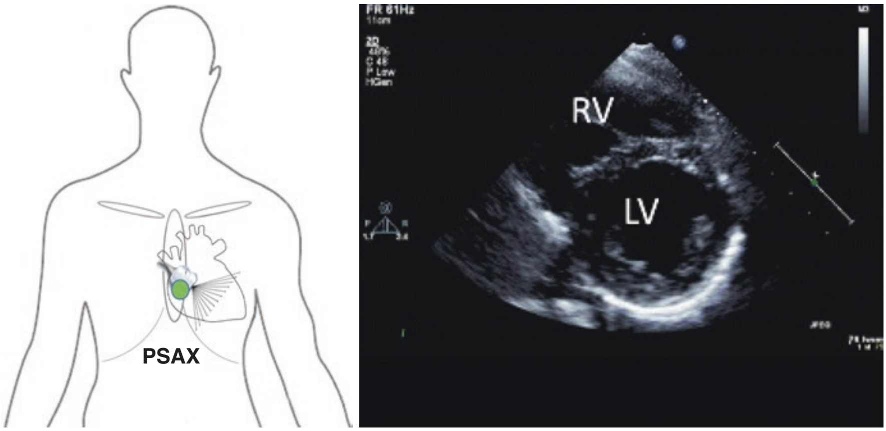
If the IVC view cannot be obtained via the SIVC view due to interference from abdominal gas, incisions, dressings or subcutaneous air, it can also be assessed by placing the probe posteriorly at the right posterior costal margin in the posterior axillary line. This has the advantage of looking through the posterior liver anteriorly without the intestinal gas being interposed. Once the hepatorenal fossa (Morrison's pouch) is identified, the probe is tilted so that the IVC, near the center of the torso can be identified. In any view, the IVC diameter is typically assessed about 2–2–3 cm below the right atrial—IVC junction, in both transverse and longitudinal views [20].

The parasternal window offers the shortest distance to the heart, but is frequently affected by chest injury, dressings and pneumothoraces. The parasternal long axis (PLAX) view is obtained by placing the probe in about the fifth interspace just to the left of the sternum (Fig. 9.10). The probe is aligned so that the long axis of the probe head is aligned along a line from the right acromion to the left upper quadrant of the abdomen, with the index mark pointing away from the right shoulder, giving a long view of the ventricles, allowing assessment of left ventricle performance. The parasternal short axis (PSAX) view is obtained by rotating the probe 90° so that the long axis of the probe head is aligned along a line from the left acromion to the right upper quadrant of the abdomen, with the index mark pointing away from the left shoulder, giving a short view across the ventricles (Fig. 9.11). The probe can be tilted with a "fanning" motion to examine the ventricles from the tricuspid or mitral annulus to the chordae and to the apex of the heart.



PLAX: Parasternal Long Axis

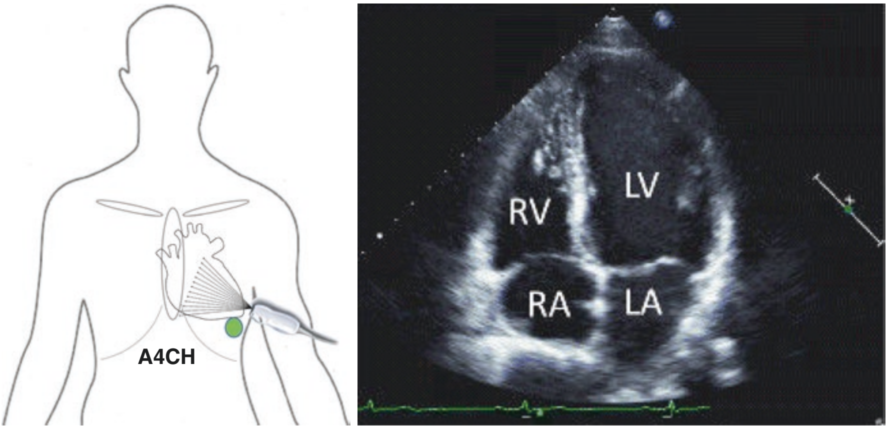
Fig. 9.10 The Parasternal Long Axis (PLAX) view—the index mark is to the patients left upper quadrant. *RV* right ventricle, *LV* left ventricle, *LA* left atrium, *AV* aortic valve. (From Walley, P.E., Walley, K.R., Goodgame, B. et al. A practical approach to goal-directed echocardiography in the critical care setting. Crit Care (2014) 18: 681. https://doi.org/10.1186/s13054-014-0681-z)



PSAX: Parasternal Short Axis

Fig. 9.11 The Parasternal Short Axis (PSAX) view—the index mark is to the patients right upper quadrant. *RV* right ventricle, *LV* left ventricle. (From Walley, P.E., Walley, K.R., Goodgame, B. et al. A practical approach to goal-directed echocardiography in the critical care setting. Crit Care (2014) 18: 681. https://doi.org/10.1186/s13054-014-0681-z)

The apical location is often unusable in critical patients as many patients must be positioned so that they are rolled onto their left side, allowing the apex of the heart to be more proximal to the chest wall. The apical 4 chamber view (A4CH) is obtained by placing the probe in about the fifth intercostal space in the midclavicular line pointing at the right acromion (Fig. 9.12). The index mark is pointed



A4CH: Apical 4 Chamber

Fig. 9.12 The Apical 4 Chamber (A4CH) view—the index mark is to the patients right acromion. *RV* right ventricle, *LV* left ventricle, *RA* right atrium, *LA* left atrium. (From Walley, P.E., Walley, K.R., Goodgame, B. et al. A practical approach to goal-directed echocardiography in the critical care setting. Crit Care (2014) 18: 681. https://doi.org/10.1186/s13054-014-0681-z)

somewhat posteriorly. This will achieve a view of all four chambers of the heart as well as the intraventricular septum. Comparison of left and right ventricular size and function can be made as well as views of the tricuspid and mitral valves obtained. Septal motion can also be assessed. Allowing the probe position to slide slightly more anteriorly on the chest achieves the "five chamber" view where the aortic valve is also seen as well as the four ventricles.

9.5.2 Left Ventricle

A rapid qualitative assessment of left ventricular (LV) performance can be obtained from the above views. A stepwise assessment of the heart can be performed by first looking for obvious pathology such as tamponade, dilation or hypokinesis, next looking at ventricular size, wall thickness and filling and in systole and diastole and then looking at contractility in both left and right ventricles. The pleura should also be imaged bilaterally to identify pleural effusions or pneumothorax.

With a reasonable amount of practice, the acute surgeon can readily identify when LV ejection fraction is below 40–45% without need of formal measurements or calculations. A baseline bedside echocardiographic study in the acute ICU admission makes subsequent identification of acute versus chronic LV dysfunction easier. Global LV dysfunction can be seen in sepsis and septic shock, post-arrest states, stress cardiomyopathy, dilated cardiomyopathy, myocarditis and in chronic congestive heart failure. Generally the acute surgeon is looking for gross changes that will help explain a shock state. Subtle dysfunction such as diastolic heart failure is beyond the scope of the limited echocardiogram by the acute surgeon.

A special form of LV stress dysfunction can have a specific appearance—Takotsubo cardiomyopathy or "broken-heart syndrome" [21]. This can be triggered by physiologic or psychologic stress, usually in critically ill patients 50–80 years old. Women comprise 90% of cases. Classically, the base of LV is seen to have normal size and contractility while the apical segment is seen to balloon outwards in systole, giving the heart the shape of the Japanese octopus trap that provides the name of this condition.

Areas of localized LV hypokinesis may be caused by localized ischemia such as seen in acute coronary syndromes. The echocardiogram is more sensitive than EKG in detection of myocardial infarction in the postoperative patient, and can add sensitivity to troponin levels, which are already abnormal in 15–30% of non-cardiac surgery ICU patients. Although specific areas of the LV can be associated with particular coronary artery occlusions, this is beyond the scope of the usual acute surgeon echocardiographic examination—in suspected acute coronary syndromes cardiology consultation is warranted.

9.5.3 Right Ventricle and IVC

The right ventricle (RV) views should not be ignored as they can be significant in the shock state. The RV is harder to visualize due to its thinner wall. The normal RV wraps around a portion of the thicker walled circular LV as seen in the short axis PSAX or SSAX views. The interventricular septum normally bulges in a convex manner from the LV into the RV in both systole and diastole. In the healthy heart the stroke volume and ejection fraction are similar in the LV and RV, so the ventricular volumes should be equivalent, although each is shaped differently. As RV pressures increase such as in right heart failure, pulmonary embolism or pulmonary hypertension, the RV can be seen to enlarge and the septum increasingly flattens the side of the normally circular LV in the short axis views. As RV pressures increase further, the septum may begin to paradoxically bulge into the LV for a greater portion of the cardiac cycle.

Significant PE associated with shock is classically associated with a distended RV, flattened septum, under filled LV, and distended IVC. Echocardiography has a specificity of 81% and 94% and a positive predictive value of 71% and 86% for pulmonary emboli, however other sources of RV failure should be considered within the clinical context [22].

The IVC views should also be part of the cardiac ultrasound of the acute patient with a suspected shock state. Under normal conditions in healthy, spontaneously breathing, supine patients the IVC will nearly or completely collapse with inspiration and expand with expiration. Ultrasonographic assessment of the diameter of the inferior vena cava in expiration (IVCe) and in inspiration (IVCi) allows assessment of the collapsibility of the inferior vena cava (IVCe-IVCi) [23]. Another measurement of intravascular volume status is the IVC collapsibility index (IVC-CI). The IVC-CI is calculated using a standard formula IVC-CI = (IVCe) − (IVCi)/(IVCe) × 100%, where IVCe is the maximum IVC diameter at expiration and IVCi is the minimum IVC diameter at inspiration [24]. Respiratory variation in IVC diameter has been found to be more pronounced in hypovolemia with abnormally low CVP being increasingly likely as IVC-CI approaches 100%. However there is not yet an exact cutoff value determined for IVC-CI for hypovolemia, although 75% has been suggested as the cutoff.

Similarly to central venous pressure measurements, techniques of IVC measurement have many of the same inaccuracies of CVP measurements. Positive pressure ventilation can invert the normal inspiratory-expiratory minimal and maximum size relationship, and high PEEP levels may reduce venous inflow to the chest and distend the IVC. Increased right atrial pressures are seen in right heart failure, valvular disease, and pulmonary hypertension and may cause increased IVC diameter that is not reflective of an increased volume status. However, these conditions would not be expected in most trauma or acute surgery admissions. Another issue with IVC diameter may be the effect of increased abdominal pressure such as seen in abdominal compartment syndrome causing narrowing of the IVC [25]. However, abdominal compartment syndrome is rarely present at admission in acute surgery patients, and when it is present at admission is usually accompanied by overt clinical signs that indicate immediate surgical intervention.

Following IVC diameters after initial therapeutic fluid challenge of the blunt trauma patient with hypotension may improve the utility of FAST in trauma patients. Yanagawa et al., in a study of 30 trauma patients presenting with shock (systolic BP < 90 mmHg) followed patients into two groups: a transient responder group ($n = 17$) in which shock recurred after an initial 2 L intravenous crystalloid fluid bolus in the emergency room and a responder group ($n = 13$) in which blood pressure remained stable [26]. IVC diameter predicted patients who would become hypotensive later despite equivalent fluid resuscitation. It also predicted those likely to need emergent hemostatic inventions such as laparotomy or angiography—the transient responder group contained a greater proportion of patients who underwent such procedures than the responder group (47.0% vs. 7.6%, $p < 0.05$).

In a American Association for Surgery of Trauma (AAST) multi-institutional trial of 144 major trauma patients, those with persistent IVC collapsibility on a second IVC measurement 60 min after admission compared with those who had increased IVC size, had significantly higher intravenous fluid requirements during the first 24 h of hospitalization (2503 ± 1751 mL vs. 1243 ± 1130 mL, $p = 0.003$) [27]. Those patients undergoing resuscitation can have repeated assessments by POCUS to assess the adequacy of resuscitation and need for further assessments.

9.5.4 Chest Injury—Pneumothorax

Rib fractures are common injuries in earthquakes and building collapses [28]. Rib fractures, sternal fractures, and pneumothorax can be detected by ultrasound [29]. Ultrasound can detect non-loculated pneumothorax more rapidly and more accurately that chest X-ray, although sensitivity can be affected by recent surgery, presence of a chest tube or subcutaneous air [10]. Specificity of a positive examination is excellent, and the size of the pneumothorax can be estimated in the supine patient, as the lung usually falls away from the anterior chest wall before the lateral chest wall. In this way, ultrasound can detect the presence of an "occult" pneumothorax that would not be visible on a supine chest X-ray. Either the phased-array or high-frequency linear probe can be used, although we prefer the higher resolution of the linear probe.

There are four ways ultrasound can be used to identify a pneumothorax:

1. Pleural sliding—the lung slides within the pleura during respirations and this sliding is evident by the sliding motion, especially of sonographic "B-lines," which appear as bright spots on the pleural surface with "ringdown" artifact, producing an appearance called "comet tails" (Fig. 9.13). There is no pleural sliding and no comet tails in locations where a pneumothorax is present.
2. M-mode—Using M-mode provides a time based graphical output of a single line over time. This can make pleural sliding more evident, with the normal exam with sliding producing an granular appearance below the ribs called the "Sandy beach" (Fig. 9.14) and where a pneumothorax without sliding generates an undifferentiated multilayered appearance called the "Stratosphere" sign (Fig. 9.15).
3. Lung point—This is a highly sensitive and specific sign of pneumothorax. As the probe is slid from the anterior portion of the chest where the pneumothorax is present to a more posterior and lateral position, the edge of the lung posterior to the pneumothorax that is just touching the chest wall may be seen. As the lung slides back and forth with respirations, periods of pleural sliding are interspersed with periods of no sliding. The edge of the lung is typically triangular in cross-section and so the name of Lung Point arises. Lung point may not be seen in large or tension pneumothoraces as no part of the lung may be found in contact with the chest wall.
4. Lung pulse—in some cases, there is little pleural sliding as respiratory movement may not be occurring in the portion of the lung under examination. This may occur during bronchial obstruction, apnea, contralateral mainstem intubation or near the heart. However, lung sliding can still be seen, only in small movements that correspond with the heart rate as the lung enlarges with every systole.

Fig. 9.13 Comet tails on pleural ultrasonography—normal—arrows indicate Comet tails

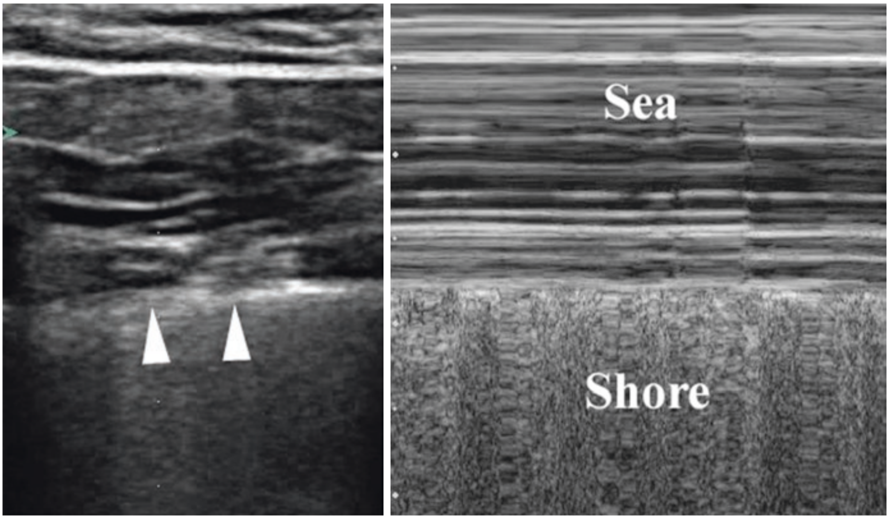


Fig. 9.14 Pleural ultrasonography—this is a split image with the left showing the 2D view of the pleural interface and the right side showing a normal M mode image showing the "Seashore" sign which is evidence of pleural sliding. (From Gillman LM, Ball CG, Panebianco N, Al-Kadi A, Kirkpatrick AW. Clinician performed resuscitative ultrasonography for the initial evaluation and resuscitation of trauma. Scandinavian Journal of Trauma, Resuscitation and Emergency Medicine. 2009;17:34. https://doi.org/10.1186/1757-7241-17-34)

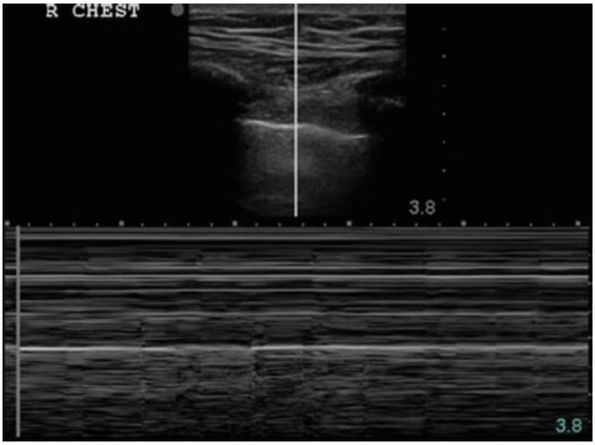


Fig. 9.15 Pleural ultrasonography—this is a split image with the top showing the 2D view of the pleural interface and the bottom showing an abnormal M Mode image showing the "Stratosphere sign" due to pneumothorax and no pleural sliding. (From Gillman LM, Ball CG, Panebianco N, Al-Kadi A, Kirkpatrick AW. Clinician performed resuscitative ultrasonography for the initial evaluation and resuscitation of trauma. *Scandinavian Journal of Trauma, Resuscitation and Emergency Medicine*. 2009;17:34. https://doi.org/10.1186/1757-7241-17-34)

9.5.5 Pleural Effusion, Atelectasis, and Pneumonia

In the same way the intra-abdominal fluid has a characteristic anechoic or black appearance on FAST examination, pleural effusions show as anechoic areas in the chest. These are usually best seen just above the diaphragm and posteriorly in the semi-recumbent patients. Ultrasound can differentiate between effusion and atelectasis or consolidation where the chest X-ray shows only basilar opacification of the lung field. Ultrasound can be superior to CT scanning in provide clues about the nature of the pleural fluid—featureless anechoic fluid is typically of a transudate, whereas exudates may have fibrinous strands that move with patient movement. Retained hemothorax will layer out into serous and cellular layers producing the "hematocrit sign". An empyema will often show areas of loculation. Assessment of pleural effusions over time in the ICU can help determine their progression, nature and potential for infection, indicating which should undergo drainage by thoracentesis.

Pneumonia with consolidation turns the normally air filled lung into a solid mass, and the lung takes on the ultrasonographic appearance of the liver. Lobar pneumonias can have quite sharp borders on ultrasound with the bright, consolidated lung adjacent to featureless normal lung lobes. Pulmonary edema increases the amount of interstitial lung water, making the "B-lines" of the lung more prominent and increasing the number of comet tails that are visible.

9.6 Useful Ultrasound Studies in Disaster and Resource-Limited Environments

9.6.1 Triage

In a high-income nation, trauma and critical acute surgery patients will typically have conventional X-rays and CT scans performed routinely at admission, such as recommended by the ATLS program [30]. In disasters and resource-limited settings, plain radiography and CT scanning may unavailable or severely limited in availability. Routine X-rays can also slow triage efforts. According to the U.S. Centers of Disease Control triage prediction tool, a single X-ray technician performing the ATLS-recommended chest, pelvis and other plain X-rays requires a mean of 10 min per patient. This would limit the flow of major trauma victims to six patients per hour per X-ray technician and X-ray machine [31]. This would be intolerably slow in many mass trauma situations.

POCUS can be used a screening tool by trauma providers at the bedside during the Initial Assessment to reduce reliance on immediate conventional radiology and CT scanning. Pneumothorax, hemothorax and shock states can be readily screened and identified. Stable patients with negative POCUS exams can forgo immediate scanning, freeing available X-ray technicians and CT scanners for more critical patients.

One of the first descriptions of POCUS in a natural disaster was following the 6.9 magnitude earthquake in Armenia in December 1988. This event caused over 25,000 deaths and approximately 150,000 injuries in area of about 700,000 people. The capital city, Yerevan was relatively unaffected, and its 1000 beds major hospital was the main medical facility for casualty victims. The only CT scanner in Yerevan was dedicated to managing head-trauma cases. Two triage areas, each with an ultrasound machine, were created in the lobby of the hospital. Six physicians staffed the two rooms on a rotating basis and performed ultrasound examinations on as many trauma victims as time permitted. In a 72-h period, 750 patients came through the hospital. Four hundred of these patients received 530 ultrasound examinations either in the triage rooms or the emergency ward. 304 of the 503 exams were considered negative, and 96 (about 20%) demonstrated some form of pathology. Sixteen patients underwent operative intervention, usually laparotomy, based solely on clinical examination and ultrasound findings. There were four false negative cases (less than 1%) among the 530 studies performed, which illustrates the usual limitations in sensitivity of POCUS in trauma: one patient was found to have a ruptured kidney on laparotomy; another, a retroperitoneal hematoma; the third had a subcapsular hematoma of the spleen; and one obese patient had a massive hemothorax [32].

POCUS also has been shown to have a role in man-made events such as terrorist bombings and conflicts. FAST examinations were performed prehospital responders and hospital personnel after the 2004 Madrid train bombing and the 2005 London Underground bombing [33, 34]. Ultrasound was also successfully used for evaluation during explosive mass casualty incidents in a battlefield hospital in Iraq and equips even the smallest surgical teams in NATO forces [35].

9.6.2 PEA and CPR

Prolonged resuscitative efforts for trauma and acute patients under cardiac arrest during disaster and limited-resource scenarios are usually futile and incompatible with the adoption of a population-based standard of care. There is evidence that performance of limited echocardiography during PEA and CPR can be useful [36]. Four immediately significant conditions can be identified from the SLAX view, even while CPR is in progress. Cardiac standstill, with no visible cardiac motion, is associated with no meaningful survival in blunt trauma patients undergoing CPR for cardiac arrest, and is considered justification for suspension of resuscitative efforts, including no resuscitative thoracotomy [37]. Cardiac tamponade, identified as a pericardial effusion with RV or right atrial collapse with tamponade physiology requires pericardiotomy for surgical causes with pericardial clot and pericardiocentesis for medically caused non-clotting effusions. An empty heart points to severe hypovolemia. Massive pulmonary embolism is associated with RV distension, septal flattening, and small LV size.

9.6.3 Airway

Confirmation of successful intubation is routinely performed for all emergency intubations.. However, no technique used for confirmation of endotracheal tube (ETT) placement has been proven to be 100% accurate. Most physicians use a combination of auscultation, direct laryngoscopy, and end-tidal carbon dioxide detection to confirm ETT placement. However, in resource-limited, austere environments, end-tidal carbon dioxide and other intubation indicators may not be available.

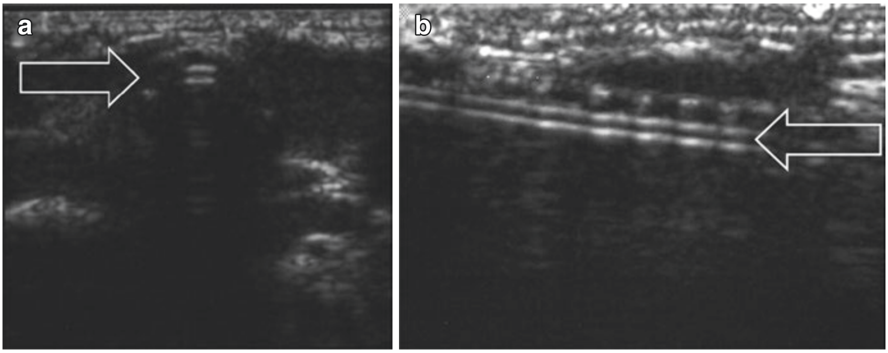


Fig. 9.16 Endotracheal tube in the proper position, as seen through the cricothyroid membrane in the transverse (**a**) and the longitudinal (**b**) views. (From Galicinao, J. et al. Pediatrics 2007;120:1297–1303)

Ultrasound has been used to confirm successful placement of the ETT after intubation, this is performed by scanning through the cricothyroid membrane with the linear probe and along the trachea. The ETT is visible as a double bright line (Fig. 9.16). A study of 99 children aged 1–17 years, revealed that the ETT was detected in all 99 patients by using bedside ultrasonography. Two views were required to show the ETT. In three cases, the colorimetric carbon dioxide detector gave negative or equivocal results but the ultrasound showed the ETT was correctly placed [38].

9.6.4 Crush Injury

Following large earthquakes, crush injury and crush syndrome may occur in thousands of extracted patients [39, 40]. Crush injury is defined as the result of physical trauma from prolonged compression of the torso, limb(s), or other parts of the body. The resulting injuries to soft tissues, muscles, and nerves can be due to the primary direct effect of the trauma or ischemia related to compression. In addition to possible direct muscle or organ injury, after release of the compressive force, severe crush injury results in swelling in the affected areas, with possible muscle necrosis and neurologic dysfunction. Crush injury can also be due to a secondary injury from subsequent compartment syndrome.

Crush syndrome is defined as the systemic manifestations resulting from crush injury, which can result in organ dysfunction predominantly acute kidney injury (AKI), but multisystem organ injury can also occur), or death. The manifestations of crush syndrome are the systemic consequences of muscle injury, specifically rhabdomyolysis, which commonly result in AKI [41, 42].

Following a 7.6 magnitude earthquake in Turkey in 1999, a study of the prognostic utility of renal Doppler ultrasound in determining the need for hemodialysis from crush injuries was performed. Out of 5302 patients admitted to regional hospitals, 639 had renal complications due to crush injuries, and 477 required hemodialysis after developing acute renal failure. Renal ultrasound in particular was used to gauge whether victims needed additional intravenous fluid resuscitation, urine alkalization and intravenous mannitol. Doppler flow to the kidneys was measured to calculate the renal resistive index, which was found to correlate well with the presence of oliguria and anuria and the need for hemodialysis. It was concluded that this measurement may be predictive for recovery from acute renal failure resulting from crush injury [43]. Similar utility for renal Doppler ultrasound was found after earthquakes in Haiti and Kashmir [44, 45].

9.6.5 Fractures

POCUS can be used to identify fractures, especially when the bone is largely subcutaneous such as in the hand, upper and lower extremities [46–48]. Fracture reduction guidance has been described for long bong fractures in children and in distal radial fractures and metacarpal fractures in adults [49–51]. Conventional X-ray has a low sensitivity for rib fractures, ultrasound has been suggested as being superior, but the quality of studies to date is poor [52].

9.6.6 Traumatic Brain Injury

Except in infants, where transfontanellar ultrasound of traumatic brain injury (TBI) can be sometimes be performed, ultrasound does not yet have a routine role in the evaluation of brain injury [53]. However there are investigations ongoing for the use of ultrasound in TBI.

Optic Nerve Sheath Diameter (ONSD) has been suggested as a potential noninvasive measure of the intracranial pressure (ICP). This would be very useful in environments where invasive ICP monitoring is unavailable or impractical. The exam is done using a linear probe and high-frequency setting. The measurement is taken of the diameter of the optic nerve sheath at the back of the eye, 3 mm behind the globe using an electronic caliper along the axis of the optic nerve. A meta-analysis of seven prospective studies of ONSD in with 320 patients with elevated ICP noted wide confidence intervals and significant heterogeneity in the studies. Transcranial Doppler has also been evaluated for noninvasive ICP assessment in three studies, with variable results. Both of these techniques are still considered investigational and should not yet be used to direct clinical management of TBI [54].

9.7 Conclusion

POCUS makes it possible to identify abdominal and thoracic injuries rapidly and efficiently, can guide procedural interventions and can hasten triage. The ability to utilize POCUS in conditions where conventional X-ray and CT imaging are unavailable further increases its utility. As physicians and allied providers become more facile with POCUS, and as POCUS machines become smaller, durable and more capable, POCUS will be an indispensable and integral component of disaster response and the provision of care in austere environments.

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