8 Trauma Ultrasound

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Introduction

Information obtained using ultrasound can often direct the management of injured patients. As an ultrasound study can be performed safely in the resuscitation room, ICU, or operating room, this technology is appropriate for use even in unstable patients. Over the past several decades, the indications for the use of ultrasound have expanded rapidly to a wide range of surgical diseases, with much enthusiasm by surgeons to perform studies independently [1–4]. It is important to note that other imaging modalities, particularly multidetector row computed tomography (MDCT), have also developed progressively over the same period [5]. The proper use of these advanced imaging modalities is key to improving the outcome of trauma patients. In this chapter, we will describe ultrasound techniques and their indications in the management of trauma patients.

History

At the beginning of the1970s, Goldberg and colleagues reported the successful visualization of as little as 100 mL of intra-abdominal free fluid using ultrasound [6]. The clinical significance of this ability was not recognized until the1980s, when care providers started using ultrasound to detect intra-abdominal free fluid (blood) in the injured patient [7, 8]. While small series on the use of ultrasound for diagnosis in trauma patients have been published in Europe and Asian countries since the1980s, it was not until the early 1990s when Tso and associates reported the first case series of trauma ultrasound in the United States [9]. Rozycki and colleagues conducted the first prospective study to investigate the sensitivity and specificity of ultrasound in injured patients [10]. They demonstrated that ultrasound studies performed by surgeons and their trainees were of high accuracy in the detection of free fluid. Their group initially named the ultrasound technique to detect pericardial effusion and intra-abdominal free fluid for the trauma patient, "FAST" (focused abdominal sonogram for trauma) [11, 12]. Subsequently, the acronym "focused assessment with sonography for trauma" has gained consensus [13].

FAST: Principle and Basic Technique

The main purpose of the FAST examination is to identify fluid in the pericardial and dependent spaces of the abdominal cavity of the patient in the supine position. The one pericardial and three intra-abdominal views are to be scanned within 5 min. FAST is currently incorporated in the ATLS (advanced trauma life support) algorithm, but the timing of performing the examination may be variable. It may be conducted during the primary survey as a part of "C: circulation" for hemodynamically unstable patients or as one of the adjunct imaging studies during the secondary survey for stable patients [14]. The ultrasound machine always needs to be powered on before a trauma patient presents to the resuscitation room. FAST can be performed by a trauma surgeon, surgical trainee, or emergency room physician. The technique for FAST examination is summarized in Table 8.1.

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Table 8.1 Summary of FAST techniques

Goal: to detect and rule out fluid collection in pericardial space and intra-abdominal cavity
Transducer: 2.5–5.0 MHz sector- or convex-type transducer
Image mode: regular abdomen image mode
Timing of study: during the primary survey for unstable patient or during the secondary survey for stable patient
Pericardial examination: longitudinal or transverse view in the subxiphoid area
Abdominal examination: longitudinal views in right and left upper quadrants, and longitudinal or transverse view of the pelvis

Pericardial Examination

The examination is typically conducted with the ultrasound machine positioned on the patient's right side, although some perform a FAST from the patient's left (personal experience, authors). A low-frequency transducer (2.5–5.0 MHz), sector or convex type, is used to maximize penetration. The pericardial examination should be performed prior to the abdominal examination to optimize the ultrasound settings (e.g., gain, depth). The transducer is first oriented in the sagittal plane in the subxiphoid area. The transducer may then be rotated 90° counterclockwise to provide a transverse view of the heart. As the primary goal of FAST is to identify free fluid which appears as an anechoic (dark) space, fluid (blood) inside the atria and ventricles can be used to adjust the settings, particularly the gain to improve image quality (Figs. 8.1 and 8.2). The examination focuses on the identification of free fluid in the pericardial space. Spending extra time to survey for a structural abnormality of the heart during the initial assessment is not necessary and may be harmful if it delays resuscitation or further diagnostic testing. For the patient who is morbidly obese, who has a narrow costal angle, or who has subcutaneous emphysema, the subxiphoid window may be difficult to visualize, and alternate views may need to be acquired.

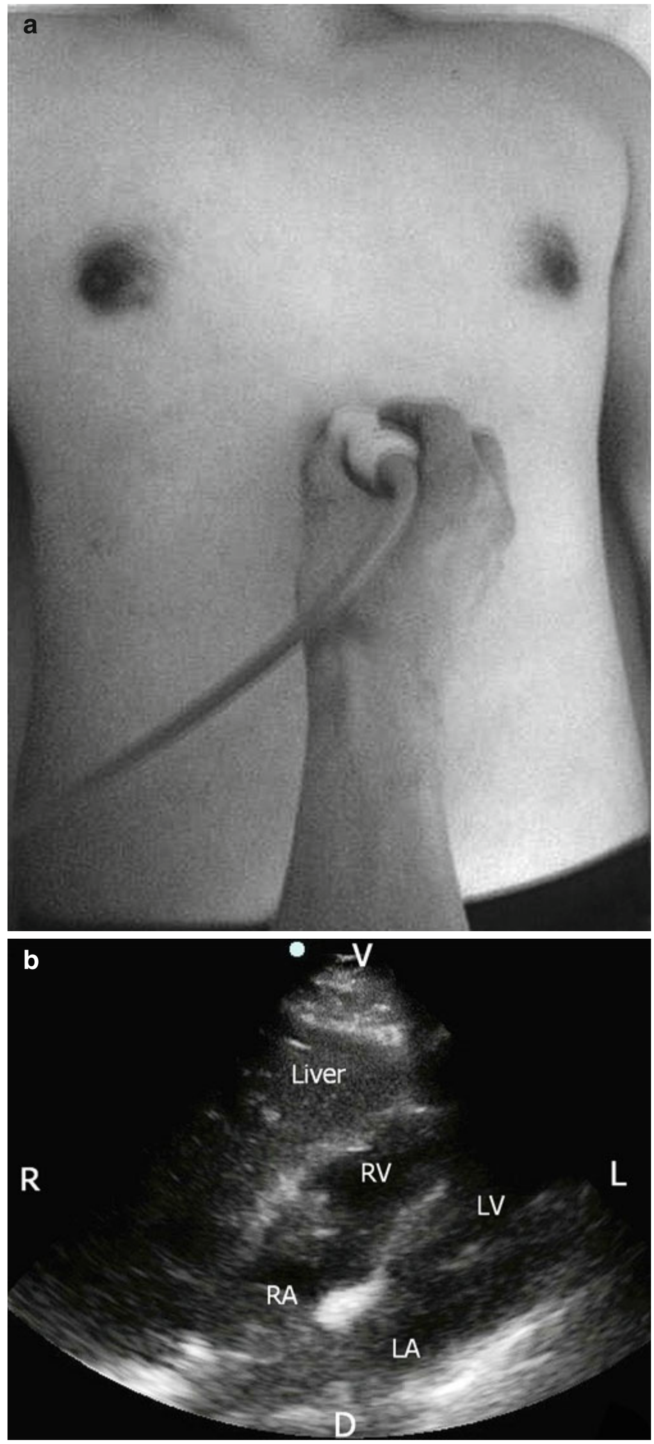

Fig. 8.1 (**a**, **b**) Transducer placement for pericardial examination and transverse view of normal pericardial examination with transducer in abdominal preset. *RA* right atrium, *LA* left atrium, *RV* right ventricle, *LV* left ventricle, *R* right, *L* left, *V* ventral, *D* dorsal

Abdominal Examination

Next, an examination is performed to survey for free fluid in the abdominal cavity. Three dependent areas are visualized: the hepatorenal recess (Morison's pouch) in the right upper quadrant, the splenorenal recess in the left upper quadrant, and the pelvic region around the bladder. First, a long-axis view is obtained at the level of 10th to 11th intercostal space in the right mid- to posterior axillary line for surveillance of the hepatorenal recess (Figs. 8.3 and 8.4). Appropriate transducer placement varies based on the patient's body habitus or history of pulmonary disease. To minimize the false-negative rate, the area of interest should be surveyed entirely by changing the angle of the transducer (fanning). Next, a longitudinal view of the splenorenal recess is obtained in the left upper quadrant (Figs. 8.5 and 8.6). Trauma patients often present with a full stomach that can obscure the penetration of ultrasound. Therefore, transducer placement should be

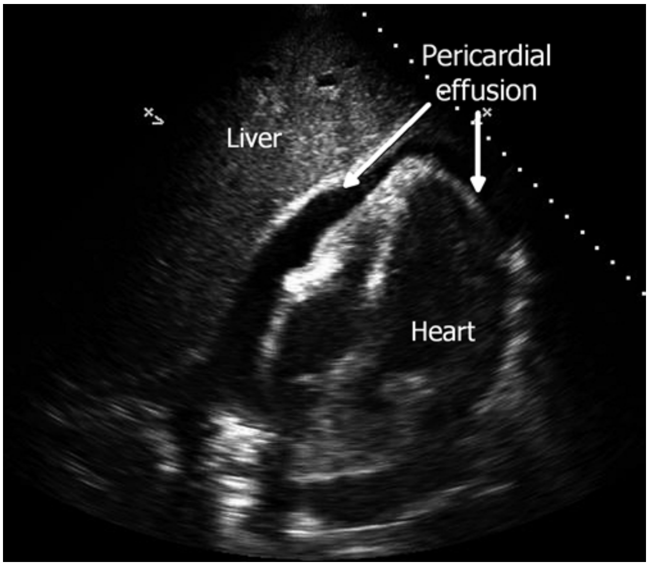

Fig. 8.2 Transverse view of the pericardial examination in an abdominal preset demonstrating a pericardial effusion. Note the small cavity size of the RV. Diastolic collapse of the RV would demonstrate tamponade physiology. *RV* right ventricle

more cephalad and posterior than the analogous view on the right side for better visualization. Finally, the transducer is moved to the pelvis just above the pubic symphysis (Figs. 8.7 and 8.8). The transducer is oriented in either the sagittal or transverse plane.

FAST: Clinical Data

Blunt Torso Injury

In the United States, the first prospective study of surgeon-performed FAST was conducted by Rozycki and colleagues in 1995 [11]. They showed 78.6 % sensitivity and 100 % specificity for the detection of free fluid among 295 blunt injury patients. Their group reported on a larger number of patients in 1998 [15]. Among 1,227 patients, the sensitivity and specificity was 78.3 and 97.4 %, respectively. While FAST could accomplish a very low false-positive rate, more than 20 % of free fluid was missed according to these data. Friese and associates reported that the sensitivity of FAST was as low as 26 % among the patients with pelvic fractures [16]. Hypotensive patients with positive FAST in the abdomen should be taken to the operating room immediately for exploratory laparotomy. In contrast, intra-abdominal bleeding should not be ruled out just based on a negative or indeterminate FAST in hypotensive patients. These patients need to undergo repeat FAST or an alternate test such as diagnostic peritoneal aspiration (DPA) to confirm the result [17]. However, repeat FAST might not be ideal in the face of continued hemodynamic instability. We also prefer DPA over lavage (DPL) because fluid instilled during the procedure can be confusing on CT images once the patient is stabilized and sent for scanning.

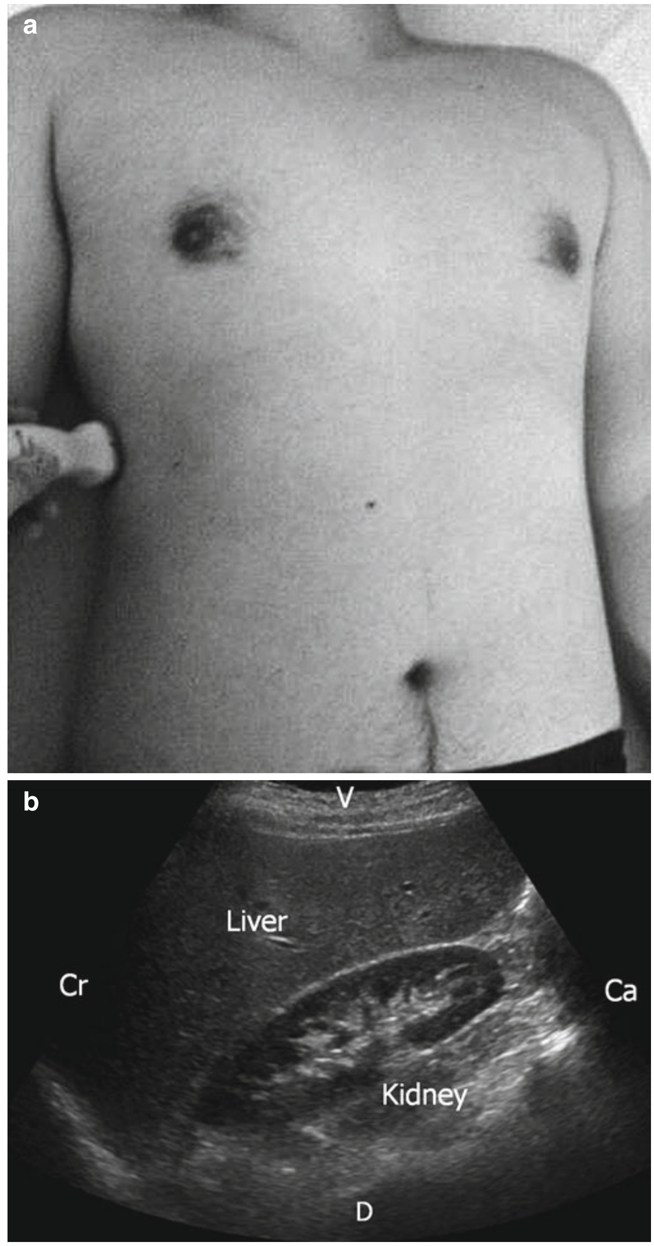

Fig. 8.3 (**a**, **b**) Transducer placement for the right upper examination and normal longitudinal view. *Cr* cranial, *Ca* caudal, *V* ventral, *D* dorsal

With the development of MDCT, the role of FAST in hemodynamically stable trauma patients is currently of little value (except for triage and education), particularly among the adult population. In addition to a higher sensitivity for intra-abdominal bleeding, the information regarding organ-specific injury can be obtained more accurately by MDCT. In a single-center retrospective study, Natarajan showed that the sensitivity

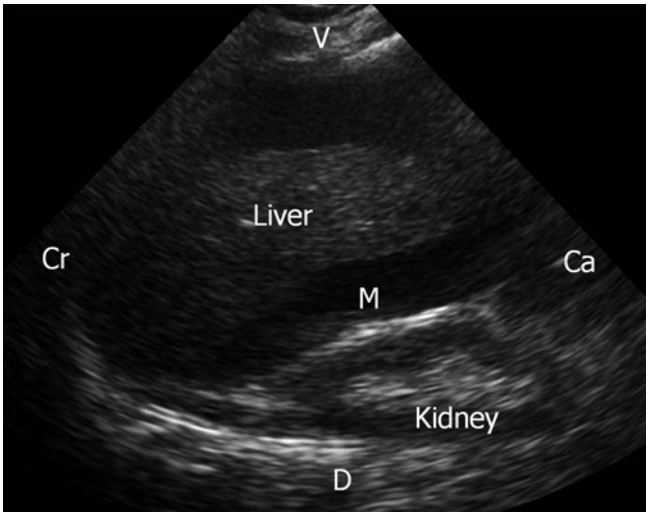

Fig. 8.4 Longitudinal view of the right upper quadrant demonstrating free fluid in Morrison's pouch and above the liver. *Cr* cranial, *Ca* caudal, *V* ventral, *D* dorsal, *M* Morrison's ouch

of FAST performed by residents under attending trauma surgeons' supervision was impressively low (40.8 %). Further, 22 % of false-negative cases required exploratory laparotomy [18]. Additional study will be needed to explore the utility of FAST for stable patients as the risk of radiation exposure by CT to trauma patients is now well recognized [19].

Penetrating Torso Injury

For the patient with penetrating injury to the area known as the "box" or "kill zone" defined as an area bounded by the nipple line bilaterally, sternal notch superiorly, and xiphoid process inferiorly (Fig. 8.9), FAST is a rapid and effective tool for the diagnosis of cardiac injury by detecting pericardial free fluid. From early experience in the 1990s, Rozycki demonstrated that the sensitivity and specificity of FAST approached100 % for the detection of pericardial fluid in the patient with cardiac injury [20]. Of note, in their multicenter study, they showed that FAST could expedite the treatment of cardiac injury (the mean time from a positive pericardial fluid FAST to operation was 12 ± 5 min) [21]. A false-negative FAST is possible in the patient whose pericardial blood decompresses into the chest cavity. The patient usually presents with a large hemothorax with unstable vital signs. Thus, an unstable patient with a "box" injury may need a surgical pericardial window despite a negative FAST. In contrast, epicardial fat pads may be mistaken for pericardial fluid because fat tissue appears as hypoechoic in ultrasound. For the patient in whom visualization of the heart is difficult due to body habitus or injury pattern (wound to the subxiphoid area), an alternate view can be obtained in the second intercostal space (parasternal view) or left nipple area (apical view). Pericardial FAST may also be beneficial to assist in

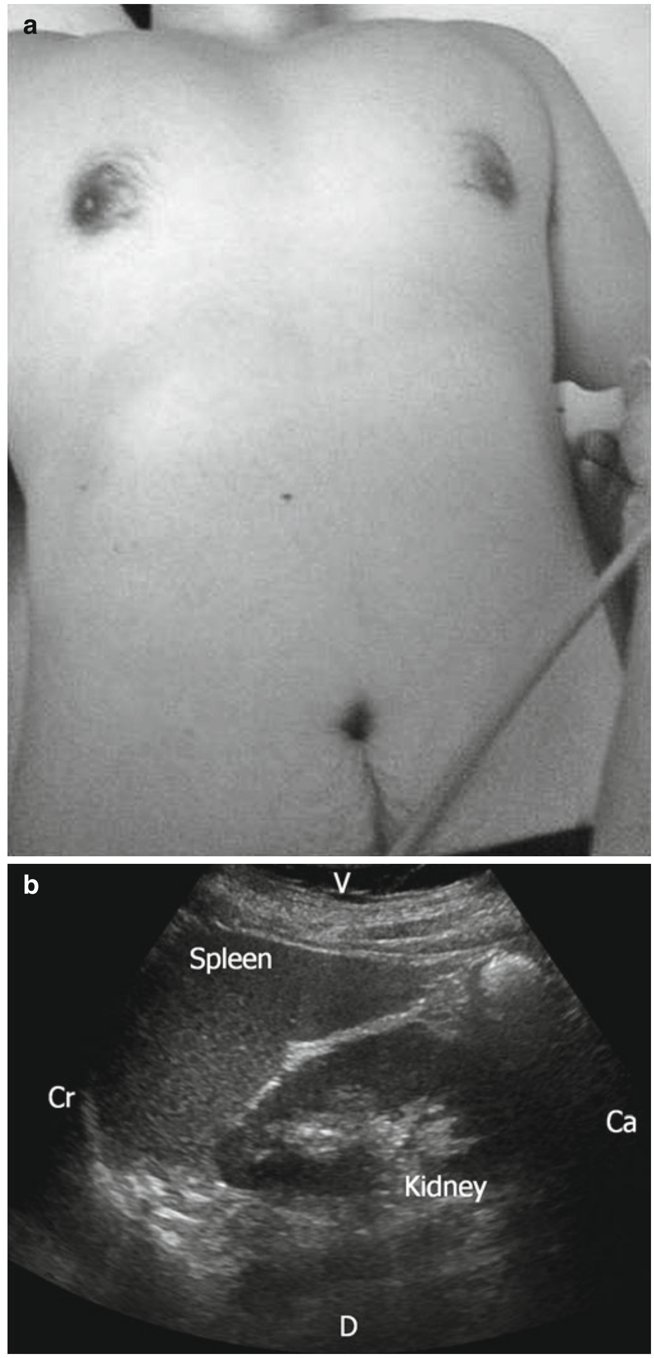

Fig. 8.5 (**a**, **b**) Transducer placement for the left upper quadrant and normal longitudinal view. *Cr* cranial, *Ca* caudal, *V* ventral, *D* dorsal

the decision to terminate resuscitative efforts in penetrating (or even blunt) torso trauma, particularly if no injury is visualized in the chest [22, 23].

In contrast to its use in blunt abdominal injury, FAST is not currently considered the standard imaging modality of choice for penetrating abdominal injury [24]. The accuracy of FAST for penetrating torso injury has been studied since the 1990s [11, 25, 26]. An early study by Rozycki showed that the sensitivity and specificity of FAST for penetrating

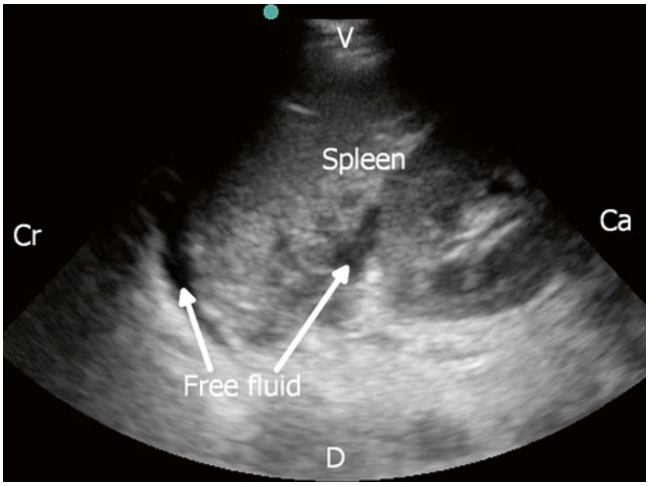

Fig. 8.6 Longitudinal view of the left upper quadrant demonstrating free fluid in the splenorenal recess and above the spleen. *Cr* cranial, *Ca* caudal, *V* ventral, *D* dorsal

injury were 83.8 and 97.4 %, respectively [11]. This result is comparable to that for blunt injury. However, a subsequently performed study showed much lower sensitivity, ranging from 46 to 67 % [27]. The biggest reason why FAST is not used for penetrating abdominal injury as often as blunt injury is its low sensitivity for detecting hollow viscus and diaphragm injury that are far more common in penetrating than blunt injury. In other words, a negative FAST cannot safely exclude these injuries. Thus, hemodynamically stable patients with abdominal gunshot or stab wounds with fascial violation may still require exploratory laparotomy to exclude visceral injury that may not be associated with an appreciable amount of free fluid [28]. Soffer demonstrated this low sensitivity of FAST (48 %) in their patients with penetrating injury performed by trauma surgeons and surgical trainees [29]. Not surprisingly, they found a significant number of missed hollow viscus and diaphragm injuries. Likewise, they showed that a positive FAST rarely added any information to change the management of the patient with penetrating torso injury. There were only three patients whose initial management was altered by a positive FAST. All these patients had unclear bullet trajectory with no signs or symptoms for immediate exploration. FAST may be helpful in the situation of the hemodynamically unstable patient with multicavitary penetrating injury to assist in deciding which body cavity to enter first or in the instance of multiple simultaneously penetrating injured patients for triage purposes.

E-FAST: Extended FAST

Principles and Technique

The incidence of pneumothorax or hemothorax is astoundingly common in injured patients [30]. In addition to physical examination during the initial ATLS protocol, chest radiography (CXR) has historically been the diagnostic study of choice to identify these potentially life-threatening injuries. However, the utility of CXR for identifying both pneumothorax and hemothorax is somewhat suspect, with surprisingly low sensitivity, as will be discussed in detail below [31]. For trauma patients, CXR is usually performed with the patient in the supine position to maintain spinal immobilization. As air tends to be loculated anteriorly and fluid (blood) posteriorly, an anterior-posterior view of CXR may not visualize air or blood. For hemodynamically unstable patients with suspected thoracic injury, a so-called normal CXR cannot safely (or often rapidly) exclude the potential for pneumothorax or hemothorax. For example, CXR diagnosis of hemothorax requires the presence of at least 175 mL of fluid in the chest cavity [32]. A recent multicenter study demonstrated that 6 % of patients with occult pneumothoraces (defined as those visualized on CT (or ultrasonography), but not on CXR) eventually required tube thoracostomy due to the progression [33].

E-FAST is performed with the patient in the supine position with the same machine position as with a conventional FAST and starts using a low-frequency transducer (Fig. 8.10). The examination typically adds no more than 2 min to a conventional FAST examination [34]. The initial portion of the E-FAST involves retracing the abdominal right and left upper quadrant views with the transducer oriented in a more cephalad fashion to search for free fluid above the diaphragm. Hemothorax (fluid) is detected as an anechoic (black) area above the diaphragm (Fig. 8.11). Ultrasound can detect as little as 20 mL of fluid in the chest cavity. Clot-bearing hemothoraces might be seen as more hypoechoic (gray). Finally, in patients with moderate to large hemothoraces, the atelectatic (collapsed) lung parenchyma will be a hyperechoic (white) structure floating in the fluid. Also, the thoracic spine can be visualized above the level of diaphragm when the transducer is aimed toward the midline ("spine sign") as ultrasound penetrates through fluid in the chest cavity. In normal individuals, air in the lung parenchyma obscures the spine in these levels.

The remainder of the E-FAST examination is typically performed with a high-frequency (7.5–10 MHz) transducer; however, it can be accomplished with a low-frequency transducer as well. As air is usually located in the anterior chest of a patient in the supine position, the ultrasound images are obtained through the anterior intercostal spaces (high, mid, and low levels) in the midclavicular line bilaterally. The transducer is oriented in the sagittal or long-axis plane. The sonographic finding of a normal lung includes lung sliding and the comet-tail sign (Fig. 8.12). Real-time observation of the parietal and visceral pleura moving in apposition to each other is called "lung sliding" [35]. Comet tails or lung rockets, characterized as vertical, narrow-based, and hyperechoic lines arising from pleural line, represent artifacts resulting

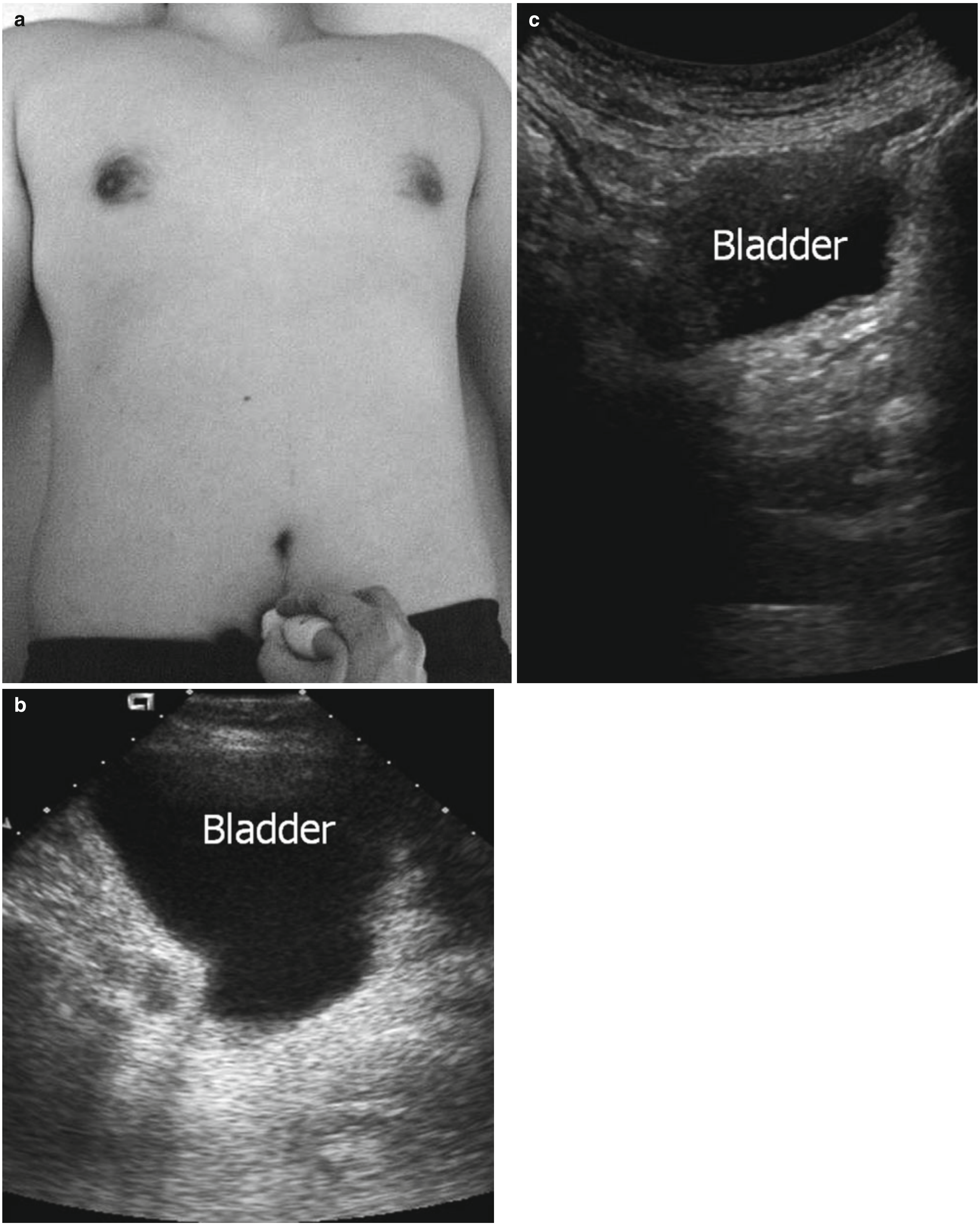

Fig. 8.7 (**a–c**) Transducer placement for the pelvic view and normal transverse and longitudinal views. (**b**) Transverse view. (**c**) Longitudinal view

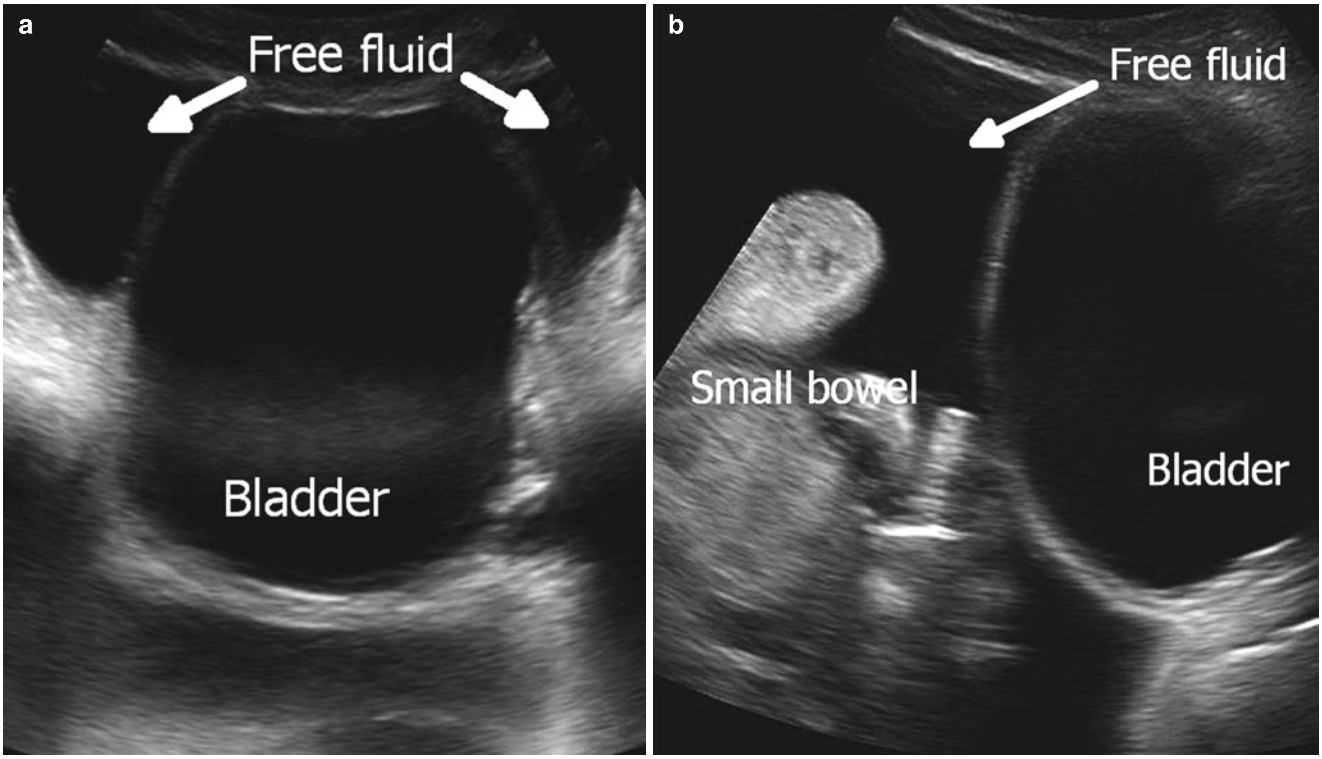

Fig. 8.8 (**a**, **b**) Pelvic view demonstrating free fluid. (**a**) Transverse view. (**b**) Longitudinal view

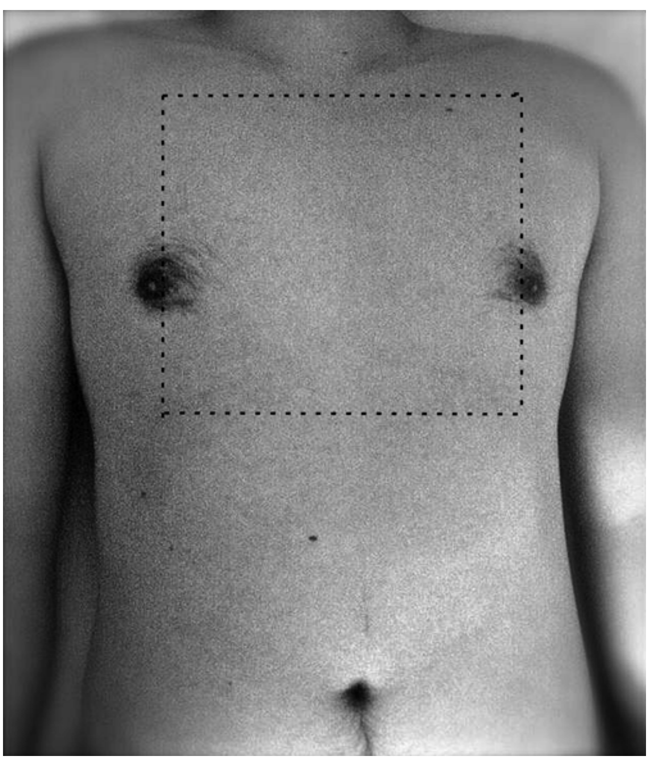

Fig. 8.9 "Box" or "kill zone" demonstrating topographic region where the heart and the great vessels are at risk of injury

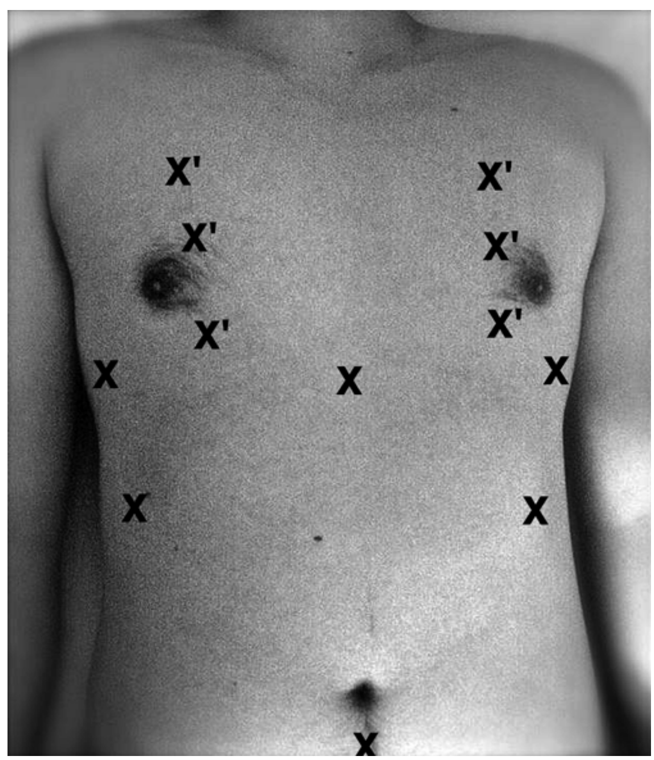

Fig. 8.10 Transducer placement for extended focused assessment with sonography for trauma. *X* low-frequency transducer, *X′* high-frequency transducer

from reverberation of ultrasound. Another technique to detect pneumothorax is performed using the M-mode (motion-mode) view as opposed to the B-mode (brightness mode) used in other portions of the E-FAST (see section "Imaging modes"). In the normal lung, a linear pattern of ultrasound image above the pleural line and a granular pattern below the pleural plane are seen, the so-called seashore sign (Fig. 8.12). Pneumothorax can be diagnosed by both the absence of comet tails and of lung sliding. The M-mode view shows loss of the seashore sign, with a similar linear pattern above and below the pleural line, the so-called barcode sign (Fig. 8.13).

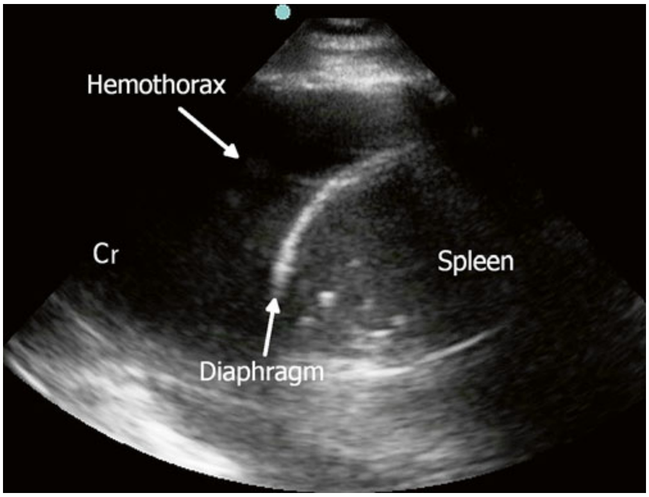

Fig. 8.11 Extended focused assessment with sonography for trauma: free fluid in the thorax (hemothorax) in a longitudinal view of the left upper quadrant with low-frequency transducer directed cranially. *Cr* Cranial

Clinical Data

In 1993, Röthlin and colleagues first described, in the English literature, using ultrasound to detect hemothoraces in injured patients [36]. In 1996, Ma and associates conducted a retrospective analysis comparing the sensitivity of ultrasound performed by emergency physicians to CXR for the detection of hemothorax [32]. For 26 patients with hemothoraces, they found a comparable sensitivity and specificity of these imaging modalities (96.2 and 100 %, respectively in both CXR and ultrasound). Sisley and colleagues conducted a prospective study to evaluate the accuracy of surgeon-performed

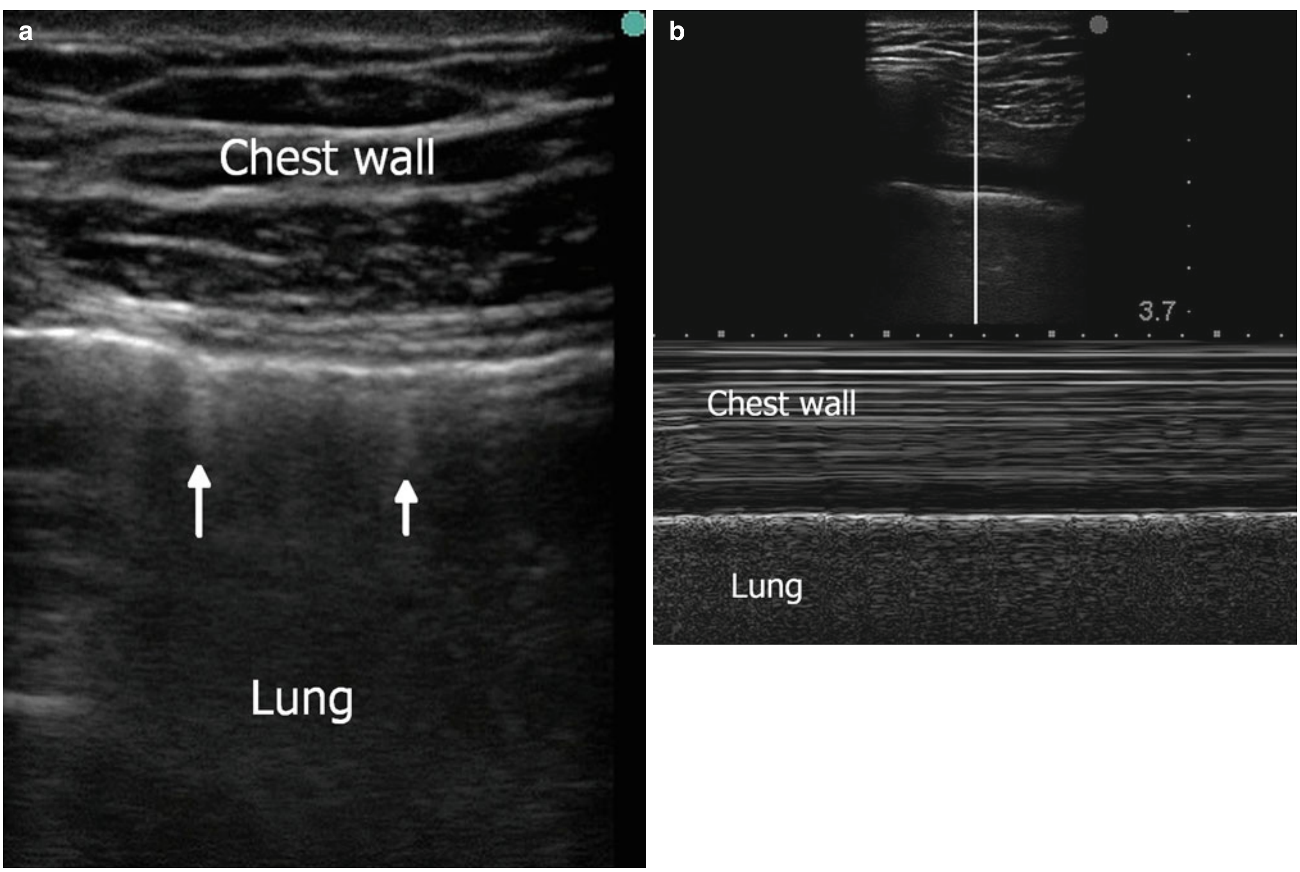

Fig. 8.12 Normal view in thoracic view of extended focused assessment with sonography for trauma using a high-frequency transducer. (**a**): In B (brightness)-mode view, pleural sliding (see text) and comet-tail sign (*arrows*) are identified. (**b**): In M (motion)-mode view, seashore sign (see text) is observed

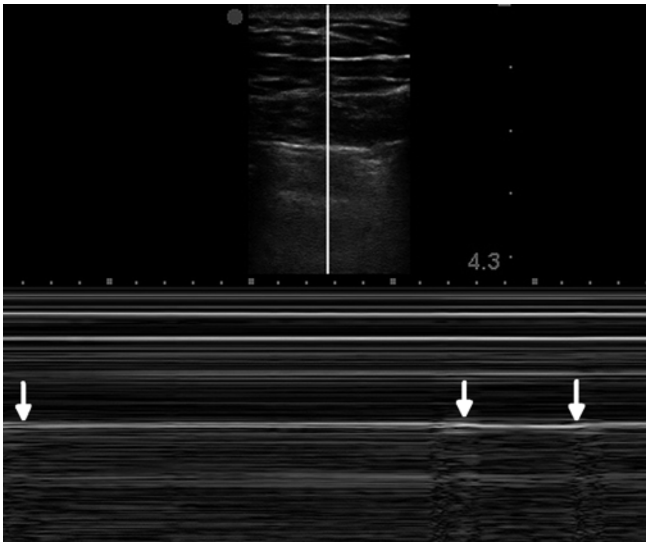

Fig. 8.13 Positive finding (pneumothorax) in thoracic view of extended focused assessment with sonography for trauma using a high-frequency transducer. Loss of seashore sign (*barcode sign*) is observed. With respiration, normal lung sliding is identified as known as "lung point" (*arrows*)

ultrasound for the detection of hemothorax [37]. Again, thoracic ultrasound and CXR had similar sensitivity and specificity (97.5 % sensitivity and 99.7 % specificity for ultrasound and 92.5 % sensitivity and 99.7 % specificity for CXR). Notably, study time for ultrasound was significantly shorter than CXR (1.30 vs. 14.18 min, $p<0.0001$). Another prospective study by Brooks documented a high sensitivity of ultrasound for hemothorax [38]. Hyacinthe and colleagues recently reported the diagnostic accuracy of ultrasound compared to clinical examination plus CXR for the detection of thoracic trauma including pneumothorax, hemothorax, and lung contusion [39]. Using CT as a comparison, thoracic ultrasound was superior to clinical examination plus CXR for pneumothorax and lung contusion while similar results were found for hemothorax.

Rantanen and associates described the utility of ultrasound for the diagnosis of pneumothorax in horses in 1986 [40]. Lichtenstein subsequently applied this thoracic ultrasound technique to critically ill patients (using a low-frequency transducer) [35]. The sensitivity and specificity of ultrasound for the detection of pneumothorax were 95.3 and 91.1 %, respectively. Dulchavsky first reported on the accuracy of ultrasound in detecting pneumothorax in injured patients [41]. Compared to CXR, the sensitivity of ultrasound was 95 %. Of note, two pneumothoraces were missed because of concomitant subcutaneous air. Similarly, Knudtson reported 100 % sensitivity and specificity in penetrating trauma and 88.9 % sensitivity and 99.7 % specificity in blunt trauma for ultrasound for the diagnosis of pneumothorax [42]. Subsequently, comparison of the sensitivity between CXR and thoracic ultrasound was performed using

Table 8.2 Summary of the bedside echocardiographic assessment in trauma/critical care (BEAT) examination

	View	Task	Goal
*B*eat	Parasternal long	Stroke volume	Cardiac function
*E*ffusion	Parasternal long	Subjective assessment	Pericardial effusion
*A*rea	Parasternal short, apical four chamber	Subjective assessment	Right and left ventricular size, movement
*T*ank	Subcostal	IVC measurement	Volume status

IVC inferior vena cava

CT as a gold standard. Kirkpatrick reported on E-FAST performed by trauma surgeons with a handheld portable ultrasound [34]. The sensitivity of E-FAST for pneumothorax detection was 48.8 %, while the sensitivity of CXR was 20.9 % in 266 patients with CT as a gold standard. A higher sensitivity (>90 %) for thoracic ultrasound in diagnosing pneumothoraces has been observed in more recent studies [43]. A meta-analysis by Alrajhi included eight studies with 1,048 patients [44]. Ultrasound was 90.9 % sensitive and 98.2 % specific for the detection of traumatic or iatrogenic pneumothorax, which was superior to that of CXR (50.2 % sensitivity and 99.4 % specific). In a subgroup analysis of trauma patients, similar results were shown.

Trauma Ultrasound in the ICU Setting

An accurate and real-time assessment of hemodynamic status is crucial to improve the outcome of critically ill patients. Historically of value, pulmonary artery catheters (PAC) have largely been abandoned based on multiple randomized studies failing to demonstrate an outcome benefit [45–47]. Currently, a myriad of options are available for hemodynamic monitoring in the ICU setting [48, 49]. Of these, noninvasive monitoring of preload status and cardiac function using ultrasound has obtained popularity in the last decade [50, 51]. Moreover, it has been demonstrated that bedside echocardiography performed by intensivists can provide accurate information on the patient in a timely fashion [52, 53]. Favorable data have been also reported among critically ill trauma patients [54–57].

Gunst and colleagues reported an ultrasound technique for hemodynamic monitoring, entitled "the BEAT exam (bedside echocardiographic assessment for trauma/critical care)" [58]. The BEAT exam consists of the assessment of (1) (B)eat, cardiac function; (2) (E)ffusion, pericardial effusion; (3) (A)rea, right and left ventricle function; and (4) (T)ank, volume status (Table 8.2). Unlike FAST, all images for BEAT are acquired using a cardiac software package. A 3.5–5.0 MHz sector-type transducer is used. Patients can be positioned in the lateral decubitus position when supine position views are not optimal. Cardiac function is evaluated both by a subjective assessment of cardiac morphology and by calculated objective values (e.g., stroke volume, cardiac output, ejection fraction) (Figs. 8.14 and 8.15). Intravascular volume status (preload) is assessed by measuring the diameter of the inferior vena cava (IVC) within 2 cm of its entrance to the right atrium (Fig. 8.16). This view is normally obtained using a longitudinal view through subxiphoid region. An IVC of smaller diameter (<20 mm) with >50 % collapsibility with patient respiration suggests intravascular volume depletion. The accuracy of the BEAT exam for the assessment of cardiac function and volume status was evaluated by comparing it to PAC for surgical ICU patients (57 % trauma) [54]. Good quality images were obtained in 59 % of cardiac index examinations and 97 % of IVC measurements performed by six trauma surgeons or trainees. For both cardiac index and IVC measurements, there were significant correlations between BEAT exam and PAC values. Similarly, Murthi and associates compared the bedside ultrasound technique, "FREE (focused rapid echocardiographic evaluation)," with PAC or pulse contour analysis via arterial line for the measurement of cardiac index [55]. They showed FREE and PAC agreement in 87 % of patients and FREE and pulse contour analysis in 76 % of patients. This technique might be too complicated for a trauma or general surgeon to perform. However, Ferrada and colleagues showed that a limited transthoracic echocardiogram for the evaluation of cardiac contractility, fluid status, and pleural effusion was successfully implemented after 1-day course including a didactic and hands-on session [59].

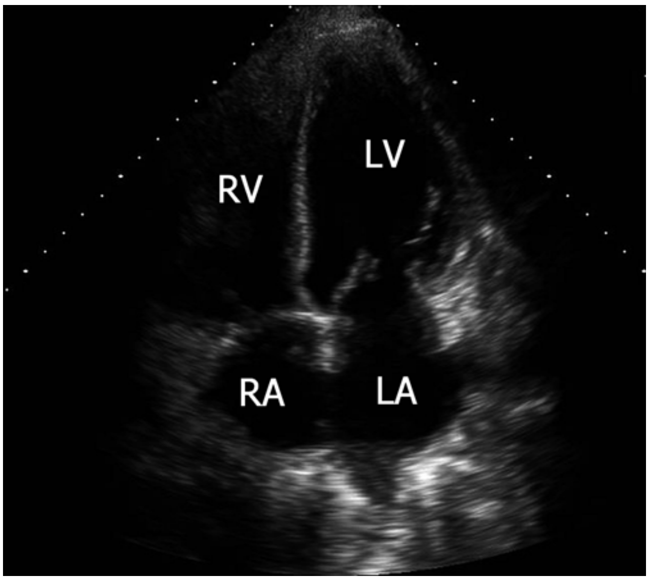

Fig. 8.14 The evaluation of heart contractility is performed with an apical four chamber view. *LA* left atrium, *LV* left ventricle, *RA* right atrium, *RV* right ventricle

Other Indications of Trauma Ultrasound

The indications of ultrasound continue to expand rapidly in trauma setting. Most of the techniques can be performed by a surgeon, intensivist, or emergency physician at bedside. Several types of fracture can be detected using portable

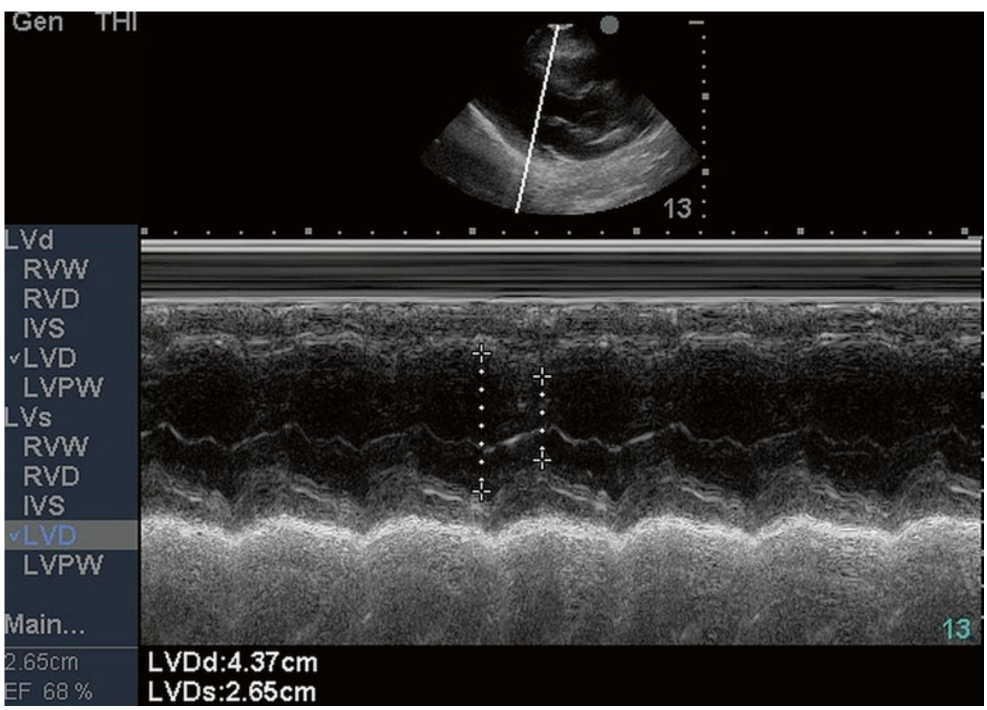

Fig. 8.15 In parasternal long-axis view, the ejection fraction of heart is calculated using the fractional shortening method

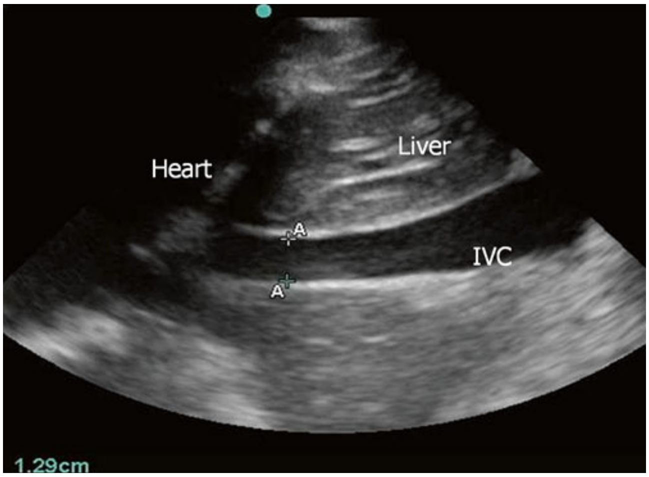

Fig. 8.16 Measurement of the inferior vena cava diameter for the assessment of volume status in a longitudinal view of the right upper quadrant in an abdominal preset

ultrasound [60, 61]. You and colleagues reported 100 % of sensitivity and specificity by ultrasound in the emergency department for the detection of sterna fracture [62]. Similarly, an ocular ultrasound has been increasingly used in the emergency department [63]. A bedside ultrasound technique to measure the diameter of optic nerve sheath is reported to be effective in identifying the patient with elevated intracranial pressure secondary to brain injury [64, 65].

Conclusion

In the last 20 years since FAST was introduced, its accuracy in diagnosing different types of injury has been studied extensively. While FAST has proven to be accurate in detecting free fluid in hemodynamically unstable blunt trauma patients and patients with penetrating injury to the "box" area, its accuracy in diagnosing stable blunt injured patients or those with abdominal penetrating injury appears to be limited. E-FAST is a useful technique to detect pneumothorax and hemothorax more quickly and accurately than CXR. Further prospective studies are needed to clarify how to choose the imaging modality between ultrasound and CT, particularly for the stable patients with suspected blunt torso injury. Surgical intensivist-performed ultrasound has been shown to be an effective tool to perform hemodynamic monitoring in the severely injured ICU patient. The use of ultrasound is expected to expand further for the management of trauma patients.

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