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The Evolving Role of Ultrasound in Emergency Medicine

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Abstract

Ultrasound has dramatically influenced the practice of emergency medicine in the twenty-first century. From its introduction to the medical landscape in the 1950s, it has been studied and utilized in various diagnostic exams and procedural guidance. Bedside ultrasound allowed emergency physicians easy access to immediate imaging, giving them the means to make management decisions quicker and improve quality of care. Ultrasound has demonstrated utility in examination of the heart, lungs, kidneys, liver, biliary system, uterus, ovaries, testicles, eyes and many other structures in the body. It decreases unsuccessful attempts and post-procedural complications in peripheral and central venous cannulation, pericardiocentesis, thoracentesis and other procedures. It has become a vital component of emergency medicine education and physicians now graduating with increased skills in ultrasound will continue to refine and develop its role in the emergent care of critically ill patients.

Keywords: ultrasound, POCUS, point of care ultrasound, echocardiography, FAST

1. An introduction to ultrasound

Ultrasound was first introduced in the early 1950s; however, individual units were not available for use until the 1960s. Its initial application was primarily experimental, and it did not enter a clinical role until the 1970s. The first ultrasound machines were large, complex and required the subject to be immersed in water. The images were difficult to interpret, requiring extensive training. Technological improvements led to a more compact device and better software that decreased the delay from signal acquisition to image display. This optimized real-time scanning and opened the door for widespread clinical use to develop [1]. In the

1970s, studies were performed to evaluate the utility of bedside ultrasound to detect artificially instilled fluid into a cadaver's peritoneal cavity, and within 1 year of this research, the first case of ultrasound used to detect hemoperitoneum was published. The first publication on ultrasound use by an emergency medicine physician appeared in 1988, and research into its use in bedside trauma evaluation began in multiple centers across the globe [1].

In the 1990s, additional advancements included color Doppler mode, the transvaginal transducer and multifrequency probes. The American College of Emergency Physicians (ACEP) offered its first emergency ultrasound course in 1990 and, along with the Society of Academic Emergency Medicine, published the first supporting position paper regarding emergency ultrasound in 1991 [2, 3]. ACEP then published the *Emergency Ultrasound Guidelines* in 2001, defining the scope of practice for emergency ultrasound and included recommendations for credentialing, quality assurance and standards for the examinations [4].

An emergency medicine ultrasound examination, also termed point-of-care ultrasound (POCUS) should be quick, focused, and performed for a specific condition for which it has proven utility. POCUS should be easily learned and attempt to demonstrate only a few easily recognizable findings at the bedside [1]. POCUS has continued to gain popularity due to the significant value it adds in decision-making, the immediate availability to imaging and the advancing technology with further device miniaturization and greater resolution [1]. In prehospital medicine, it is being investigated for its utility in expediting care prior to arrival and has demonstrated the ability to accurately assess trauma patients, allowing early communication of necessary resources to hospitals [5, 6]. It has also demonstrated significant utility in aeromedical evacuation and field assessment of remote-access trauma [7–10]. However, the remainder of this chapter will focus on the utility of POCUS in the hospital and its developing role in emergency department evaluation.

2. Ultrasound machine basics

Ultrasound uses probes that act as transducers for the ultrasound waves. Each transducer uses a piezoelectric crystal material that converts electricity to ultrasound waves, and then converts the returning waves to an electrical signal that is interpreted by the machine to create the two-dimensional image we recognize as the internal structures [11, 12]. The interchangeable probes vary by the ultrasound wave frequency emitted, which provides an array of image acquisition capabilities that favor resolution in different areas. The curvilinear probe emits a lower frequency of 2–5 MHz, providing greater lateral resolution and better penetration for deeper structures. The linear transducer emits higher frequencies of 7–13 MHz, providing much higher resolution for superficial structures. The phased array probe lies between these two, emitting a frequency of 2.5–5 MHz and providing moderate resolution for superficial structures and good penetration for deep structures [9, 11].

If the ultrasound pulse encounters a structure that reflects most waves, it will appear bright white and is termed hyperechoic. If the pulse encounters a structure that does not reflect much or any of the waves, it appears darker or black and is termed hypoechoic or anechoic, respectively [13].

There are also various ultrasound modes that allow us to address specific questions related to movement or flow. “B” mode (brightness mode) is primarily used for diagnostic imaging with two-dimensional displays in gray-scale based on the tissues echogenicity. “M” (motion) mode depicts the motion through time of structures along a single vertical line within the B-mode image. This mode is frequently used to look for subtle movement in images or better characterize the degree of movement experienced by a structure like as a heart valve [12]. Color flow mode depicts direction and flow velocity of fluids, such as blood within the heart or vessels. Power Doppler mode emits short bursts of waves, allowing more accurate localization of echo sources and is more sensitive in measuring flow velocity in low-flow states [12, 13].

3. Diagnostic ultrasound

3.1. Cardiac ultrasound

The phased array probe is typically used in cardiac evaluation, and four basic views are obtained. Parasternal long view visualizes the mitral valve, left ventricle and right ventricle. Apical four view is demonstrated just infero-lateral to the nipple, and demonstrates both atria and ventricles. A pericardial effusion can be easily demonstrated using ultrasound. An acute pericardial effusion of as little as 50 mL can lead to tamponade and requires immediate intervention [14, 15]. Small effusions usually occur in the posterior and inferior areas, and as they grow they extend to the apex. Moderate effusions are defined as 10–20 mm (anterior plus posterior) separation from the pericardial sac and the myocardium, and a large effusion is >20 mm [12]. The effusion will appear as a dense anechoic or hypoechoic area surrounding the heart, between the muscle and the hyperechoic pericardial sac [12]. It is important to determine if an effusion is causing tamponade, a condition when fluid accumulation in the pericardial sac increases the pressure enough to overcome the diastolic pressure of the right heart and prevent sufficient filling [14, 16]. Using ultrasound, visualization of right ventricle (RV) collapse during diastole is more reliable to determine the presence of tamponade, with a sensitivity of 48–100% and specificity of 72–100%. Right atrial collapse has a sensitivity of 50% in early tamponade and 100% in late tamponade, but a poor specificity of 33–100% [14, 17]. If the effusion has pus, blood or fibrin, it can appear less hypoechoic than expected. It is important to differentiate these more obscure pericardial effusions from the “epicardial fat pads” that some patients will have, and performing the ultrasound in a supine position will help as fluid should collect posteriorly and a hypoechoic layer only apparent anteriorly most likely represents fat [12].

The FOCUS (focused cardiac ultrasound) exam was created to protocolize a comprehensive exam looking for pericardial effusion, relative chamber size, global cardiac function and volume status (via left ventricle size, ventricle function or inferior vena cava size and change with respirations) [15]. In the hands of skilled practitioners, this exam can lead to decreased morbidity and mortality in blunt and penetrating trauma [15].

In determining the left ventricle (LV) function, there are three parameters used to give a rough estimate of “good,” “moderate” or “poor” ejection fraction. All parts of the ventricle wall should contract equally and symmetrically toward the its center, the myocardia must

be thicken during systole and the mitral valve must approximate the septum, demonstrating normal mobility [12]. These three data points allow a rough approximation of LV function, but there are more specific ways to estimate function. Simpson's method involves estimating the LV end-systolic volume (by tracing the two-dimensional area of the LV during a freeze-frame of systole) and end-diastolic volume, using the ultrasound software to perform the calculation [11]. End point septal separation (EPSS) has also been used to estimate cardiac function. EPSS uses the measured distance from the anterior mitral valve leaflet to the ventricular septum in early diastole in the parasternal long view. A value greater than 7 mm indicates poor LV function and likely low ejection fraction [18].

Cardiac ultrasound has recently been incorporated into cases of cardiac arrest and has shown utility in the difficult determination of continued cardiopulmonary resuscitation when it may be futile. Survival of cardiac arrest in the field is less than 5%, and cardiac activity which demonstrates no kinetic cardiac activity suggests only a 1–2% probability of return of spontaneous circulation [19]. Using the ultrasound criteria of no flickering of the ventricle walls or valves lowers the false negative rates even further [19–21]. It is important to hold artificial respirations and medication infusion during ultrasound as these small movements may be misinterpreted as movement of heart muscle [12]. The presence of cardiac contractility does not demonstrate the same prognostic significance, as in these cases, return of spontaneous circulation occurred in only 50% of cases [19].

Cardiac ultrasound can also be used to assess for right heart strain in cases of known or suspected pulmonary embolism. The right ventricle (RV) is typically less than 2/3 the size of the LV, but in acute right heart strain, the RV will appear the same size or larger than the LV [12]. The enlarged RV will put pressure on the septum, causing it to bow in and give the LV a "D" shape on the parasternal short axis view. Enlargement of the RV can also occur with chronic conditions such as pulmonary hypertension from chronic lung disease, so it is important to have a good background and clinical context when looking for this finding [12].

3.2. Pulmonary ultrasound

Air is a poor ultrasound wave transducer, as air molecules scatter ultrasound waves. Historically, sonographers believed that ultrasound could not be used to derive useful information about the lungs; however, artifacts created by normal lungs are helpful, mainly by their absence in pathologic lungs. A linear probe is typically used in the midclavicular area of anterior chest, oriented in the sagittal plane to capture ribs and the intercostal spaces between them [11]. Ultrasound is used commonly to look for pleural sliding, which is absent in a pneumothorax [22–24]. "B" mode can be used to examine the hyperechoic pleural line and look for bright white dots that appear to move along the surface, known as "ants marching on a log." "M" mode can be used as well, with the normal finding being a uniform gray sheet below the hyperechoic pleura, known as the "seashore sign." In the absence of pleural sliding, there will be numerous straight lines in sequence below the pleural line, giving a barcode appearance [11, 12]. Compared to chest radiography, anterior lung ultrasound has a higher sensitivity (59–80%) and comparable specificity (89–99%) [25, 26]. False negatives occur primarily in smaller, clinically insignificant pneumothoraces [27]. The transition point on lung ultrasound images where features of a normal lung and of a pneumothorax converge is known as the

“lung point.” This finding is controversial, but some sources report a specificity of 100% for this finding in diagnosis of a pneumothorax [23, 28, 29].

Pleural effusions can be visualized using the phased array or abdominal probe in the coronal plane of the right upper quadrant (RUQ) and left upper quadrant (LUQ). In these views, the diaphragm is visible as a hyperechoic, curvilinear line, with the liver or spleen inferior, and the lungs superior [11]. In normal lungs, the lung tissue superior to the diaphragm has the same echogenicity as the liver or spleen due to a “mirroring” phenomena caused by ultrasound waves refracting off the diaphragm. In pleural effusions, this is replaced with a hypoechoic or anechoic signal, and it is possible to visualize the vertebral bodies at the bottom of the screen due to improved penetration of the ultrasound waves through the fluid [29]. The lung border is typically identified in the fluid and will move during inspiration and expiration [24, 30]. Like pneumothoraces, lung ultrasound is superior to chest radiography in detecting clinically significant pleural effusions, with higher sensitivity (91 vs. 74%) and specificity (100 vs. 31%) [31–33].

The lung parenchyma can also be assessed using ultrasound. Ultrasound has demonstrated similar diagnostic reliability as computed tomography (CT) for detecting atelectasis [23, 30]. Overall, it has a sensitivity of 90–93% and specificity of 89–100% for complete atelectasis [23, 34]. The most common ultrasound finding is the “shred sign,” the appearance of irregularities, similar to shredded tissue, at the inferior pleural margin in the RUQ and LUQ views [34, 35]. Other findings noted in atelectatic lung include visualization of cardiac activity in the tissue (normally prevented by sliding pleura), lung tissue with similar echogenicity to the liver (“lung hepaticization”), mediastinal shift toward collapsed lung, or hemidiaphragm elevation [23, 24, 30]. Lung contusions and pneumonia can mimic atelectasis; however, air artifacts will be present within the tissue in contusion, and in pneumonia, air can be visualized moving within the bronchioles, known as dynamic air bronchograms (intermittent bright white spots within the small airways). Both of these findings will be absent in complete atelectasis [22, 24, 36]. The lung parenchyma can also be assessed for volume overload termed pulmonary edema. The phased array or abdominal probe is used in the lateral, anterior or posterior approach, and the parenchyma is visualized to a depth of >16 cm, looking for “B” lines. These are spotlight-like artifacts that appear bright white and traverse the lung vertically to a depth of at least 16 cm. The presence of three or more “B” lines in a lung field has an overall sensitivity of 94.1% and specificity of 92.4% for pulmonary edema, outperforming chest radiography [12, 37, 38].

Other less utilized exams related to the thoracic area include airway edema and diaphragm rupture. Smoke inhalation can lead to significant endotracheal injury and resultant respiratory distress. A case study has demonstrated that ultrasound can visualize thickening of the anterior tracheal wall following inhalational injury and allow responders to potentially anticipate the need for airway protection [39]. Acute diaphragm rupture can occur in severe trauma and, because clinical manifestations vary, the diagnosis can be challenging without quick access to a CT scanner. Ultrasound has been investigated for its potential to rule out diaphragmatic rupture. Inability to visualize the spleen or heart due to herniated bowel overlying these organs, poor movement of the diaphragm with respirations, and subphrenic effusions are all associated with diaphragm ruptures. Unfortunately, ultrasound is neither sensitive nor specific for rupture, and if suspected, a CT scan should be performed immediately [30, 40].

3.3. Abdominal ultrasound

In modern trauma evaluation, the FAST (focused assessment with sonography for trauma) exam is a regular part of the secondary survey. It is a rapid evaluation looking for fluid within the abdominal, pericardial and pelvic cavities, using the subxiphoid, RUQ, LUQ and suprapubic views [31, 41, 42]. In RUQ and LUQ views, fluid will appear first within the hepatorenal and subdiaphragmatic recesses. It is critical to visualize the entire hepatorenal area on the right, including the inferior pole of the kidney, and the subdiaphragmatic margin above the spleen on the left, to maximize the sensitivity for finding intraperitoneal fluid [12]. In the transverse suprapubic view, fluid accumulation is visualized as anechoic collections to the left or right of the bladder. The longitudinal view is more sensitive for free fluid in this area, because it better captures the most dependent region adjacent to the posterior bladder wall [12]. This exam provides reliable detection of hemoperitoneum and hemopericardium (96–98% specificity, 99% accuracy), which outperforms physical exam (57% accurate) and hemodynamic monitoring [31, 41, 42]. Portable ultrasound has slightly lower sensitivity (60–85%) in the detection of these abnormalities compared to bedside ultrasound [31, 42]. Given the low sensitivity of the exam, experts recommend using only a positive finding to guide triage or management decisions. However, serial exams can be used to improve sensitivity for an evolving or occult injury [43].

Ultrasound has long been the study of choice for the biliary system, and moving it to a bedside POCUS exam provides quick, actionable information. The curvilinear probe is used in this exam and is typically placed in the right or anterior infracostal margin. The gallbladder will appear as a small sac with a hyperechoic lining and hypoechoic interior. Lying the patient in left lateral decubitus and having them take deep breath will help bring the gallbladder closer to the abdominal wall and into view [11]. Gallstones are hyperechoic masses that tend to fall to the most dependent part of the gallbladder [13]. When one of these stones becomes impacted in the gallbladder neck, it can lead to cholecystitis (inflammation of the gallbladder). Typical ultrasound findings indicative of cholecystitis includes the presence of gallstones, pericholecystic fluid (thin, anechoic layer surrounding gallbladder wall) and thickening of the anterior wall, which is normally less than 3 mm [13]. Gallstones can also become lodged in the common biliary duct and lead to distension of the extra- and intrahepatic biliary system, a condition known as choledocholithiasis [12]. The common biliary duct can be measured using ultrasound, evaluating for this pathology. However, the duct's diameter must be interpreted in clinical context as the normal internal diameter can range from 0.6 mm to 1 cm, increasing with age [12]. Measurements greater than 1 cm can usually be assumed to be pathologic [11].

Though not routinely performed, the pancreas can be visualized using ultrasound to investigate for signs of pancreatitis such as pseudocyst formation, peripancreatic fluid and areas of necrosis which would appear as focal, hypoechoic areas [11]. An ultrasound exam of the appendix could reveal signs of appendicitis although this is typically reserved for children. It can be difficult to visualize the appendix well due to the presence of bowel gas, especially in its normal state. The diameter of the normal appendix should be less than six millimeters and it is compressible. Evidence of appendicitis on images obtained using ultrasound includes a larger diameter of over six millimeters, periappendiceal fluid, inability to compress the lumen and in one-third of cases a fecalith can be visualized [13].

3.4. Renal and genitourinary tract ultrasound

Ultrasound can be used to evaluate the genitourinary system for pathology. The major organs of interest in this system are the kidneys and bladder. The normal kidney appears oblong with a hypoechoic outer ring, the cortex, and a hyperechoic central area that contains the collecting system. Ultrasound is often used to evaluate for hydronephrosis, which generally occurs secondary to some downstream obstruction, such as a ureteral stone [13]. Hydronephrosis will appear as increased hypoechoic dilations within the renal pelvis and is graded as mild, moderate or severe depending on the integrity of the remaining structure, the calyceal separation and involvement of the renal pelvis [11, 13]. Renal stones may be visualized within the collecting system as hyperechoic structures that cause shadowing (hypoechoic artifact beyond the stone due to its highly reflective surface). Ultrasound is not sensitive for demonstrating ureteral stones, but the appearance of bilateral ureteral jets in the bladder can help exclude a diagnosis of obstructive uropathy secondary to a stone [11–13]. The renal parenchyma can also be analyzed for changes such as increased echogenicity which occurs in the early stages of medical renal disease [13]. The bladder volume can likewise be analyzed to determine if a patient is retaining secondary to an obstructive process or neurogenic process such as cauda equina [12].

3.5. Aortic ultrasound

Ruptured aortic aneurysms have a high mortality, and the size of the aneurysm is related to its risk of rupture [13]. Most abdominal aortic aneurysms occur below the level of origin of the renal arteries. Ultrasound is effective in visualizing the abdominal aorta. It is the choice screening study in asymptomatic patients and can provide life-saving information in an unstable patient who cannot be transported safely to a CT scanner. The abdominal aorta is normally less than three centimeters in diameter, but as the diameter passes five centimeters, the risk of rupture increases over 25% [13]. One difficulty with obtaining the necessary views is bowel gas that scatters the ultrasound waves and obscures the deeper structures. To minimize the artifact, apply slow steady pressure or jiggle the probe while pressing to encourage peristalsis and movement of the gas out of the bowel segment. Imaging from an angle or turning the patient on their left side to use the liver as an acoustic window can also help [12]. A false negative can occur with this scan if a mural thrombus is present in the periphery of the aneurysm, causing an internal wall that will decrease the diameter of the measured aorta. For this reason, it is important to measure from outer wall to outer wall of the aorta [13]. Aortic dissection can also be detected using these views, and will appear as a free flap within the lumen of the aorta. However, ultrasound is not nearly as accurate or sensitive as CT and should not be used to rule out a dissection [12].

3.6. Pelvic ultrasound

Ultrasound is the choice study for investigating female pelvic organs, especially in pregnancy. One of the most common questions related to a pregnant female in emergency medicine: Is this an intrauterine pregnancy? The definition of intrauterine pregnancy is the presence of a gestational sac with a yolk sac or fetal pole, within the uterus [12, 13]. A physician can use the ultrasound with either a curvilinear transabdominal or a transvaginal (more sensitive) probe to

image the female pelvic organs. In conjunction with human chorionic gonadotropin (hCG) levels, ultrasound can be used to determine the likelihood of an ectopic pregnancy. Discriminatory zones refer to the hCG levels at which an intrauterine pregnancy should be apparent on ultrasound, if present [12]. For transabdominal pregnancies, this would be between 4000 and 6500 IU/mL, but for transvaginal ultrasound, it is 1500 IU/mL, due to the higher frequency and better resolution [12]. If hCG is measured above these levels and no intrauterine pregnancy can be visualized, an ectopic pregnancy should be assumed until proven otherwise. The potential deadly consequence of an ectopic pregnancy is its rupture and subsequent massive hemorrhage into the peritoneal cavity, which can go undetected if not specifically investigated. Using ultrasound, the pelvic, RUQ, and LUQ views of a FAST exam can be performed to look for evidence of a ruptured ectopic pregnancy by evaluating for fluid in the peritoneal cavity [12, 13].

A general fetal ultrasound exam can also be performed bedside. While the formal obstetric ultrasound includes many different measurements and assessing for various fetal abnormalities, these considerations are out of the purview of emergency medicine. The principle measurements that are taken bedside typically include the fetal heart rate, which is depicted in M mode, and the estimated gestational age [11, 13]. The fetal heart rate is obtained by placing the line in M mode through the fetal heart and obtaining the tracing of the movement through time. It is important to note that pulsed Doppler mode should not be used on the fetus at any time, as it is believed to have adverse effects on fetal development [11]. The estimated age can be calculated using specific measurements depending on the trimester. In the first trimester, crown-rump-length has been shown to be very accurate (within 3 days for 42–70 days and within 5 days for 70–90 days) and have great correlation between measurements performed by emergency physicians and those performed by obstetricians [44, 45]. In the later part of the first trimester and the second, additional measurements can be used such as femur length, abdominal circumference and transcranial diameter [13].

Molar pregnancies can also be demonstrated on a pelvic ultrasound. Suspicion for a molar pregnancy should arise, if hCG levels exceed 100,000 mIU/mL, with cases of severe hyperemesis gravidarum, or with vaginal bleeding in pregnancy. Ultrasound findings of a molar pregnancy include an enlarged uterus with echogenic material within the endometrial cavity (“snowstorm pattern”), numerous small cystic spaces within the tissue (hydropic villi) and enlarged, cyst-filled ovaries [13, 46].

Outside of pregnancy, ultrasound is used to visualize the female pelvic organs to demonstrate other infectious or structural abnormalities. Transvaginal ultrasound of the normal uterus will appear as a normoechoic outer layer of myometrium with a hyperechoic interior endometrium [13]. Ultrasound can demonstrate intrauterine abnormalities such as endometrial thickening (potentially indicative of endometrial hyperplasia or endometrial carcinoma) or fibroids, which may provide clues to the etiology of new or increased vaginal bleeding [13]. The endometrial cavity appears as a thin, bright line on the interior of the uterus. When performing a transabdominal study of the uterus, a full bladder provides an acoustic window and increases image resolution. However, a full bladder will impede the views of a transvaginal study, which is performed with a higher frequency probe that is better for superficial structures [13].

One of the most common gynecologic emergencies is ovarian torsion, and the consequence of missing this pathology is potential infertility. The presentation is not straightforward, and ultrasound is the best noninvasive technology to investigate the likelihood of torsion [47]. It is difficult to visualize normal ovaries on a transabdominal ultrasound; however, on a transvaginal study, they appear like large chocolate chip cookies, with the chocolate chips being small cystic follicles inside the larger, circular ovary [13]. The most common finding in ovarian torsion is ovarian enlargement [47]. Doppler ultrasound or color ultrasound modes can be used during a transvaginal exam to differentiate venous and arterial blood flow within the ovaries, and ensure that both are present. As torsion can be intermittent, a scan demonstrating adequate flow does not necessarily rule out torsion, and has a high false-negative rate. However, specificity of inadequate blood flow has been quoted from 91 to 97% and is a reliable determinant of torsion [47].

In a similar manner, power Doppler can be used to examine the testicles for potential torsion, but with the same principles of sensitivity and specificity. Each testicle should be examined separately and within the same image, as the most common finding is testicular enlargement and hypoechoic color change compared to the contralateral testicle. Other findings on a scrotal exam include hydrocele (a large fluid collection around the testicles), varicocele (large collection of tortuous and dilated veins appearing next to the testicle), spermatocele and epididymitis. Epididymitis is the most common cause of scrotal pain in postpubertal males, and will appear as increased blood flow posterior to the testicle compared to the contralateral side [48–50]. Following scrotal trauma, hemorrhage can be visualized within the testicle. As a general principal, any abnormality in the traumatized testicle compared to the other side represents testicular rupture until proven otherwise [48–50].

3.7. Ocular ultrasound

Ocular ultrasound has many applications within emergency medicine. All structures of interest are superficial and therefore the linear probe is the probe of choice. The structure of the eye is easy to delineate using ultrasound. The fluid-filled globe is separated into the anterior and posterior chamber, with the lens visible as an oval echogenic structure just posterior to the ciliary body [51]. Lens dislocation will appear as displacement of the small, oblong structure from this usual resting place into the anterior or posterior chamber, and has been well described in ophthalmology literature [12]. Retinal detachment has also been well described and will appear as a flat, worm-like structure in the posterior chamber that moves with eye movement and is attached at one or two points to the posterior wall. Emergency physicians were found to have a 97–100% sensitivity and 83–99.7% specificity for detection of retinal detachment using ultrasound [51]. Vitreous hemorrhage will also appear in the posterior chamber as a heterogeneous mass of swirling gray material within the black globe, often likened to seaweed swaying in the waves with eye movement [11, 12, 51].

A relatively new application of ocular ultrasound is to indirectly assess for increased intracranial pressure (ICP) due to processes such as traumatic brain injury, intracranial bleeding, hydrocephalus or a hypertensive emergency. Various studies have demonstrated that the optic nerve sheath diameter (ONSD) is an accurate diagnostic sign of increased ICP and outperforms CT

scan [11, 52, 53]. The globe provides a good acoustic window for visualization of the optic nerve, which appears as a large hypoechoic stripe posterior to the globe. ONSD is measured 3 mm posterior to the optic disc and is normally less than 5 mm. Using a stricter cutoff of greater than 5.8 mm for increased ICP (>20 mmHg) yields a sensitivity of 90% and specificity of 84% [51]. ONSD has mixed reviews for real-time trending of ICP. For increased ICP that is sudden onset, it has been shown that immediate intervention to decrease ICP also leads to resolution of the ultrasound findings [54]. However, for sustained increases in ICP, ONSD does not appear to normalize in real time with measures to decrease ICP [53].

Ocular injuries are a common presentation to the emergency department, and foreign bodies are involved in many cases. Sonography can detect foreign bodies within the globe, which typically appear as a twinkling object and a comet-tail-shaped reverberation artifact posteriorly. Ocular ultrasound has a sensitivity of 87.5% and a specificity of 85.2% for foreign bodies, and is more reliable in the detection of metallic material. However, care must be taken to avoid pressure on a potential open globe secondary to a foreign body. If open globe is suspected, other imaging modalities such as CT are preferred [51]. Lesser utilized ocular exams include demonstration of the ocular vasculature using color Doppler to evaluate for central retinal artery and central retinal vein occlusion, and evaluation of the posterior orbital space for hemorrhage (hypoechoic area) or distortion/flattening of the posterior globe ("guitar pick sign"), indicative of a retrobulbar hematoma [51].

3.8. DVT ultrasound

Deep venous thrombosis (DVT) is commonly asymptomatic, however suspicion for the pathology increases with unilateral pain and swelling of an extremity. Ultrasound is the exam of choice for the initial evaluation of an extremity for DVT. The highest yield exam is for a symptomatic patient, and it has much lower sensitivity for asymptomatic extremities. As the clinical relevance of isolated calf DVT is controversial, most radiology performed and POCUS DVT exams focus on the larger vessels above the knee [12, 13]. However, those who advocate for whole leg ultrasound point out that finding the isolated calf DVT obviates the need for a repeat scan at a later time, which is recommended with a negative two-point compression scan [12].

Two-point compression studies involve complete compression of the common femoral and greater saphenous vein in the inguinal area, and of the popliteal vein in the popliteal fossa of the posterior knee. The veins should compress to a very thin line, and inability to fully compress may indicate a DVT. False positives can occur if structures such as a lymph node, Baker's cyst or pseudoaneurysm, are mistaken for a noncompressible vessel. These structures can be better characterized by placing color Doppler over the structure and evaluating for flow. In low-flow states, squeezing the calf can help to provide extra venous return and allow easier identification [12].

3.9. Soft tissue and bone ultrasound

Ultrasound exams of soft tissue and bone focus on superficial structures, utilizing the linear probe. The different components of soft tissue are easy to differentiate. Skin will be the hyperechoic

layer just below the transducer surface, subcutaneous tissue is the hypoechoic layer below the skin, muscle will appear relatively hypoechoic (more than subcutaneous tissue) and feather-like with linear striations, tendons are hyperechoic and fibrillary, and bone is linear and hyperechoic with shadowing posteriorly [11].

On a soft tissue exam, “cobblestoning” or fluid tracking throughout the subcutaneous layer is indicative of cellulitis or edema of the tissues. This is differentiated from a frank fluid collection indicative of an abscess, which will require incision and drainage, versus cellulitis, which is managed using antibiotics alone [12]. Two views can be helpful as the purulent material within an abscess can have increased echogenicity and a collection may be missed, especially if it is a thin collection in the anterior-posterior plane. Sonography can be used to demonstrate nearby vasculature prior to incision and drainage of an abscess to determine optimal incision location [11, 12].

Evaluation of tendons for potential rupture can be performed bedside, and will appear as a break in the normal linear appearance, potentially with hypoechoic hemorrhage separating the two parts [12]. A similar finding is noted in fractures. Ultrasound evaluation of bones clearly demonstrates the hyperechoic, linear cortex. In a suspected fracture, the ultrasound probe is scanned along the bone looking for defects or discontinuity of the cortex. Patient history and physical examination have poor accuracy in determining the presence of a fracture in trauma. Ultrasound has up to 90–95% sensitivity in fracture detection, making it useful to rule out a fracture, but has lower specificity and usually cannot reliably rule in a fracture [9, 11, 55]. Ultrasound is less accurate if a fracture occurs close to a joint, but additional evidence such as soft tissue swelling or a hypoechoic hematoma adjacent to the bone provide clues that a fracture may be present [9, 11].

4. Procedural ultrasound

When the ultrasound is used for procedural guidance, precautions are taken to keep the probe sterile. A probe cover and sterile gel are used for this purpose, and some procedural kits are found where ultrasound guidance has become more standardized. Since most procedures using ultrasound guidance involve superficial structures, the linear probe is regularly utilized. The orientation of the probe becomes critical, as movements of equipment on the screen, such as needles, need to correlate with movement relative to the patient [11]. There are two general methods for procedure guidance using ultrasound: static and dynamic. Static guidance usually entails either visualization of internal structures before the procedure to mark the ideal entry site, or post-procedure to verify success. Dynamic guidance entails visualization during the actual procedure [12].

4.1. Venous cannulation

Insertion of intravenous catheters using visual guidance is one of the most common procedural uses for the ultrasound [56–58]. Ultrasound-guided peripheral and central line placement is nearly always performed dynamically, watching the needle advance until there is successful cannulation of the vein. Peripheral vein cannulation uses either 1.5-inch cannulated needle,

or a longer angiocath for deeper veins. Ultrasound guidance is most useful in patients with difficult IV access, such as obese, young, IV drug abusing or prior chemotherapy patients. In patients with difficult to obtain IV access, ultrasound-guided IV placement was demonstrated to be consistently twice as fast and decrease the total number of punctures needed by an average of two, but still had variable success (80–90%) [9]. Physicians with greater ultrasound experience have more than 60% increased success rates between ultrasound and landmark guidance compared to novice practitioners with no ultrasound background [9, 56, 59].

In general, there are two methods to visualize dynamic IV placement. In the transverse approach, the probe is held perpendicular to the vessel. The probe can be used to apply compression and differentiate artery from vein. The depth of the desired vessel is measured and needle is inserted at the same distance distal to the ultrasound probe at a 45° angle. This allows visualization of the needle tip, which appears as a bright, white dot, just as it enters the vessel below the ultrasound probe [11]. The other technique is to place the probe in line with the needle so that the vessel is visualized running across the screen from left to right, and the entire length of the needle can be visualized as it tracks through the skin and soft tissue to the vessel [11].

Central line placement follows the same principles and ultrasound has become routinely used in internal jugular and common femoral vein cannulation. While advancing the needle during central line placement, just as in landmark-based techniques, applying slight negative pressure to the syringe allows you to feel when you have punctured the vein rather than relying only on ultrasound visualization. Once blood is withdrawn, the ultrasound probe is set aside in the sterile field while the wire is inserted. Ultrasound can then be used to verify the placement of the wire within the lumen of the vein and not the adjacent artery. The use of ultrasound in central line placement has led to reduction in complications by 78%, reduction in attempts needed by 40% and reduction in unsuccessful cannulation by 64% [9, 12].

4.2. Paracentesis and thoracentesis

Paracentesis can be performed for both diagnostic sampling and/or therapeutic drainage. Although the landmark-based approach has generally been safe, ultrasound allows several advantages including the ability to find the deepest fluid pocket and avoid inadvertent puncture of the internal organs, visualization of overlying or underlying vasculature or abnormal anatomy to avoid, and confirmation that the abdominal distension is secondary to ascites and not another disease process [60, 61]. Physical exam itself has poor reliability in the diagnosis of ascites, and ultrasound demonstrated improved sensitivity (94% compared to 50%) and specificity (82 vs. 29%) in detection [62]. In landmark-based paracentesis, success is determined mainly by the overall volume of ascites, success rates are 44% for 300 mL and 78% for 500 mL, but virtually never successful with volume is less than 50 mL [63]. A prospective, randomized study involving inexperienced emergency medicine residents performing ultrasound-guided paracentesis compared to this landmark-based technique demonstrated higher success rates (95 vs. 61%, $P = 0.0003$) [64]. Another retrospective study demonstrated the association of ultrasound guidance with lower adverse events rates such as post-paracentesis infection, hematoma, and seroma (1.4 vs. 4.7%, $p = 0.01$) [65].

The abdominal or phased array probe is typically used in a static exam, finding the best fluid pocket with the patient supine or in left lateral decubitus, marking that spot on the skin and then placing the ultrasound aside for needle insertion. The practitioner should avoid the upper quadrants, given the proximity of the liver and spleen to the abdominal wall. They should also avoid 11 and 2 o'clock angles of the abdomen to prevent inadvertently puncturing the inferior epigastric arteries, a known cause of hemorrhagic complications [66]. A pocket of 3–4 cm between the abdominal wall and the free-floating loops of bowel is adequate and is usually found in the lateral-most aspect of the abdomen [11].

Thoracentesis follows similar principles and can be used for diagnostic or therapeutic collection. Ultrasound guidance for bedside thoracentesis has resulted in overall shorter hospital stays, less overall cost and fewer complications [67]. Specifically, ultrasound reduces the rates of iatrogenic pneumothorax by 29%, which complicates 20–39% of physical exam-guided thoracenteses [68]. In cases of iatrogenic pneumothorax, ultrasound guidance also reduced the number of those ultimately requiring tube thoracostomy [69]. Ultrasound increases the accuracy of site selection by 26% and decreases the number of unsuccessful attempts [70]. It can also be used to estimate the size of a pleural effusion which helps to predict the utility of drainage. In patients with a pleural effusion greater than 500 mL, successful drainage leads to improvement in their oxygen saturation to inspired oxygen ratio [27]. With the patient supine, a distance from the thoracic wall to the visceral pleura over 5 cm at the posterior axillary line can identify an effusion larger than 500 mL (90% specificity and 100% sensitivity) [24, 71].

Similar to a paracentesis, a phased array transducer is used with the patient either supine or sitting up, and a static exam is performed to demonstrate the deepest fluid pocket within the thoracic cavity. The diaphragm should be visualized and care should be taken to avoid the needle tip coming in close proximity to it. A depth of 15 mm between the visceral and parietal pleura over three sequential intercostal spaces is adequate to perform the procedure. Real-time ultrasound guidance can also be used to actively visualize the needle passing through the pleura and into the fluid [11].

Ultrasound can be used in tube thoracostomy pre-procedure to optimize site selection and decrease complications, or post-procedure to quickly verify correct placement. Pre-procedure ultrasound lowers the rate of iatrogenic pneumothorax (4–30 to 1.3–6.7%), helps avoid intercostal vessels and allows visualization of aberrant anatomy that can lead to complications. Post-procedure ultrasound can be used to detect complications such as a misplaced tube, iatrogenic pneumothorax and re-expansion pulmonary edema [22, 72, 73]. Extra-thoracic placement of chest tubes is estimated to complicate 0.5–2.6% of attempts, and ultrasound has demonstrated a sensitivity of 83–100% and specificity of 83–100% for differentiating intra- and extra-thoracic placement [74]. When viewing the thorax with ultrasound, a correctly placed chest tube will disappear as it enters the thorax, but an extra-thoracic tube can be viewed in its entirety [74].

4.3. Pericardiocentesis

The significant drop in cardiac output in tamponade can be life-threatening, and emergent pericardiocentesis can be life-saving. As previously mentioned, ultrasound can be used to

diagnose pericardial effusion and tamponade and can help in its immediate management. Ultrasound guidance allows visualization of the area of maximum fluid accumulation and real-time needle guidance to decrease complications such as inadvertent puncture of the internal mammary artery or the neurovascular bundle at the inferior edge of the ribs [11, 75, 76]. The traditional technique involved a subxiphoid approach and blind needle advancement until blood or fluid was withdrawn. Using ultrasound, the initial approach in over 80% of patients was changed to an apical puncture site due to better fluid accumulation here [75, 77].

The procedure is performed with the curvilinear or phased array transducer and can be placed either subxiphoid or in the parasternal position for viewing the pericardial effusion. The ideal site for needle placement is where the effusion has maximal depth, is closest to the skin and farthest from structures the needle could damage, such as the liver or lung. The ultrasound beam is used to simulate the needle tract, so if the liver or lung lies above the pericardium on the screen, the needle will penetrate these structures [11]. The placement of the pericardiocentesis catheter can be confirmed using ultrasound. After the needle or catheter is deemed likely to be in the pericardial sac, a syringe filled with agitated saline can be connected and injected while viewing with the ultrasound. A “snow-storm” of bubbles, showing as white dots, will be seen within the pericardial sac if the catheter is correctly placed, or may be apparent within the ventricle if the myocardium was penetrated during the procedure [9, 11].

4.4. Lumbar puncture

The complication rate for lumbar punctures is exceedingly low; yet in patients with increased body-mass-index and excess soft tissue, the success rates can vary greatly. Anesthesia literature from Russia first mentioned the concept of ultrasound guidance used during lumbar punctures in 1971 [78]. Following this publication, further anesthesia literature has documented a reduced number of unsuccessful attempts, fewer interspaces punctured, and decreased needle repositioning within the skin when using pre-procedure ultrasound guidance [79–81]. Ultrasound was recently demonstrated to be a preferred rescue method in failed neonatal lumbar punctures [82]. Likewise, a 2005 case series demonstrated its utility in localization in three failed adult lumbar punctures performed by experienced physicians [83]. In patients with difficulty to palpate landmarks, ultrasound has proven value to identify the lumbar vertebral landmarks as well as other relevant structures that help to guide a lumbar puncture [84, 85].

As the best utility in ultrasound guidance is experienced in patients with a high amount of overlying soft tissue, a curvilinear transducer will typically be the choice probe to gain a greater amount of depth. The transducer is placed parallel to the vertebral column at first to view the spinous processes and the desired para-vertebral space. The spinous processes will be hyperechoic and rounded, and there will be a notable gap where the space occurs. Ultrasound allows alignment in both the vertical as well as the horizontal axis, providing an exact point for needle puncture to optimize success. Real-time guidance is generally not performed given the difficulty of needle insertion with one hand while holding the probe, and typically static guidance and skin marking are sufficient [11].

4.5. Endotracheal intubation confirmation and tracheostomy

Intubation is a common procedure performed in emergency medicine and has high rates of first pass success [86]. However, one of the well-known complications is accidental endobronchial intubation which would result in ventilation of only one lung, or intra-esophageal intubation which would result in neither lung being ventilated. As many as 55% of these endobronchial intubations are missed by auscultation of the bilateral lung fields alone, and in cases of poor cardiac output (e.g., cardiac arrest), patients may lack sufficient circulation to the lungs to expel enough carbon dioxide for accurate capnography [87]. Ultrasound has demonstrated utility in verifying the correct placement of the endotracheal tube (ETT) directly and indirectly [9, 88]. Indirect verification involves demonstration of pleural sliding in the anterior, midclavicular line bilaterally once the ETT is placed. This technique would be limited in the setting of a pneumothorax [31, 87]. Direct verification involves real-time visualization during intubation with the probe placed midline over the trachea in the suprasternal notch. Evidence of successful intubation is seen as a single air artifact, and unsuccessful, esophageal intubation would be apparent as a double air artifact (air in the tube and the trachea). The direct method has overall sensitivity of 98.9, with 100% specificity in noncardiac arrest patients, and 75% specificity in cardiac arrest patients [89]. This technique is limited if the trachea lies directly over the esophagus, as it would obscure visualization of the air artifact within the esophagus [88].

If intubation is ultimately unsuccessful, ultrasound can also provide guidance in cricothyroidotomy [9]. Inaccurate landmark identification using digital palpation is one of the leading causes of cricothyroidotomy failure and complication [90]. Excess soft tissue in the neck can result in significant difficulty palpating and identifying the thyroid and cricoid cartilage. Ultrasound has demonstrated increased reliability in identification of the cricothyroid membrane and its use has the potential to decrease moderate-severe injuries to the trachea and larynx by up to one third compared to landmark-based technique [90].

5. Conclusion

Ultrasound has helped to transform the practice of emergency medicine by providing an efficient and powerful tool that allows rapid information acquisition and subsequently informed, quick decision-making. Its utility continues to expand and, with technological advancements, it will continue to become more versatile and widespread in its use, not only in the emergency department, but in the prehospital and more austere settings. It allows the emergency physician to expedite care by decreasing time needed to obtain imaging and speak with consultants or to order additional tests or treatments based on the findings. It decreases procedural complications by allowing real-time guidance of needles along specific tracts, avoiding inadvertent organ or vessel injury.

Ultrasound education is established as an essential part of all emergency medicine residencies, as well as some general surgery residencies, and is offered as an accredited fellowship. As physicians graduate from these training programs, the expectations of their ultrasound

skills will grow. Bedside ultrasound is increasingly available, and emergency medicine physicians will continue to refine and optimize its use.

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Conflicts of interest

I have no conflicts of interest to declare.

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