Bedside US imaging in multiple trauma patients. Part 1: US findings and techniques

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Abstract

Objectives The aim of this review article is to present the current views and visions of the role of ultrasound (US) in the management of patients with multiple trauma. The article is divided into two parts. Part 1 (US findings and techniques) will mainly deal with the technical aspects of US imaging in trauma patients and is written also for educational purposes. Part 2 (pathophysiology and US imaging in trauma patients) will deal with integration of US in the clinical and pathophysiological management of multiple trauma patients.

Methods A non-systematic review of the literature through PubMed search (restricted to the last 10 years) of original articles and review articles.

Results 80 publications were selected for Part 1. Of these 80 articles, the author selected 50 according to personal criteria on the basis of their innovative or original contents (48 original articles and 2 literature review articles); 19 articles were furthermore extracted from the references of the selected publications. The information extracted from these 69 publications was organized into sections dealing with different fields of applications of US imaging in multiple trauma patients.

Conclusions US imaging in trauma has evolved from the initial use, i.e., early diagnosis of peritoneal effusion (focused abdominal sonography for trauma), to a wider use known as resuscitative ultrasonography, and is today

considered as an extension of physical examination to implement a more effective approach to clinical problems and increase the timeliness and safety of interventions.

Keywords Trauma · Ultrasound · Ultrasound findings · Ultrasound technique

Riassunto

Obiettivi L'obiettivo di questa ricerca è di presentare la visione e le opinioni correnti sul ruolo dell'ecografia nella gestione del paziente con politrauma. L'articolo è diviso in due parti: nella prima ('Semeiotica ecografica e tecnica di esecuzione dell'esame') verrà data attenzione agli aspetti prevalentemente tecnici dell'ecografia nel trauma, con intento anche didattico; nella seconda (Fisiopatologia e ecografia clinica del trauma) sarà esplorato il tema dell'integrazione dell'ecografia con la clinica e la fisiopatologia nella gestione del politraumatizzato.

Metodi Revisione non sistematica della letteratura. Ricerca su PubMed (restrizione agli ultimi 10 anni) di articoli originali e revisioni.

Risultati Per la Parte prima sono stati selezionati 80 articoli, tra i quali sono stati scelti con criteri personali quelli ritenuti innovativi o originali nei contenuti (48 articoli originali, 2 revisioni di letteratura). 19 articoli sono stati estratti dalla bibliografia delle pubblicazioni prescelte. I contenuti estratti dai 69 articoli sono stati organizzati in paragrafi intitolati ai singoli ambiti di applicazione dell'ecografia nel politrauma.

Conclusioni L'ecografia del trauma è evoluta dalla iniziale applicazione nella diagnosi precoce del versamento peritoneale (Focused Abdominal Sonography for Trauma o FAST) all'accezione più ampia di Resuscitative Ultrasonography (RUS) e viene oggi vista come un'estensione e un potenziamento dell'esame fisico, finalizzata a orientare

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in modo più sicuro l'approccio al problema clinico e aumentare la tempestività e la sicurezza degli interventi.

Introduction

Multiple trauma is a major challenge for the emergency department staff due to the potential complexity and severity of the traumatic injuries, their immediate impact and evolution and the need to identify and treat them promptly giving priority to injuries which are life threatening. In multiple trauma patients, more than one anatomical region is involved.

“Severe multiple trauma” refers to a subgroup of trauma patients with increased risk of fatal outcome due to various circumstances such as the need for tracheal intubation or already performed tracheal intubation on arrival at the emergency room, systolic blood pressure <90 mmHg, Glasgow coma scale score (GCS) <9, penetrating injury to the skull, thorax or abdomen or an injury severity score (ISS) >15.

Also in prehospital medical care there are criteria for a high index of suspicion of severe trauma (the dynamics of the event e.g., fall from height >5 m, head-on collision, passenger ejection from a vehicle, alteration of physiological parameters, evidence of traumatic lesions which are life-threatening or carrying a high risk of disability). Regardless of this categorization, each trauma patient should be evaluated accurately upon arrival at the emergency room to exclude the presence of potentially life-threatening injuries, which may also be occult. The predominant cause of early death in trauma patients continues to be head trauma (21.6–75.1 % of cases) followed by uncontrolled hemorrhage (12.5–26.6 %) [1]. The presence of abdominal trauma in a multiple trauma patient increases the risk of death by 25 %, and in patients with hypotension, abdominal trauma and indication for laparotomy, mortality increases by 1 % for every 3 min delay in life-saving intervention [2]. This helps to understand the success of focused abdominal sonography for trauma (FAST) which is still used as a rapid and focused bedside examination to identify the presence of intraperitoneal or pericardial free fluid [3]. However, the concept of FAST has undergone a significant evolution and the acronym now stands for “Focused Assessment with Sonography for Trauma” [4], as an increasing number of other aspects of trauma are being included. Ultrasound (US) assessment is now integrated in the ABCDE triage [5] and in the concept of resuscitative ultrasound (RUS), a “holistic” approach which includes evaluation of almost all aspects of multiple trauma patients in whom US is increasingly being used as an important bedside tool to enhance the sensitivity of clinical examination [6].

This article presents a review of the literature dealing with current aspects of the use of US in trauma patients. Part 1 will address US findings and investigation techniques, whereas Part 2 will address the pathophysiological and clinical aspects of trauma illustrating the potential and significance of US in the assessment of multiple trauma patients.

Methods

Articles dealing with the use of US in the assessment of trauma patients were selected through PubMed search (keywords: focused assessment with sonography for trauma, focused ultrasound, airway ultrasound, chest trauma, chest ultrasound, abdominal trauma, emergency ultrasound). The research was restricted to the last 10 years; however, some original articles published earlier were extracted from the references of the selected articles or using specific keywords. No review articles were excluded.

Results

A total of 80 publications were selected for Part 1. Of these 80 articles, the author selected 50 according to personal criteria on the basis of the innovative or original contents (48 original articles and 2 literature review articles); 19 articles were extracted from the references of the selected publications. The information extracted from these 69 articles was organized into sections dealing with the individual anatomical areas assessed using US imaging in multiple trauma patients.

Airway US

Assessment of patency and protection of the airway is the initial priority in medical care of trauma patients, and emergency endotracheal intubation is the intervention of choice for keeping the airway open. Certain conditions, such as injury to the face involving the upper airway, pre-existing facial abnormalities or anatomical peculiarities, obesity and obstructive sleep apnea syndrome may make it difficult or impossible to perform emergency endotracheal intubation. These conditions are only partly predictable on the basis of anatomical and clinical criteria [7].

The inability to secure the airway in a patient with respiratory paralysis caused by drugs can have serious permanent sequelae. Correct evaluation of the airway before emergency endotracheal intubation and assessment of correct endotracheal tube placement are two crucial

steps in critical care. US can play an important role in the safety of emergency airway management to evaluate the successful outcome of emergency endotracheal intubation and to guide emergency back-up maneuvers (needle cricothyroidotomy). Other applications such as percutaneous tracheostomy and US-guided cricothyroidotomy, correct laryngeal mask airway placement and US-guided anesthesia of the upper airway [8] are beyond the scope of this paper.

US assessment of the airway

The upper airway includes the oral and nasal cavities, pharynx, larynx and trachea, all of which are almost completely filled with air. For this reason, US imaging cannot directly depict the internal surfaces of these structures, whereas some or all of the lateral and anterior walls of the airway can be visualized as they are located on the surface; a high-frequency linear probe is the most appropriate for the study of the airways. However, in special circumstances involving e.g., large swelling or edema, a preliminary panoramic scan using a convex probe may be useful. Scans are performed in transverse, sagittal median and paramedian views [9]. The bones appear as hyperechoic linear structures with posterior acoustic shadowing, and the cartilage is hypoechoic, bounded posteriorly by the air-mucosal interface which appears hyperechoic. The anterior intraluminal surface of the airway, therefore, appears hyperechoic, whereas the posterior intraluminal surface is not visible.

The larynx is a musculo-cartilaginous structure located below the hyoid bone. The laryngeal skeleton is made up of nine cartilages of which the most important are the thyroid cartilage and the cricoid cartilage located below. Both are clearly visible; hypoechoic structures connected by two isoechoic membranous ligaments under which the air is visible. The tracheal ring is located below the cricoid cartilage adjacent to the pretracheal soft tissue and is clearly visible in sagittal and transverse views. The typical image of a longitudinal scan is that of a black rosary crown. A high-frequency linear probe is required to identify the vocal cords in a transverse view near the cricothyroid membrane. The vocal ligaments appear as two hyperechoic lines forming a triangle with the apex toward the probe; externally the vocal muscles are visible, hypoechoic in appearance and of varying thickness. The false vocal cords are hyperechoic in appearance due to an elevated level of lipid content (Fig. 1).

Pre-intubation assessment

1. Pretracheal fat measurement is performed at the vocal cords; it is the mean value of the distance in millimeter

Fig. 1 Normal US appearance of the vocal cords. The vocal ligaments appear as two hyperechoic lines forming a triangle with the apex toward the probe, laterally bounded by a thin hyperechoic line (vocal ligament), the vocal muscle and the false vocal cords (externally)

(mm) between the skin and the trachea measured on the central axis and 15 mm on each side. In obese patients, a pretracheal soft tissue thickness >28 mm is a more accurate predictor of difficult laryngoscopy than thyromental distance, mouth opening, modified Mallampati score, upper teeth abnormality and obstructive sleep apnea [10].

2. Recognition of vocal cord disorders. In some cases, difficult intubation is linked to functional or structural abnormality of the vocal cords. US has been employed to explore vocal cord motility and to detect inflammatory masses and tumors, particularly in children. In a study performed on adults, the authors suggest the following investigation technique: the patient is positioned with the neck extended, and the probe is placed along the midline of the submandibular region and then rotated transversely without moving it and tilted downward until an oblique plane is reached, referred to as the G plane. This plane divides the epiglottis and most of the anterior portion of the vocal cords including the arytenoids into two parts. The movement of the vocal cords is best viewed when the patient is phonating. US can show (1) alignment of the immobile vocal cords compared to the midline to assess any possible superior or inferior misalignment, and (2) latero-medial and supero-inferior movements during phonation to appreciate a possible discrepancy in the mobility of the vocal cords secondary to an imminent or known paresis [11]. US has also been used for detecting neoplastic masses or vocal cord inflammation [11–13].

Assessment of correct endotracheal tube placement

US can show the presence of the endotracheal tube in the trachea [14] either directly or after increasing the echogenicity (by gently moving a stylet inside it or by inflation of the tube cuff using fluid or air bubbles) [15]. In case of esophageal intubation (occurring in 15 % of cases), the endotracheal tube can be visualized directly in the esophagus (on transverse scans posterior to the left lobe of the thyroid) due to the appearance of a second interface, referred to as a “double airway tract” in the esophagus, or by gently moving the tube up and down.

The diaphragm and lung movements, which are qualitative and quantitative signs that the lungs are properly ventilated, can be directly and easily documented by US [16]. If the movements of the diaphragm are symmetrical on both sides, and intercostal US scan shows the presence of bilateral lung sliding synchronous with the ventilation, it can be inferred that the endotracheal tube is correctly placed in the trachea [17, 18]. In cases of esophageal intubation, assisted ventilation is not followed by lung expansion, but the diaphragm movements may follow the patient's spontaneous breathing if it has not been pharmacologically suppressed. On the other hand, if the patient is in apnea with the endotracheal tube in the esophagus, the diaphragm remains immobile or makes paradox movements, i.e., toward the rib cage, due to increased intra-abdominal pressure caused by progressive insufflation of the stomach through the endotracheal tube. The absence of lung sliding may be associated with the presence of lung pulse in the non-ventilated side, i.e., a vertical pleural movement perpendicular to the probe, synchronous with the cardiac systoles, whose energy is transmitted to the pleura from the non-ventilated lung [19].

Needle cricothyroidotomy

Needle cricothyroidotomy is a procedure which provides a temporary secure airway. It is performed particularly in prehospital emergency care in cases where it is impossible to practice emergency endotracheal intubation or other techniques to ensure airway patency. The cricothyroid membrane is identified in sagittal neck scans using a linear probe. The membrane appears as a thin hyperechoic stripe above the cricoid cartilage, which is hypoechoic and located in front of a mucosal air interface and multiple reverberation artifacts (Fig. 2). Correct identification of the cricothyroid membrane allows a fast and safe insertion of the needle in the appropriate location [20].

Chest and pleura, eFAST

Injuries to the chest are caused by road accidents in 70–80 % of cases and they are the leading cause of about

Fig. 2 US-guided needle cricothyroidotomy. The *black arrow on the left* indicates the thyroid cartilage; the *black arrow on the right* indicates the cricoid cartilage. The *white arrow* indicates the cricothyroid membrane where the needle is inserted

20 % of injury deaths with a slight prevalence in elderly subjects, in whom the mortality is higher also in less severe chest injuries. The most frequent injuries to the chest and the internal organs are: (1) rib fracture, (2) pneumothorax, (3) lung contusion, (4) clavicle fracture, (5) cardiac injury (myocardial contusion and laceration), (6) sternal fracture, (7) scapular fracture, (8) hemothorax, (9) traumatic aortic injury, (10) flail chest [21].

The majority of these lesions are treated conservatively, as thoracotomy is indicated only in case of massive loss of air and blood, which is most frequently linked to penetrating trauma. At least four chest injuries are immediately life threatening and must be identified and treated in primary survey (7): hypertensive pneumothorax, massive hemothorax, cardiac tamponade and flail chest. Extended-FAST (eFAST) is an acronym coined in 2004 [22] to include not only a rapid evaluation of the abdomen and pericardium for the presence of free fluid, but also of the chest for a fast exclusion of pneumothorax. For years, US imaging of the lungs was thought to be impossible because the US beams are attenuated by the air contained in the lungs. However, in the last two decades, the artifacts arising in the pleuropulmonary complex due to reflection of the US beams in the air–water interface have attracted considerable interest [23]. Today it is believed that the interpretation of these artifacts can provide substantial information about the condition of the underlying pleural space and the lung.

Fig. 3 *Left* subcutaneous emphysema. Just below the skin surface the US beams are scattered in all directions and are prevented from penetrating deeper into the ribs. *Right* normal US appearance, the pleural line is visible under the ribs

US imaging of the chest and the pleura, scanning techniques

The thoracic cage is made up of bones (dorsal vertebrae, scapula, sternum, clavicle, ribs) and muscles (paravertebral, intercostal, diaphragm) which support the skeleton and involve it in the respiratory dynamics. The bones reflect the US beams thereby blocking the view of the underlying structures, with the exception of the ribs which may not completely block the view thanks to their small size and to the ability of modern US imaging to use the crossed-beam method. Also in this case a preliminary panoramic view using a convex probe may be helpful, whereas a linear probe is required to clarify possible doubts or better interpret some findings.

The probe is positioned longitudinally on the chest wall perpendicular to the direction of the ribs which are identified by the characteristic posterior shadow. On the plane about 5 mm below two contiguous ribs, there is a thin hyperechoic line, i.e., an artifact corresponding to the interface between the parietal and visceral pleura, known as the “pleural line”. The two contiguous ribs and the underlying pleural line form a point of reference, referred to as the “bat wing” configuration [24]. This configuration makes it possible to identify with certainty the pleural line and distinguish between an air-filled lung and subcutaneous emphysema, which has a similar appearance but without the characteristic rib shadows (Fig. 3).

A healthy lung displays a to-and-fro movement at the pleural line which is synchronized with respiration. This movement is called “sliding” [25] and it is caused by the movement of the mobile visceral pleura along the static parietal pleura. It is not always visible, especially in the anterior portion of the chest and the apices. To observe the

Fig. 4 “Seashore sign” in a normal lung

movement, the use of the M-mode is helpful. In the presence of lung sliding, the M-mode will construct an image composed of a series of parallel lines overlying the pleural line corresponding to the layers of the chest wall which are not moving. A homogeneous grainy pattern will appear below the pleural line, generated by the pleura in constant motion showing the appearance of a sandy beach, referred to as the “seashore sign” (Fig. 4) [26]. The image of lung sliding may be exaggerated at power Doppler, which is more sensitive to movement than color Doppler, as there is power Doppler signal also from a slight movement but no signal when the pleura is immobile (“Power slide”) [27]. Below the pleural line, other echoic lines are visible parallel to the pleural line, separated from each other by a gap of the same size as the gap that separates them from the pleural line. They are caused by reverberation artifacts and are called “A-lines”.

Fig. 5 “Stratosphere sign”

Fig. 6 “Lung point”: in the *middle* of the image, an abrupt change is visible in the “background” of the lung: the *left side* is gray, and on the *right* the hyper-reflective pleural line and several A-lines are visible. This is the point where the parenchyma of the ventilated lung is attached to the pleura in inspiration; there is no lung sliding due to pneumothorax

Pneumothorax

In a trauma patient placed in the supine position, the air trapped in the pleural space causing pneumothorax is generally located in the antideclive pleural space, i.e., anteriorly [28]. When pneumothorax is suspected, the first location to evaluate is, therefore, where the patient should be treated with needle decompression, i.e., at the second space between the ribs on the right hemiclavear line. An important sign of pneumothorax is absence of lung sliding while the M-mode shows a series of parallel lines above and below the pleural line, referred to as the “stratosphere sign” [24] (Fig. 5).

Using the absence of lung sliding as a sign of pneumothorax, sensitivity is 80–98 % and specificity 91–99 % [25, 29–32]. If pneumothorax is suspected, all the chest

Table 1 Diagnostic techniques in pneumothorax

	eFAST vs CS ^a (%)	eFAST vs CT (%)	Plain film X-ray vs CT (%)
Sensitivity	58.9	48.8	20.9
Specificity	99.1	98.7	99.6
PPV	91.6	87.5	90.9
NPV	93.8	90.9	86.7
Accuracy	93.6	90.6	93.9

^a Composite standard, i.e., leakage or aspiration of intrapleural air at the time of drainage or identification of pneumothorax on plain film X-ray or CT (33)

should be scanned to define size and extension of the pneumothorax, particularly the lateral extension, in search of the point where the normal lung pattern shifts to pneumothorax pattern (absence of sliding), referred to as the “lung point”. The sliding does not appear during exhalation; during inspiration, the lung expands and the visceral pleura of the ventilated lung moves toward the parietal pleura under the probe so that the sliding is seen again (Fig. 6).

The “lung point” finding is diagnostic of pneumothorax with a sensitivity of 66 % and a specificity of 100 % [26]. The “lung point” can be visualized also using the M-mode, which shows the shifting from “seashore sign” to “stratosphere sign” and vice versa.

It is obvious that the role of US in pneumothorax is mainly to rule out some disorders, except in cases where the “lung point” is identified. Table 1 shows the results of an interesting study that has compared the diagnostic accuracy of the different techniques used in the diagnosis of pneumothorax [33] (Table 1).

The most common pitfalls in US imaging of pneumothorax are: bilateral pneumothorax, as this means that the US operator cannot compare the pattern of the normal lung to that of the affected lung [22], false positive outcome due to pre-existing bullous emphysema and false negative outcome due to failure to complete the examination. Diffuse subcutaneous emphysema makes it impossible to identify the pleural line, and US imaging, therefore, becomes ineffective. However, this is of little importance in the diagnosis and management of patients with severe trauma, as subcutaneous emphysema is actually already diagnostic of post-traumatic pneumothorax [34].

Hemothorax

The most common cause of massive hemothorax is bleeding from an injured intercostal artery, but in hemodynamically unstable patients the cause may also be injury to the heart, lung or great vessels. The base of the lungs and

the diaphragm can be evaluated simultaneously with the upper abdomen using the same probe. In a trauma patient placed in the supine position, pleural effusion can be identified using longitudinal scans searching in the dependent region of the chest outlined by the posterior chest wall and inferiorly by the diaphragm. The sensitivity of US is higher than that of standard radiography and specificity is similar [35]. The presence of massive hemothorax can be confirmed by specific pattern recognition or by M-mode depiction of the respiratory variation in the contours of the intrapleural fluid collection, referred to as the “sinusoid sign” (Fig. 7) [36]. The fluid collection appears hypoechoic and homogeneous and is visible during inspiration and expiration. As the pleural effusion acts as an acoustic window, the lung may be seen as a hyperechoic pleural line if it is ventilated, or as a “parenchymatous” pattern in case of atelectasis. US imaging of the lung is useful for measuring the amount of pleural fluid, and several methods are proposed in the literature. One is measurement of the interpleural distance at the base of the lung, defined as the distance between the lung and the posterior chest wall; the distance is measured with the patient in the supine position at the end of inspiration and at the end of exhalation. A distance of ≥ 50 mm is highly predictive of a quantity of liquid ≥ 500 ml, but some authors agree that these measurements are not accurate enough for small (≤ 500 ml) or very large ($\geq 1,000$ ml) fluid collections [37, 38]. A sufficiently accurate estimate of the amount of pleural fluid can be done using the simplified formula $V(\text{ml}) = 20 \times \text{Sep}(\text{mm})$. “Sep” is the maximum distance

between the parietal and the visceral pleura at the end of inspiration. It is measured with the patient in the supine position by moving the probe from the diaphragm upward along the posterior axillary line to design a cross-section perpendicular to the longitudinal axis of the body from the base of the lung, where the separation between the two pleurae is visible. In this study, a significant correlation was found between “Sep” and the amount of pleural fluid evacuated at thoracentesis with a success rate of 100 % and a mean prediction error of 158.4 ± 160.6 ml [39].

US can distinguish between transudates (anechoic) and exudates (echoic and loculated) and is also increasingly used to guide bedside thoracentesis and thoracostomy. US furthermore permits identification of possible adhesions thereby providing the possibility to increase the effectiveness of drainage and to reduce the risk linked to insertion of chest tubes into the intrafissural or intraparenchymal space.

Pulmonary contusion

In case of trauma, pulmonary contusion usually occurs due to the direct impact force on the lung or to a backlash effect within the lung parenchyma. Histologically, an initial hemorrhage is succeeded by edema of the interstitial spaces (2–3 h after the trauma) and by early infiltration of monocytes and neutrophils as well as invasion of the air spaces by proteins, red blood cells and a massive accumulation of inflammatory cells, while fibrin and loss of normal lung structure progress along with the increasing edema (24 h after the trauma) [40].

About 7–10 days after the trauma, the lung appears to be completely healed with small residual scars. US appearance of pulmonary contusion is that of an “interstitial syndrome” or localized pulmonary consolidation depending on the location and dynamics of the injury without delimitation of the lobes (Fig. 8). The interstitial syndrome is defined by the presence of multiple pleural and pulmonary artifacts referred to as “B-lines”. An interesting hypothesis is that B-lines are generated in a ventilated lung by the air–water interface in the air-filled alveolar spaces, whose geometry is modified because of the thickening or distortion of interstitial septa [23]. B-lines arise from the pleura extending to the bottom of the field of view without dissolving; they move synchronously with the sliding lung. Pulmonary consolidation appears as a subpleural area which is hypoechoic or presenting a “parenchymatous” echotexture. Unlike B-lines, this image is generated by lung tissue containing little or no air, as the air spaces are totally obstructed by cells and proteins. US imaging of pulmonary contusion has certain limitations linked to the location of the lesions (only peripheral lesions and those extending to the pleura are visible), concomitant absence of pneumothorax, subcutaneous emphysema or other physical obstacles such as bone structures and certain

Fig. 7 Left intercostal view of the pleural cavity. M-mode set at a slow shutter speed: from top to bottom: layers of the chest wall, an anechoic area about 3 cm high (pleural effusion), an isoechoic band with a dual wavy margin about 2 cm high (atelectasis due to pleural effusion: the “sinusoid sign”), another anechoic band under the lung (pleural effusion). The posterior profile of this second area is wavy, showing the movements of the diaphragm

Fig. 8 *Left* left side view of the back of a patient with chest trauma using a multi frequency linear probe. Under the ribs, a pleuropulmonary complex is visible, characterized by (a) slight pleural effusion, (b) thick and irregular hyperechoic pleural artifact, (c) several B-lines; the background of the lung is white (pulmonary contusion). *Right* view of the left hemiclavicular line. The pleural line is thin and hyperechoic with lung sliding; the background of the lung appears finely dotted and presents clearly visible A-lines (normal lung)

medications [41]. The presence of interstitial syndrome is suggestive of pulmonary contusion with a sensitivity, specificity, positive predictive value (PPV) and negative predictive value (NPV) of US imaging of 94.6, 96.1, 94.6 and 96.1 %, respectively, while diagnostic accuracy is 95.4 %. The presence of lung consolidation is suggestive of pulmonary contusion with a sensitivity and NPV of 18.9 and 63 %, respectively, while diagnostic accuracy is 65.9 % and specificity and PPV rise to 100 % [42]. In the normal lung, a few B-lines are usually visible, but the number increases in all conditions involving enlarged interlobular septa, such as acute pulmonary edema, acute respiratory distress syndrome, pulmonary contusion, infectious pneumonia and aspiration pneumonia [43–45]. B-lines are, therefore, not specific findings of particular diseases; they are often associated with other suggestive US patterns [46] involving also pleural artifacts and must be correlated to clinical signs and symptoms. In pulmonary contusion, the lesions are typically located at the impact site and characterized by lung sliding associated with interstitial syndrome and/or subpleural hypoechoic areas with irregular or ill-defined margins without air bronchogram (consolidation) [41, 42]. As the B-lines originate from the parenchymal surface of the lung, their presence in the field of view of the probe suggests juxtaposition of the two pleural layers thereby excluding pneumothorax with a NPV close to 100 % [44].

Heart and pericardium

Cardiac lesions are more common in penetrating trauma than in blunt trauma. Severe injury to the heart involves

bleeding and rapid death. A patient with cardiac trauma may be alive on arrival at the hospital and present with an apparently stable cardiac injury. However, if the injury is severe, it may rapidly become unstable unless recognized and treated promptly. The most common sign is pericardial effusion that may progress rapidly in case of cardiac tamponade. The sensitivity of FAST in the diagnosis of cardiac injury is about 100 % with a specificity of 97–99 %. FAST has thus an undisputed diagnostic value in this type of trauma. Scans of the pericardium can differentiate cases of pulseless electrical activity (PEA) from cases with residual electrical activity.

Abdomen and peritoneum, FAST

Focused assessment with sonography for trauma (FAST) [4] involves US imaging focused entirely on the identification of intraperitoneal and intrapericardial free fluid, and it is the main surrogate indicator of free fluid secondary to trauma. FAST is the examination of choice in many trauma centers, as it provides a rapid and effective trauma triage as well as a binary response (yes/no) to the question: is there free fluid in the cavity? The incidence of abdominal trauma and the consequent risks are very high in patients with injury severity score (ISS) >15. In patients with abnormally low blood pressure or hemodynamic instability, US imaging can help physicians to decide whether the patient should immediately be transferred to the operating room or if he/she should undergo further diagnostic investigation. In 2004, FAST was included in the ATLS procedure where it replaced diagnostic peritoneal lavage in the diagnostic

work up of trauma patients. According to the study published by Ollerton et al. [47], FAST has modified assessment of trauma patients in 33 % of cases.

FAST

The parietal peritoneum lines the abdominal cavity from the diaphragm to the pelvis forming the peritoneal folds (ligaments, mesenteries, omentum), and it covers most of the intra-abdominal organs (visceral peritoneum). In this way, abdominal compartments, spaces and peritoneal recesses are delimited. Some organs such as liver, spleen and stomach are completely covered with visceral peritoneum, while spaces and recesses—such as the supra- and submesocolic spaces, the omental bursa and the foramen of Winslow, Morison's pouch or the pouch of Douglas—creep between ligaments and between hollow viscera and organs. The peritoneal fluid is found in the abdominal cavity where it follows particular flow directions depending on the abdominal compartments, gravity and suction occurring when the diaphragm moves during respiration.

In the trauma patient, peritoneal free fluid is an indirect sign of acute bleeding and injury to the viscera or solid organs, until proven otherwise [48], and this is the main objective of FAST. The depth resolution of the US beams must be at least 20 cm to assess the abdomen, and a 3.5–5 MHz convex probe should, therefore, be preferred. However, sector or micro-convex probes seem to be more versatile, because they provide a better view of the heart and seem to make better use of the acoustic window of the intercostal spaces in the study of the base of the lung and the hypochondriac regions. Hemoperitoneum generally appears anechoic; it is visible in the sloped surfaces of the peritoneal cavity and can be modified by US probe compression. Occasionally, hemoperitoneum may appear echoic, when the blood has coagulated or is collected near the source of the bleeding.

FAST scanning is carried out with the patient in the supine position and in the following order: (1) a transverse scan of the subxiphoid region to assess the pericardial sac, (2) longitudinal scans of the right upper quadrant to assess the right lobe of the liver, the right kidney and the hepatorenal recess or Morison's pouch which is filled with fluid when the patient is the supine position, (3) longitudinal scan of the left upper quadrant to assess the spleen, left kidney and the splenorenal space, (4) longitudinal and transverse scans of the suprapubic region to study the bladder and the space between the rectum and uterus (the pouch of Douglas) in females and the space between the bladder and rectum in males. In addition to these four standard scans, longitudinal right and left scans of the chest are easily acquired to exclude the presence of

pleural fluid. Also the paracolic gutters are easily assessed. If FAST is performed correctly by an experienced operator, it does usually not require more than 5 min. In trauma patients, free fluid is typically accumulated in Morison's pouch, the splenorenal fossa, the pouch of Douglas and the paracolic gutters and is found in 66, 56, 48 and 36 %, respectively [49]. In the literature, sensitivity of FAST in detecting free intraperitoneal fluid is 68–98 %. This great discrepancy of results probably occurred because the procedure was performed by US operators with different levels of experience and because the results were compared to different diagnostic standards, such as computed tomography (CT), laparotomy or clinical observation; however, a common finding is that the specificity of FAST is very high, about 86–100 % [50]. Visibility of free fluid at FAST mainly depends on the quantity of liquid and the distribution in relation to the particular anatomy of each patient, the presence of scars and/or adhesions and—last but not the least—on the conditions under which the examination is carried out and on the US operator's experience. Obese patients with accumulation of gas in the abdomen or the intestine and patients with paralytic ileus, which frequently occurs in case of fracture of the lumbar spine, are particularly difficult to study. When the patient is in the supine position, a minimum of 619 ml of free fluid (introduced for peritoneal lavage) is necessary to make it appear in Morison's pouch [51]. Smaller volumes of fluid tend to accumulate in the pelvis (where they can best be detected if the bladder is distended) or near the source of bleeding. In patients with liver injury, free fluid is usually visualized in Morison's pouch where US imaging—not CT—may identify a fluid collection caused by splenic laceration or isolated intestinal perforation. The splenic loggia is more difficult to assess correctly due to the presence of the left colic flexure, the stomach which is often not distended, the spleen located in the upper portion of the abdomen, the interference of the pleural “curtain” during inspiration and the adjacent rib shadows. In rare cases, the patients have fluid accumulation limited to the paracolic recesses which may be caused by isolated gastrointestinal injury. In 30–40 % of women of childbearing age, a fluid collection of more than 50 ml in the pouch of Douglas is physiological. In FAST, any amount of free fluid is generally considered a sign of internal injury. However, it is important to assess the quantity of fluid to correlate with the hemodynamic status of the patient. For this reason, scoring systems have been proposed to establish if the patient requires laparotomy. They correlate the amount of free fluid estimated at US with the amount of peritoneal fluid infused for diagnostic peritoneal lavage. A score of ≥ 3 provides a reasonably accurate indication that laparotomy is required [52, 53].

Fig. 9 The *right lobe* of a hyperechoic liver in a patient with abdominal trauma (pauci-symptomatic). The hypoechoic area with frayed margins is large with branches and no segmentation and is located near the vessels. The injury was initially diagnosed as lacerated liver, but this diagnosis was not confirmed by CT

During FAST also, the abdominal organs are visualized. The study of these organs is not the objective of FAST, but it is still possible to obtain information about their status and the possible location of the injury. However, it should be kept in mind that FAST and US imaging in general have a very limited role in the diagnosis of abdominal trauma; 26–34 % of patients with abdominal trauma have organ lesions which are not associated with free fluid, and about 25 % of these patients require laparotomy. Sensitivity of FAST in the diagnosis of organ lesions is 44–95 % but specificity is high (84–100 %). The discrepancy of results is linked to different study designs and the examined organ [50]. In blunt trauma, the injuries affect the abdominal organs in the following order of frequency: spleen, liver, small intestine and retroperitoneal space (kidneys, hematomas). As to the type of injury, the OIS classification (based on anatomic and topographic criteria established using CT) lists at least 5 traumatic injuries to the abdominal organs: (1) hematoma (subcapsular or intraparenchymal with or without active bleeding), (2) capsular laceration with or without vascular involvement, (3) ruptured hematoma, (4) complete destruction, (5) vascular shutdown [54].

US characterization of the lesions is less certain, as there is no specific US pattern which evidences the various internal injuries [55]. Hematomas usually appear hypoechoic, especially subcapsular hematomas, but intraparenchymal hematomas, such as ruptured hematomas, may initially appear hyperechoic or hypoechoic; however, this US pattern is seen mainly in the evolution of cysts. US appearance of intraparenchymal hematoma of the spleen is similar to that of pseudo-aneurysms, which can be detected

using color Doppler [56]. Some confounding factors, e.g., in hepatic steatosis or pre-existing focal lesions, may generate false positive results (Fig. 9). Sensitivity of contrast enhanced US in solid organ lesions is higher than that of gray-scale US and similar to that of CT [57].

IVC and IVC collapsibility index

Several studies have shown that inclusion of inferior vena cava (IVC) assessment in the US examination of trauma patients may be useful to obtain more information about some hemodynamic aspects [58–61]. The caliber of the IVC and variations during breathing are in a constant fixed relationship with the right atrial pressure and/or the patient's volume status. The IVC can be visualized using cardiac sector probes and abdominal probes in a longitudinal subxiphoid view; it is visible posterior to the liver at the mouth of the hepatic veins before it pierces the diaphragm to open into the right atrium. Maximum and minimum diameter of the IVC should be measured in the proximal segment about 2 cm from the opening into the right atrium. US can be performed in B-mode or in M-mode. In a patient presenting with normal hemodynamic values and spontaneous ventilation, the IVC collapses only slightly in inspiration. The opposite occurs in patients receiving mechanical ventilation, as the diameter of the abdominal IVC increases during inspiration. The IVC collapsibility index is calculated as the difference between maximum and minimum diameter, divided by the maximum diameter (Table 2) [62]. If the IVC diameter (measured at the end of expiration) is <2 cm and the collapsibility index is higher than 40–50 %, the right atrial pressure is low (<10 mmHg) suggesting that the patient may be hypovolemic. On the contrary, if the diameter is >2 cm and the collapsibility index is <40–50 %, the right atrial pressure is high (>10 mmHg) suggesting that the patient may not be hypovolemic (Fig. 10). These US findings must be compared to other findings and should not be considered as definitive measures of the right atrial pressure or intravascular volume, since there is little evidence in the literature supporting these measurements in critically ill patients. Changes in IVC diameter may be linked to a chronic pulmonary heart disease or to previous

Table 2 Measurement of the inferior vena cava (IVC) diameter and right atrial pressure (62)

Maximum expiratory IVC diameter (cm)	Collapsibility index % $100 \times (\text{max. diameter} - \text{min. diameter}) / \text{max. diameter}$	Estimated right atrial pressure (mmHg)
<2	>40–50	<10
>2	<40–50	>10

Fig. 10 Collapsibility index of the inferior vena cava (IVC). The diameter is measured at the end of inspiration and at the end of exhalation. Expiratory diameter is 2.04 cm; using the formula $100 \times (\text{maximum diameter} - \text{minimum diameter} / \text{maximum diameter})$ collapsibility index is about 30 %

pulmonary embolism. Changes in the IVC diameter furthermore correlate with changes in intrathoracic and intra-abdominal pressure. The IVC diameter and collapsibility index must, therefore, be evaluated together with other data related to the heart volume, dimensions of the ventricles, heart wall motion and presence or absence of pericardial fluid.

Post-traumatic intracranial lesion, the optic nerve

In severe cranial trauma, early recognition of intracranial hemorrhage is crucial as it is associated with increasing intracranial pressure which requires surgical treatment. Monitoring of increased intracranial pressure is indicated in patients with Glasgow coma scale score (GCS) <8 and abnormal CT scan. Nevertheless, in patients with multiple trauma, diagnosis of traumatic brain injury requiring immediate surgery and monitoring of intracranial pressure may be severely delayed. Identification of a rapid method for the detection of high intracranial pressure is, therefore, desirable. Increased intracranial pressure can be rapidly assessed through examination of the optic nerve sheath diameter (ONSD), as the optic nerve sheath is anatomically continuous with the dura mater through which cerebrospinal fluid percolates. As a result intracranial pressure changes are transmitted through the subarachnoid space to the optic nerve [63]. Several studies have shown that ONSD correlates with the intracranial blood pressure measurements [64, 65] and the technique has now been standardized [66]. The patient is studied in the supine

position; a layer of gel is applied over the closed eyelid and a high-frequency linear probe is gently positioned on the temporal area of the eyelid to visualize the entry of the optic nerve into the globe. Two measurements are made for each optic nerve, one in the sagittal plane and one in the transverse plane by rotating the probe 90°. To obtain maximum contrast resolution, a point of reference is chosen 3 mm behind the globe, as this is the most distensible part of the nerve sheath and the one which is most likely to lead to the most reproducible results [67]. Reference ranges are >5 mm in adults, 4–5 mm in children 1–15 years old and 4 mm in very young children [68].

However, the method seems to present some limitations: there is no complete agreement in the literature on the reference ranges, and there is furthermore some doubt about the anatomical correlation between the structure currently identified at US imaging as ONSD and the actual ONSD [69]. ONSD assessment is a promising technique for the early assessment of intracranial pressure in patients with unstable multiple trauma, as it is non-invasive and carried out using readily available equipment; however, further confirmation of its effectiveness is probably required. According to some authors, of all the FAST assessments, ONSD assessment seems to be the one that requires the highest level of practice and experience [6].

Conclusions

US imaging aimed at detecting free fluid in the serous cavities of the trauma patient is the most studied example of clinically “focused” US. Despite the large number of studies published on the subject, no one has demonstrated that FAST improves survival rate in trauma patients. There is a great methodological heterogeneity among these studies and there is no study designed to evidence the small proportion of trauma patients who benefit without a shadow of a doubt from a rapid diagnosis of abdominal bleeding. Inspired by FAST, US imaging has been used in different ways in trauma patients and also in many other disorders encountered in emergency medicine and urgent care settings. The current view is that every aspect of a patient arriving in critical condition can be addressed and dealt with using US imaging combined with clinical evaluation. US imaging is thus considered as an extension of physical examination to implement a more effective approach to clinical problems and increase the timeliness and safety of interventions.

Some US imaging applications are supported by well-designed cohort or case-control analytic studies and important publications, whereas others such as ONSD assessment in post-traumatic intracranial pressure require additional evidence. Some applications, such as US-guided

procedures (only alluded to briefly in this review) are of obvious interest but they would require a separate discussion due to the complexity of the subject. CT and MRI provide more information and a better image quality, but these examinations must often be requested and performed elsewhere, sometimes involving transport which may impair the patient's condition.

US imaging is a safe procedure, which allows the physician to “see” beyond the skin and draw simple but fundamental conclusions at the bedside. The challenge faced by US imaging is to stay focused on identifying new and better procedures to improve decision-making and thereby avoid unnecessary delays thanks to early detection of life-threatening conditions in trauma patients.

Conflict of interest Dr. Soccora Sofia declares that she has no conflict of interest related to this paper.

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