Ultrasound in Intensive Care Unit: What to Ask, What to Expect

3

Manlio Prosperi, Maxim Neganov, and Andrea De Gasperi

3.1 Introduction

The treatment of the ICU patient ("critically ill" by definition) has witnessed in the last three decades a continuous improvement, both for the expanding of knowledge and the availability/development of a wide range of rapidly evolving technologies. This led the ICU provider to deepen and master several areas previously considered to be of exclusive competence of other specialists (cardiologist, radiologist, surgeons, etc.). Where dedicated resources and specific expertise exist, they represent a high added value: in order to be effective, the approach of individual specialists to the critically ill patient must be focused and coordinated. Aided by well-defined protocols, the multidisciplinary of the ICU physician has as main goal the treatment of the failing organs, the most consistent tract of the critically ill patient; together with urgent treatments, the steady "everyday clinical pursuit" is added and consists of diagnosing, treating, and monitoring the evolution of the ongoing illness. Fields of application of ultrasounds (US) are extremely wide when treating the critically ill: this is one of the reasons intensive care treatment deserves subspecialists with different skills to guarantee the quality of care. The use of POCUS is one of the areas in rapid, continuous development over the past few years: initially used and implemented to assess the respiratory system, it has been introduced into the daily clinical practice for the perioperative assessment of the hemodynamic profile and for a fine-tuning of the invasive maneuvers, both in and outside intensive care units. The POCUS is in some sense the physician's phonendoscope of the third millennium. The further development of training programs stems from the need to have advanced expertise in different specialistic areas, such as the initial approach of the major trauma patient, the neuro-cardiac or general surgical patients, the complex

M. Prosperi • M. Neganov • A. De Gasperi (✉)
2° Servizio Anestesia e Rianimazione, ASST Ospedale Niguarda Ca Granda, Milan, Italy
e-mail: andrea.degasperi@ospedaleniguarda.it

D. Chiumello (ed.), *Practical Trends in Anesthesia and Intensive Care 2017*,
http://doi.org/10.1007/978-3-319-61325-3_3

medical patients, and the solid organ-transplanted patients. The benefit of the point-of-care examination is evident, for example, in the decision-making algorithms of the dyspneic patients while managing hemodynamic instability in the acute patient in the prehospital setting, in the emergency department, or in medical or surgical wards. However, the initial stabilization of the critically ill and the treatment of the progressive multi-organ failure development proceed as a continuum during the entire ICU stay, US being one of the best tools to guide into differential diagnosis algorithms and to help in defining the severity of organ(s) failure. Examples of US applications (among many others) in acute care both in ED and in the ICU (but also in the wards) are optic nerve measurements and transcranial Doppler (central nervous system); A, B, and C lung profiles and diaphragm mobility/width (chest and pulmonary medicine); transthoracic echocardiography (TTE) for both heart and large vessel assessment; evaluation of renal function and causes of renal failure (mechanical causes and measurement of intraparenchymal renal resistances); and hepatic assessment (parenchymal and vascularization: echo Doppler of hepatic artery, portal vein, suprahepatic veins). The FAST (Focused Assessment Sonography for Trauma) and CA-FAST (Chest Abdominal-Focused Assessment Sonography for Trauma) [1] exams provide the evaluation of intra-abdominal collections in abdominal spaces (such as hepatorenal, splenorenal, and Douglas spaces), relevant for abdominal screening in case of perforation or acalculous cholecystitis, together with an evaluation of intestinal peristalsis. Finally, the examination also includes the evaluation of the compressibility of the femoral vein axes in case of suspected deep venous thrombosis (CUS).

One of the first protocols used to create a systematic screening in the dyspneic patient was proposed by Lichtenstein along with the basic principles of pulmonary ultrasound: the BLUE (Bedside Lung Ultrasound Evaluation) protocol [2] is a fast, focused protocol (3 min evaluation) when performed with appropriate devices and standardized points of analysis scan. It has six different profiles with a step-by-step approach, and, considering pathophysiological aspects, it helps in the diagnosis of most pulmonary pathologies encountered in the emergency room.

If the large variety of ED and ICU applications are of the utmost importance, even more relevant is the definition of the relationship between these domains and the level of the required training. Ultrasound in the ICU may in some cases have a high specificity and a reduced sensitivity, and since this involves some risk, the diagnostic test should always be integrated with all the available clinical data. A key aspect of the problem is therefore to standardize the degree of expertise and the training needed to gain basic and advanced competences. There are many coding levels which allow a correct way of operating while reducing the chance of errors/misinterpretation: for example, in case of the US examination, the American Heart Association in agreement with the American Cardiology Association provides 12-h training classes to achieve a basic skill level in detecting pericardial effusion, severe left and right ventricular dysfunction, regional dysfunction in case of severe coronary syndrome, broad evaluation of valvular apparatus defects, and vena cava collapsibility related to the respiratory activity. In the same line, WINFOCUS [3] provides certified training pathways for ICU providers, combining expertise and levels of recommendations in the ICU diagnostics. These levels of recommendation have recently been endorsed by the Critical Care Medicine Society, which has issued recommendations (1A-1B-1C-2A-2B-2C) to define guidelines for the use of US in the ICU, both for general US examination [4] and for echocardiographic evaluation [5]. The shift from evidence to recommendation came not only from the level of evidence but also from the judgment of a large group of experts, who focused on the ultrasound use by intensivists looking at a broad spectrum of skills (such as the brain, chest, lung, heart, abdomen) rather than by single-field specialists, taking into consideration all the possible bias. Therefore, 1C is a strong recommendation, although the quality of evidence is poor (C); on the contrary, 2A, while having a lesser degree of recommendation (2), is supported by high-quality evidence (A) (see Tables 3.1 and 3.2).

Table 3.1 Summary of recommendation of US in critically ill patient [4]

General ultrasound in ICU	Overall grade
Diagnosis of pleural effusion (ruling in)	1A
Guidance of small pleural effusion drainage	1-B
Diagnosis of pneumothorax	1-A
Interstitial and parenchymal lung pathology	2-B
Ascites (nontrauma setting)	2-B
Acalculous cholecystitis (by intensivist)	2-B
Renal failure (mechanical causes)	2-C
DVT by intensivist	1-B
Central venous access general	1-A
Access location internal jugular	1-A

Table 3.2 Recommendation for the use of echocardiographic examination in critical patient [5]

Echocardiographic examination in ICU	Overall grade
Preload responsiveness, ventilated	1-B
Sepsis resuscitation	1-C
Left ventricle systolic function	1-C
Diastolic function	2-C
Acute cor pulmonale	1-C
Pulmonary hypertension	1-B
Right ventricle infarction	1-C
Pulseless electrical activity	2-C
Symptomatic pulmonary embolism	1-C
Ventricular tachycardia/fibrillation	1-B/C
Acute coronary syndrome	1-C
Cardiac tamponade	1-B
Valvular dysfunction	1-C
Native/prosthetic valve endocarditis	2-B/1-C

3.2 Pulmonary Ultrasound

A systematic pulmonary ultrasound approach is recommended as a primary procedure in patients with respiratory failure (1B). However, this approach also belongs to the daily assessment of pulmonary disease, to assist and guide invasive procedures related to the respiratory tract and finally for the integration of clinical data during ventilation and respiratory weaning process, including the estimation of diaphragm dynamic function [6, 7]. Pulmonary ultrasound is largely based on the analysis of artifacts that are generated by the interaction of air and water in the pulmonary parenchyma [2, 6, 7]. All the profiles of artifacts originate from the pleural line: pneumothorax and interstitial syndrome appear more evident in upper and anterior fields, while pulmonary effusions and consolidations are best detected at the lower and posterior areas in supine position. The involvement of the pulmonary surface by the vast majority of acute diseases allows a correlation between the artifacts and the pulmonary alteration by using the US. In fact, only lesions reaching the pleural line can be detected by lung ultrasound.

3.3 Pulmonary Ultrasound Examination

Pulmonary examination is performed on a patient in the supine position by a longitudinal scanning of four lung zones with a convex or microconvex probe for deeper structures or linear probe for superficial structures (pleura and ribs):

L1: second, third, and fourth anterior intercostal space
L2: fifth and eighth anterior intercostal space
L3: fourth and tenth mid axillary intercostal space
L4: posterior chest wall (mainly for US-guided thoracentesis)

The image outlining the longitudinal scan B-mode is the first sign, *bat sign*, where the wings indicate the rib's shadow cones. The pleural line is hyperechoic and located in the middle of the image below the two adjacent ribs, whose sliding interface of the visceral over the parietal *layer gives origin* to the underlying movement and allows the vision of the "lung sliding." Through the M-mode examination, the sliding sign is depicted as the *seashore sign* where the upper (still) and lower portions (created by lung inflation/deflation) of the screen are divided by the pleural line itself (Fig. 3.1).

3.4 Nomenclature of Pulmonary Artifacts

The *A line* is repetitive, horizontal artifact originating from the pleural reverberation. This is a transversal hyperechoic line in the intercostal space, placed 1 or half centimeter below the outer surface of the ribs, the so-called

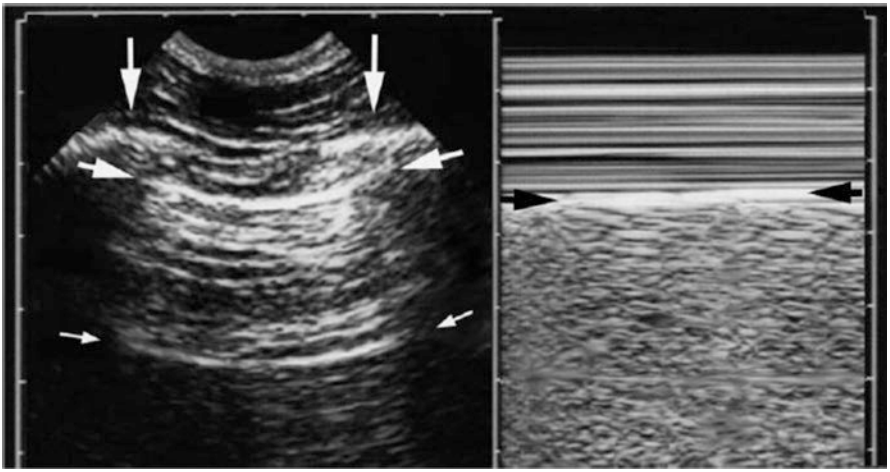

Fig. 3.1 Normal lung surface. (*Left*) Scan of the intercostal space. The ribs (*vertical arrows*). Rib shadows are displayed below. The pleural line (*upper, horizontal arrows*), a horizontal hyperechoic line, half a centimeter below the rib line in adults. The proportions are the same in neonates. The association of ribs and pleural line make a solid landmark called the bat sign. The pleural line indicates the parietal pleura in all cases. Below the pleural line, this horizontal repetition artifact of the pleural line has been called the A line (*lower, small horizontal arrows*). The A line indicates that air (gas more precisely) is the component visible below pleural line. (*Right*) M-mode reveals the seashore sign, which indicates that the lung moves at the chest wall. The seashore sign therefore indicates that the pleural line also is the visceral pleura. Above the pleural line, the motionless chest wall displays a stratified pattern. Below the pleural line, dynamics of lung sliding show this sandy pattern. Note that both images are strictly aligned, of importance in critical settings. Both images, i.e., lung sliding plus A lines, make the A-profile (when found at the anterior chest wall). The given basic information on the level of capacity pressure

pleural line (this is the physical site of the tissue-air interface, represented by the parietal and visceral pleura in touch).

The *B lines* are *comet tail*-like vertical artifacts originating from the pleural line; they are long, hyperechoic, well defined, and dynamic; they delete lines A at the intersection. Comet-tail artifacts are due to multiple reflections of the beam between an object and its surroundings when there is a marked difference in acoustic impedance. Small water-rich structures surrounded by air are at the origin of these artifacts. They could be found, as an example, in the case of aerated lung with abnormally thickened interlobular septa and extravascular water. Detection of multiple and diffuse vertical artifact B lines in lung ultrasound is usually associated with a diagnosis of radiological and clinical alveolar-interstitial syndrome. It has to be underlined that B lines can also be seen in the latero-basal scans in close to 25% of the patients with normal lungs. The *Z lines* are longitudinal artifacts and originate from the subcutaneous tissue.

3.5 Definition of Lung Profiles According to the BLUE Protocol [2]

The *A-profile* associates anterior lung sliding with bilateral A lines.
The *A′-profile* is an A-profile with abolished lung sliding.
The *B-profile* associates anterior lung sliding with bilateral B lines.
The *B′-profile* is a B-profile with abolished lung sliding.
The *A/B profile* is a half A-profile at one lung, a half B-profile at another.
The *C-profile* indicates anterior lung consolidation (a thickened, irregular pleural line is an equivalent).
The *PLAPS-profile* indicates posterolateral alveolar and/or pleural syndrome.

3.6 Syndromes Visualized on Lung Ultrasound

Pleural disease: effusion, hemothorax, and pneumothorax
Interstitial syndrome: mono or bilateral
Lung consolidation: pneumonia, atelectasis due to hypoventilation, atelectasis due to extrinsic compression, atelectasis related to endoluminal obstruction, abscess, pulmonary thromboembolism

3.7 Pneumothorax

The ultrasound features of pneumothorax are the following: the absence of lung sliding, absence of B lines, absence of pulmonary pulse, presence of lung consolidation, lung point and stratosphere sign (M-mode)

Sensitivity and specificity are 79–100% for pneumothorax not visible at thoracic X-ray and 96–100% with a complete pneumothorax: a pneumothorax may rule out in the presence of lung sliding and B lines, but in the absence of such signs, it can be confirmed only by the presence of a “lung point” which is the respirophasic re-appearing of the lung in touch with the chest wall in the lung region explored (Fig. 3.2).

The absence of sliding with M-mode appears as aligned dots next to the other on the time scale, hence straight lines, such as the representation of the pre-pleural tissues. This M-mode appearance has been named as *stratosphere sign*.

3.8 B Profile: Interstitial Syndrome

Echographic signs: multiple B lines (anterior B line + sliding).

Positive B line: the B lines can be counted ideally by defining the percentage of the hyperechogenic field and dividing it by ten (Fig. 3.3).

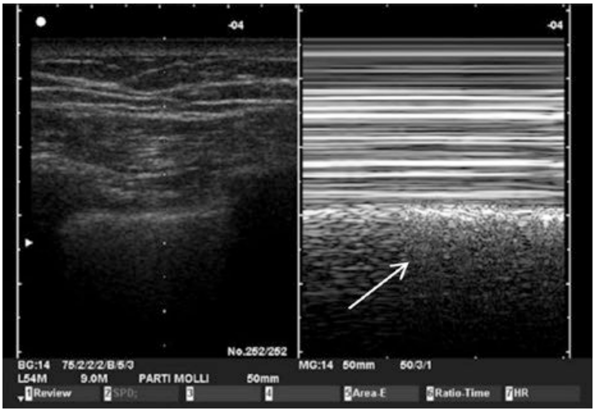

Fig. 3.2 Lung point (abrupt shore appearance of ventilated lung)

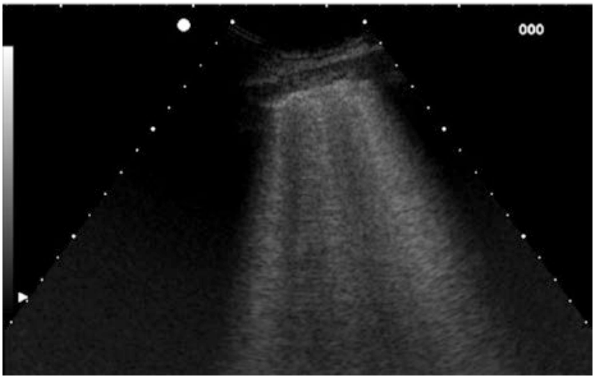

Fig. 3.3 B lines

3.9 Characteristics of Pulmonary Consolidation

The main signs of consolidation are the well-defined superficial boundaries and subpleural echo-poor region or one with tissue-like echotexture. Additional signs in the static and dynamic images of a consolidation include bronchogram, thickening and irregularity of the pleural line, the presence of *shred sign* (irregular deep boundaries), vascular features, lung pulse, and associated effusion.

The *air bronchogram* is represented by light branching bands within pulmonary densities; the bronchogram is *dynamic* if air inside such ramifications is displaced by respiratory acts; on the contrary, if there is no motion related to respiratory movements, the air bronchogram is defined as *static*. The bronchogram is instead *fluid* if the bronchial branching contains liquid which is hypoechoic. The *shred sign* is a static sonographic sign observed in lung consolidation. The deeper border of consolidated lung tissue that makes contact with the aerated lung is "shredded" and irregular. There is no effusion inside. This sign is not seen in massive translobar consolidation where it is more difficult to appreciate the deeper border of the lung.

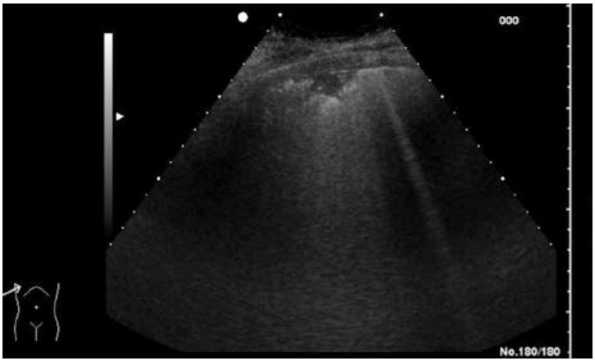

Fig. 3.4 Shred sign

The vascular features within the pulmonary parenchyma may exhibit a mediastinal ipsilateral retraction.

The lung pulse is the evidence of cardiac activity on the pleural line when the compliance is low or the lung is not/poorly ventilated.

Atelectasis may have different echogenicity characteristics depending on their origin and nature: flogistic consolidation, extrinsic compression, bronchial obstruction, bronchial exclusion, and hypoventilation.

The *lung pulse* is an indirect sign of complete atelectasis, observed in bronchial obstruction and selective intubation. Among the patients with pulmonary consolidation with an air bronchogram, a dynamic bronchogram may indicate the presence of pneumonia (differential diagnosis with an atelectasis). A static bronchogram is instead observed in many cases of atelectasis related to absorption and in one third of pneumonia's cases. This finding increases the understanding of the physiopathology of pulmonary disease within a given clinical condition, addressing to bronchoscopy procedure for a bronchoalveolar lavage or to remove bronchial obstruction. Flogistic subpleural consolidation has generally well-defined, thick, and irregular pleural margins, a poor echogenic structure beneath the pleural line, and a presence of *shred sign* (Fig. 3.4). The air bronchogram is dynamic and sometimes may have fluid characteristics; there are no vascular abnormalities. In case of differential diagnosis between pneumonia and atelectasis, a dynamic bronchogram has sensitivity of 61% and a specificity of 94%. Onset of subpleural or lobar consolidation and dynamic arborescent linear air bronchogram is a reliable tool to detect early VAP in the ventilated patient, positive predictive value being 94% [8].

3.10 Pleural Effusion

The ultrasound examination is strongly recommended (1A) to diagnose and locate a pleural effusion (84% sensitivity and 100% specificity). The accuracy is also high, quantifying and qualitatively defining the fluid present in the pleural cavity. The US-assisted/-guided drainage procedure of pleural effusion is recommended (1B); in addition, significant reduction of complications (failure to drain large amounts of

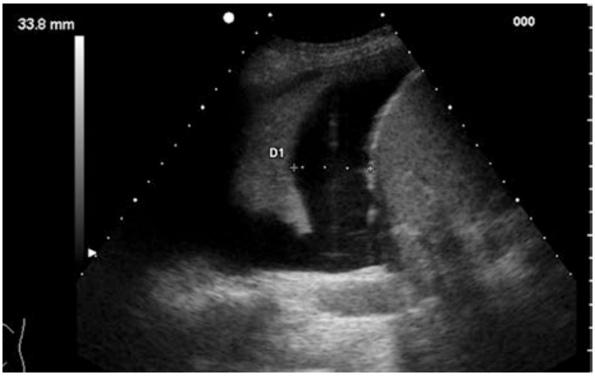

Fig. 3.5 Pleural effusion

fluid or causing a pneumothorax) has been observed, compared to blind techniques. It should be noted that in cases of surgery-related increased intra-abdominal pressure, compartmental syndrome or dynamic/mechanical ileus, the hemi-diaphragms can be very high and that the phrenic nerve lesions can alter the localization of a pleural effusion (Fig. 3.5).

3.11 Pulmonary Embolism

Nazarian [9] conducted a prospective study including 357 patients with suspected pulmonary embolism (Wells score 4) using multi-organ ultrasound examination (the heart, lungs, and lower limbs). Compared with CT angiography, it resulted in sensitivity and specificity of 90 and 86%, respectively. Right ventricular size, filling, and function compared to left should always be looked in the presence of hemodynamic instability if a thromboembolic disease is suspected: CUS positivity will confirm diagnosis.

3.12 Diaphragm and Respiratory Weaning

Weaning from mechanical ventilation is a complex process involving on the one hand evaluation of pulmonary parenchyma, pleura and diaphragm, and volemic status and cardiac performance on the other [10–12]. The assessment of a diaphragmatic dysfunction is a contributing factor to the success of respiratory weaning among the ventilated patient in intensive care unit. It can be altered in case of neuromuscular diseases, phrenic nerve paralysis, after abdominal and cardiothoracic surgery, and in patients with prolonged periods of mechanical ventilation; the ultrasound assessment of diaphragm, together with the above described other elements, is a wise and efficient way of monitoring the weaning process of the critically ill in the ICU [13] (Fig. 3.6).

Di Nino [14] conducted a clinical trial among 63 patients during respiratory weaning with pressure support ventilation or spontaneous breathing. He found a

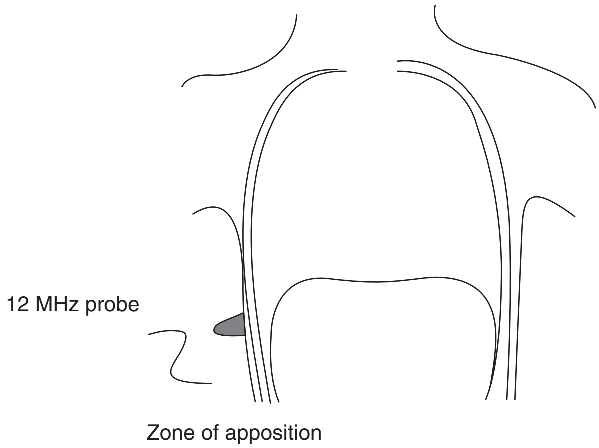

Fig. 3.6 The study of diaphragmatic function (from Matamis D)

sensitivity and specificity of 88% and 71%, respectively, for successful extubation within 48 h when a 30% of diaphragm thickness modification was documented. Evaluation of diaphragmatic excursion can be performed during spontaneous respiratory activity, with noninvasive or invasive ventilation with pressure support, using a high-resolution linear probe placed in the tenth intercostal space, over anterior or mid-axillary lines. The US probe should be directed perpendicularly to the diaphragm, usually finding the area of interest ca. 5–20 mm below the costophrenic recess. The lower edge of the costophrenic recess is identified at the end expiration at the transition zone between the appearances of the *curtain sign*, given by lung caudal displacement during the following inspiration, preventing the visualization of the diaphragm and the liver (or spleen) because of the lung air content. Diaphragmatic thickness can be observed and measured in M-mode. Normal values, measured at residual functional capacity volumes, can range from 1.8 to 3 mm, with an average thickening of 54% (42–78%), when forced vital capacity is reached. Diaphragmatic function can also be evaluated by measuring the diaphragmatic excursion through a subcostal window, applying a convex probe directed toward the diaphragmatic dome always in *time-motion mode* [15]. During the respiratory weaning phase with pressure support ventilation, Kim [16] suggested a cutoff value of 18 ± 3 mm for weaning trial and 7.8 cm during forced exhalation.

3.13 Airway Management

There are several aspects that should be considered while managing the airway using US (linear probe 7–11 MHz) [17]:

1. Preliminary evaluation of the anterior region of the neck for pharyngeal and laryngeal abnormalities and in case of an obese patient, control of the adipose tissue located anteriorly to the trachea (its quantification might be predictive of difficult intubation).

2. Determination of the transverse width of the trachea, because of its relationship with the size of the double-lumen tube: 18 mm for 41 Fr tube, 16 mm for 39 Fr, 15 mm for 37 Fr, and 14 mm for 35 Fr [18].
3. Check of the tracheal tube position by looking for lung sliding and diaphragmatic movement (pulmonary expansion) or lung pulse detection, which is associated with a not collapsed, not ventilated lung (main stem intubation).

3.14 Percutaneous Tracheotomy

The ultrasound evaluation of the anterolateral neck region may precisely detect thyroid, cricoid, and tracheal rings by a very quick longitudinal scan using a linear probe. These findings may be very useful during preliminary evaluation of the percutaneous tracheotomy in the ICU. First step of this examination includes the evaluation of blood vessels and flow in the anterior region of the neck to detect and rule out any abnormalities about arterial or venous anatomy [19], which may result in immediate or post-procedural bleeding complications. The second part, using the same probe performing a transversal scan, has the main goal of evaluating the precise position of the tracheal rings, their centrality, and the transverse tracheal diameter at subglottic level (Fig. 3.7).

Once tracheal position and size of the thyroid lobes and the isthmus are identified, the physician proceeds marking the site of the puncture for subsequent guide wire insertion (as an alternative, the puncture could be US guided). Concomitant fiberoptical vision confirms the correct positioning of the guide wire before the passage of the cannula [20, 21].

3.15 Echocardiographic Diagnostics in Intensive Care

The transthoracic echocardiogram (TTE) of the patient with cardiovascular instability [22–24] has a 1B degree of recommendation and depends on the operator skill. This examination should not be confined to cardiothoracic ICUs, where this technique is normally implemented together with transesophageal echocardiography (TEE). The latter offers better image quality compared to the TTE, particularly of

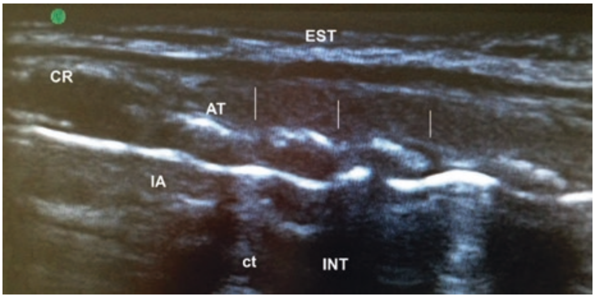

Fig. 3.7 Ultrasound image of the trachea. *CR* cricoid, *AT* tracheal rings, *IA* air interface, *CT* artifacts "comet tail," *white arrows*: tracheal spaces

the posterior structures, such as the pulmonary veins, the left atrium, the mitral valve, and otherwise non-visible structures during the TTE such as the aortic isthmus.

3.16 Fluid Responsiveness

Very often preload static parameters such as central venous pressure (CVP), wedge pressure, and ventricular volumes do not predict fluid responsiveness, and this is because every patient might actually have his own Frank-Starling response, which depends on heart contractility, venous return, and afterload. Furthermore, right atrial (RA) pressure is related to venous return, which in turn depends on venous capacitance gradient. Cyclic changes of ventricular filling induced by increased intra-thoracic pressure variations and heart-lung interaction during mechanically ventilation lead to delta-up and delta-down variations of stroke volume and IVC size. Fluid responder is usually defined the patient whose stroke volume increases by 10–15% following a 3 mL/kg (usually 250 mL) crystalloid or colloid fluid bolus [25]. According to some, close to half of the fluid challenges in ICU could be useless if not, in some cases, even harmful. The correct B-mode measurement of IVC must be performed 1–2 cm from its junction with the RA in a patient well adapted to the ventilation (tidal volume 6–8 mL/kg); mechanically ventilated patients with positive end-expiratory pressure in which the distensibility of the inferior vena cava (IVC) during the inspiratory phase is greater than 12% compared to the expiratory phase can be considered fluid responders (grade 1B). There are no rigid recommendations about the fluid responsiveness based on IVC collapse measurement during spontaneous ventilation or intra-abdominal compartment syndrome. Nevertheless, during spontaneous ventilation, an IVC diameter of less than 10 mm indicates fluid tolerance, while in case of mechanically ventilated patients, there is a poor correlation between IVC diameter and CVP. Passive leg-raising technique may be performed both during mechanical and spontaneous ventilation; it transiently increases venous return, allowing the physician with advanced echocardiographic training to predict the fluid responsiveness through the visualization of 10% increase in stroke volume or simply VTI (velocity time integral). In the presence of small hyperdynamic ventricles with critical variation of IVC size, hypovolemia has always to be considered and a fluid challenge warranted. Among hypotensive conditions in which hypovolemia has to be immediately ruled out, worth to be mentioned is the dynamic obstruction of left ventricular outflow tract, usually associated with hypertrophic cardiomyopathy and associated with the systolic anterior movement (SAM) of the mitral valve (Table 3.3). Pressors or inotropes in such a setting would be deleterious, volume optimization being instead even lifesaving.

3.17 Septic Shock

The evaluation of left ventricular contractility in patients with pre-existing or ICU-acquired vascular and heart abnormalities improves volume management and inotrope or pressor administration (1C). The association between systolic and diastolic

Table 3.3 Echocardiographic fluid response (FR) prediction

Dynamic parameter	Signs and values	FR prediction	Considered variable and pitfalls
Left ventricular size (PSA*x*)	LV area <10 cm2	+/–	Hypertrophy, inotropic drugs, vasodilatation
	Kissing wall		
LV size variation	>16%	+	Detection on beat to beat during ventilation cycle
Dynamic outflow tract obstruction	Systolic narrowing of outflow tract	+	Hypovolemia accentuates obstruction specially in hypertrophic obstructive cardiomyopathy (SAM)
Mitral valve (MV) flow	Pattern E/A	+/–	Diastolic dysfunction
Stroke volume variation (AV)	>12%	+	Arrhythmia, spontaneous respiratory efforts
			TV >8 mL/kg, compartment syndrome
IVC size	<10 mm	+	Low correlation with RAP in ventilated points
IVC diameter variation	>12% (>18% DI)	+	distensibility index DI
RV	Increased size	+	High negative predictive value
	Paradoxical septal motion		
Passive leg raising	SV o VTI >10%	+	Can be used in spontaneous breathing or arrhythmic points

dysfunction and septic shock is very high and can reach 50% according to some authors, particularly in case of Gram-negative bacterial infection. Moreover, left ventricular outflow dynamic tract obstruction can be observed during hypovolemic status if (inappropriately) treated with catecholamine infusion (hyperdynamic state of the septic shock). Chauvet et al. demonstrated a mechanical outflow tract obstruction together with a small, hyperdynamic, and pseudohypertrophic left ventricle in 22% of patients admitted to the ICU with a diagnosis of septic shock [26]. The use of echocardiography is supported by 2C quality of evidence during the vasoactive therapy and in the diagnosis of specific medical conditions, such as the Takotsubo syndrome, characterized by dilation and apical dyskinesia with a preserved function of the remaining cardiac segments.

Clinical studies demonstrate that up to 23% of the ICU patients have pure diastolic dysfunction, while 40% have variable systolic and diastolic dysfunction. Diastolic function assessment requires advanced training: nevertheless, a global heart dysfunction should be sought in patients with unstable hemodynamic status. Diastolic function is influenced by many variables (among them age, respiratory rate, heart rate, and P-R interval), along with non-diastolic physiological factors (e.g., preload, blood flow, systolic function of the left ventricle and contractile function of the left atrium); however, in the presence of normal contractility and size and thickness of the left ventricle's walls, diastolic function can be estimated using the E/A ratio, the ratio of peak velocity flow in early diastole (the E wave) to peak velocity flow in late diastole caused by atrial contraction (the A wave) [27].

3.18 Cor Pulmonale

In certain clinical conditions, the signs of the right ventricular dysfunction due to the pressure or fluid overload should be sought (1C). The acute cor pulmonale is caused by a sharp increase in the afterload of the right ventricle with a consequent flattening and paradoxical septal movement, diastolic dysfunction, and increased RV/LV diameter ratio (>0.6). Estimation of pulmonary artery systolic pressure (PASP) could add to the interpretation of the origin of the dysfunction (myocardial or valvular causes) (1B). Tricuspid annular plane excursion (TAPSE) measurement has low prognostic utility without any level of recommendations. In case of hemodynamic instability associated with suspected pulmonary embolism, the functional assessment of the right ventricle (1C) should be followed by lower extremities compression ultrasonography (CUS), if deep venous thrombosis is suspected, before considering angiographic CT, even if the former test results are negative. If myocardial infarction is suspected, an estimation of the telediastolic volumes, the contractility of both ventricles, and the abnormal movement of the interatrial septum toward left atrium can be obtained through the subcostal short-axis US approach (1C).

Clinical conditions such as ARDS and VILI require careful evaluation of the hemodynamic status and right ventricular function, which might be reduced in 20–25% of patients. Increased right ventricular strain is proportional to the increase in lung resistance, which in turn is conditioned by the mean airway pressure. Simultaneously, mechanical ventilation interacts with the patient's hemodynamic status since pleural pressure affects venous return and transpulmonary pressure interacts with right ventricular filling. Usually, the ratio between the right and left ventricle area at the end of the diastole should be less than 0.6; a value between 0.6 and 1 indicates a moderate dilation of the right ventricle, which becomes severe for values greater than 1. Although transthoracic examination is limited due to the high pulmonary expansion and a narrow ultrasound window of the four-chamber view, it is still useful in a decision-making algorithm for hemodynamic control and protective ventilation; assessment can take place, where possible, through TEE examination or by using a subdiaphragmatic approach [28].

3.19 Deep Venous Thrombosis

Among the major concerns of intensivists are venous thrombosis and pulmonary embolism. Many are the factors able to promote these conditions: sedation, muscle paralysis, indwelling intravascular devices, major surgery, and malignancies. Since a consistent part of the pulmonary emboli originates from the common femoral and popliteal veins, the initial approach to the patient with suspected pulmonary embolism starts with ultrasound evaluation of the lower district. Using high-frequency linear probe (5–10 MHz), intensivists have a powerful tool for a high-sensitivity and high-specificity diagnosis; there are two main techniques, which can be used alone or combined for a more accurate diagnosis. The first one is the compression ultrasound (CUS), which uses B-mode to obtain a cross-sectional visualization of the vessel. The detection of the vessel is followed by an external gentle compression by the probe, which normally should lead to the collapse of the vein, being minimal the deformation of the artery. Inability to compress the veins and the presence of echogenic intravascular material are the diagnostic signs of deep venous thrombosis [29]. The second technique is Duplex and combines CUS with pulse wave Doppler imaging.

3.20 Cardiopulmonary Resuscitation

American Heart Association (AHA) Advanced Cardiac Life Support (ACLS) and the European Resuscitation Council (ERC) and International Liaison Committee on Resuscitation (ILCOR) guidelines clearly emphasize to seek and treat any potentially reversible causes of cardiac arrest during the resuscitation manoeuvers. Recently updated ERC guidelines introduce cardiac US as a potential tool for detection of these conditions [30]. Considering that the diagnostic procedure and the intervention must yield quick results with minimal impact on CPR maneuvers and minimal impact on no flow intervals, ALS-conformed echocardiography could have an important role in this scenario. The use of focused ultrasound became widely used in emergency setting both in prehospital and hospital setting, leading to the development of various echocardiographic protocols. Among them, focused echocardiography evaluation in life support (FEEL) algorithm is a quick ten-step/four-phase approach, which may help intensivists during CPR [31]. Using subcostal window, which provides a better cardiac visualization during resuscitation, the FEEL algorithm enables to distinguish between pseudo-PEA (pulseless electrical activity) and true-PEA, influencing the actual management of the patient. Of the utmost importance is to underline that FEEL must not delay for any reason CPR and should not take more than ten seconds. Although there are no precise indications for timing of cardiac US, it is usually performed immediately after the ECG analysis and at the end of CPR cycle [32].

Cardiac US may be additionally applied following the return of spontaneous circulation (ROSC) after ventricular tachycardia/fibrillation resolution. The echocardiographic examination allows the detection of segmental hypokinesia and a possible ischemic origin of the cardiac event (1B), thus allowing to anticipate the possible indication of an early revascularization procedure [5].

Several studies have examined the use of ultrasound during cardiac arrest to detect potentially reversible causes. Although no documentation exists able to document improved outcomes using cardiac US, there is no doubt that echocardiography has the potential to detect reversible causes of cardiac arrest. The integration of ultrasound into ALS algorithm requires considerable training in order to limit a minimum the interruption of chest wall compressions.

3.21 Acute Myocardial Infarction

In case of cardiogenic shock, the TTE as point of care helps to save time when acute myocardial infarction is suspected, allowing visualization of segmental kinesis, ventricular function, transient mitral dysfunction, and papillary muscle rupture and, in the case of inferior myocardial infarction, to exclude the right ventricular involvement.

3.22 Pericardial Effusion and Cardiac Tamponade

The classical clinical picture of Beck's triad (hypotension, jugular distension, and soft or absent heart sounds) is not always present during cardiac tamponade. Echocardiography can help intensivist not only to diagnose this condition but also to guide pericardiocentesis. The pericardial effusion is considered minor if the separation between parietal and visceral pericardium is <0.5 cm, moderate if the width is >0.5, but <2 cm and large if >2 cm; moreover, its hemodynamic impact is related not only on the amount of pericardial fluid accumulation but specifically on the speed of fluid accumulation. A parasternal approach helps to differentiate between pericardial effusion and left pleural effusion, the latter being localized posteriorly to the descending aorta, the former anterior to it. Cardiac tamponade is characterized by systolic collapse of right atrium, right ventricle diastolic collapse, and a paradoxical respiratory modification of left and right ventricular filling, along with inferior vena cava distension. Using apical four-chamber view, there is a visible increase in right ventricle width during the inspiratory phase, with displacement of the septum toward the left ventricle in diastole and toward the right ventricular in systole. The patient with aortic dissection (90% of the cases at isthmus area, which is not detectable with the classic transthoracic echo) may develop pericardial effusion.

3.23 Valvular Dysfunction

Every patient with a newly diagnosed heart murmur at ICU admission should undergo an echocardiographic assessment to evaluate the presence of clinically significant valvular lesions, such as aortic stenosis and aortic or mitral insufficiency/regurgitation. A physician with a basic training is able to recognize clear vegetation in a high-risk patient (2C).

3.24 Renal Function and Resistive Index

The color-Doppler is also used to calculate the renal resistive index (RRI) at the level of interlobular arteries (normal RI <0.7). It measures the changes in blood flow velocity in the renal vessels and provides indirect information of renal blood flow and microcirculation. RRI is a semiquantitative parameter related to the sensitivity and Doppler settings (gain, PRF, filter, depth of field) and related to the loss of cortical diastolic flow and to the trend of RRI. Although a variation of this index relies upon a wide variety of extrarenal mechanisms, it could be considered in ICU as a predictor of persistent renal failure, thus well beyond the evaluation of the "simple" renal response to a fluid challenge. An increase in renal vasculature resistance is associated with a reduced renal perfusion, likely turning into an acute tubular necrosis. Feedback mechanisms, such as the renin-angiotensin system and endothelin secretion by the renal endothelium, are involved in the renal vascular regulatory mechanism. Renal perfusion pressure relies upon a delicate balance of mean arterial blood pressure, venous pressure, and intra-abdominal pressure; taken together (or in some cases also alone), these factors are able to play a relevant role in jeopardizing oxygen transport to high-energy structures (as sodium pumps of kidney tubule are). Experimental studies showed a linear relationship between intra-abdominal pressure and RI correlating IAP of 25 mmHg to RRI of 0.81 [33]. According to Darmon et al., a RRI value of 0.80 also represents the cutoff for a non-transient AKI in the critical patient [34]. Dewitte et al. reported, in patients with sepsis and non-transient renal failure (inability to recover a satisfactory excretory function within 3 days), higher renal resistances when compared to subjects with transient renal failure (0.76 vs 0.72). This figure did not show any clear relationship with norepinephrine dose. In a recent meta-analysis, Ninet et al. performed a systematic review on nine randomized clinical trials. In their conclusions RRI >0.80 was able to predict the persistence of acute renal failure in critically ill patients. Although the limit of this meta-analysis is the heterogeneity of the patients (clinical condition of shock, sepsis, extracorporeal circulation after cardiac surgery), it might help to understand the pathogenetic mechanisms of the renal injury in critically ill patients, and it should play an interesting role when monitoring the evolution of acute kidney injury [35]. Currently, there is no evidence-based recommendation for the RRI, mainly because of the paucity of experimental studies on homogeneous groups of patients. However, this index might prove to be of extreme interest while treating the oliguric phase of shock or during renal replacement therapy, giving a sort of "marker" of the kidney response to the acute injury and whether or not renal perfusion is "defended" by the treatment.

3.25 Ultrasound Evaluation of Muscle Function and Strength Wasting in Intensive Care Patient

Critical ill patients in the ICU are exposed to a gradual muscle wasting and loss of function due to various concomitant factors (bed rest without passive or active movements, poor nutritional status, now defined "sarcopenia" and medications); this process starts immediately and has its peak in the first 10 days. The ultrasound can be used to determine and monitor this condition through qualitative and quantitative evaluation of different muscle groups. Parry and Puthucheary demonstrated how the muscle volumetric assessment, measured using ultrasounds and including thickness and cross-sectional area of quadriceps and of vastus intermedius, can express the loss of strength and muscular function of the critical patients [36, 37].

Conclusions

Ultrasound in the ICU setting allows a fast, accurate, reproducible bedside examinations of most of the acute disorders encountered in the critically ill. As emphasized by many, but championed by Lichtenstein since the beginning, US enables a pathophysiological approach to a large part of the "failures" found in the critically ill, respiratory and circulatory dysfunctions being the most common. Visual medicine, made easy by the versatility of ultrasound, has to become a priority for the intensivist in the everyday clinical practice in and out the intensive care units.

Acknowledgments We would like to express our gratitude to Enrico Storti MD, who reviewed the manuscript and gave us appropriate and useful suggestions.

References

1. Zanobetti M, Coppa A, Nazerian P, Grifoni S, et al. Chest abdominal focused assessment sonography for trauma during the primary survey in the emergency department: the CA FAST protocol. Eur J Trauma Emerg Surg. 2015. PMID:26683569. doi:10.1007/s00068-015-0620-y.
2. Lichtenstein DA, Mezière GA. Relevance of lung ultrasound in the diagnosis of acute respiratory failure: the BLUE protocol. Chest. 2008;134(1):117–25.
3. Storti E, Neri L. Lung ultrasound in the ICU: from diagnostic instrument to respiratory monitoring tool. Minerva Anestesiol. 2012;78:1282–96.
4. Frankel HL. Guidelines for the appropriate use of bedside general and cardiac ultrasonography in the evaluation of critically ill patients—part I: general ultrasonography. Crit Care Med. 2015;43(11):2479–502.
5. Levitov A, Frankel HL. Guidelines for the appropriate use of bedside general and cardiac ultrasonography in the evaluation of critically ill patients—part II: cardiac ultrasonography. Crit Care Med. 2016;44(6):1206–27.
6. Nazerian P. Accuracy of lung ultrasound for the diagnosis of consolidations when compared to chest computed tomography. Am J Emerg Med. 2015;33:620–5.
7. Gallard E. Diagnostic performance of cardiopulmonary ultrasound performed by the emergency physician in the management of acute dyspnea. Am J Emerg Med. 2015;33:352–8.
8. Mongodi S, Via G, Girard M, Rouquette I, Misset B, Braschi A, Mojoli F, Bouhemad B. Lung ultrasound for early diagnosis of ventilator associated pneumonia. Chest. 2016;149(4):969–80.
9. Nazerian P. Accuracy of point-of-care multiorgan ultrasonography for the diagnosis of pulmonary embolism. Chest. 2014;145:950–7.
10. Zanforlin A. Lung ultrasound in the ICU: from diagnostic instrument to respiratory monitoring tool. Minerva Anestesiol. 2014;78:1282–96.
11. Goligher EC. Measuring diaphragm thickness with ultrasound in mechanically ventilated patients: feasibility, reproducibility and validity. Intensive Care Med. 2015;41:642–9.
12. Mayo P. Ultrasonography evaluation during the weaning process: the heart, the diaphragm, the pleura and the lung. Intensive Care Med. 2016;42(7):1107–17.
13. Vivier E, Mekontso Dessap A, Dimassi S, Vargas F, Lyazidi A, Thille AW, Brochard L. Diaphragm ultrasonography to estimate the work of breathing during non-invasive ventilation. Intensive Care Med. 2012;38:796–803.
14. DiNino E. Diaphragm ultrasound as a predictor of successful extubation from mechanical ventilation. Thorax. 2014;69(5):423–7.
15. Matamis D, Soilemezi E, Tsagourias M, Akoumianaki E, Dimassi S, Boroli F, Richard JCM, Brochard L. Sonographic evaluation of the diaphragm in critically ill patients. Technique and clinical applications. Intensive Care Med. 2013;39:801–10.
16. Kim W. Young Diaphragm dysfunction assessed by ultrasonography: influence on weaning from mechanical ventilation. Crit Care Med. 2011;39(12):2627–30.
17. Sustic A. Role of ultrasound in the airway management of critically ill patients. Crit Care Med. 2007;35(5 Suppl):S173–7.
18. Brodsky JB. The relationship between tracheal width and left bronchial width: implication for left-sided double-lumen tube selection. J Cardiothorac Vasc Anesth. 2001;15:216–7.
19. Sooby P. An anterior jugular vein variant in a patient requiring tracheostomy, demonstrating the importance of preoperative/procedural ultrasound. BMJ Case Rep. 2016;31:1757–90.
20. Dinh VA, Farshidpanah S, Lu S, Sokes P, Chrissian A, Shah H, Hecht D, Nguyen B. Real time sonographically guided percutaneous dilatational tracheostomy using a long axis approach compared to the landmark technique. J Ultrasound Med. 2014;33:1407–15.

21. Alansari M, Alotair H, Al Zohair Z, et al. Use of ultrasound guidance to improve the safety of percutaneous dilatational tracheostomy: a literature review. Crit Care. 2015;18:19–229.
22. Volpicelli G. Point-of-care multiorgan ultrasonography for the evaluation of undifferentiated hypotension in the emergency department. Intensive Care Med. 2013;39(7):1290–8.
23. Via G, Tavazzi G, Price G. Ten situations where inferior vena cava ultrasound may fail to accurately predict fluid responsiveness: a physiologically based point of view. Intensive Care Med. 2016;42:1164–7.
24. Via G. International evidence-based recommendations for focused cardiac ultrasound. J Am Soc Echocardiogr. 2014;27(7):683.e1–683.e33.
25. Miller A, Mandeville J. Predicting and measuring fluid responsiveness with echocardiography echo research and practice. Guidelines and recommendations. Echo Res Pract. 2016;3(2): G1–12.
26. Chauvet JL, et al. Early dynamic left intraventricular obstruction is associated with hypovolemia and high mortality in septic shock patients. Crit Care. 2015;19:262.
27. Otto CM. Textbook of clinical ecocardiography. 5th ed. Philadelphia: Elsevier; 2013.
28. Vieillard-Baron A. Experts' opinion on management of hemodynamics in ARDS patients: focus on the effects of mechanical ventilation. Intensive Care Med. 2016;42:739–49.
29. Di Bello C. Diagnosis of deep venous thrombosis by critical care physician using CUS. Open Crit Care Med J. 2009;3:43–7.
30. Monsieurs KG, Nolan JP. ERC Guidelines 2015. Resuscitation. 2015;95:1–80.
31. Breitkreutz R. Focused echocardiographic evaluation in resuscitation management: concept of an advanced life support-conformed algorithm. Crit Care Med. 2007;35(5 Suppl):S150–61.
32. Breitkreutz R, Price S, Steiger HV, et al. Focused echocardiographic evaluation in life support and peri-resuscitation of emergency patients: a prospective trial. Resuscitation. 2010;81: 1527–33.
33. Andrew W, Kirkpatrick K, Laupland B. The higher the abdominal pressure, the less the secretion of urine: another target disease for renal ultrasonography? Crit Care Med. 2007; 35(5 suppl):S206–7.
34. Darmon M, Schortgen F. Diagnostic accuracy of Doppler renal resistive index for reversibility of acute kidney injury in critically ill patients. Intensive Care Med. 2011;37:68–76.
35. Ninet S, Schnell D, Dewitte A, et al. Doppler-based renal resistive index for prediction of renal dysfunction reversibility: a systematic review and meta-analysis. J Crit Care. 2015;30(3): 629–35.
36. Parry SM. Ultrasonography in the intensive care setting can be used to detect changes in the quality and quantity of muscle and is related to muscle strength and function. J Crit Care. 2015;30(5):1151–4.
37. Puthucheary ZA. Qualitative ultrasound in acute critical illness muscle wasting. Crit Care Med. 2015;43(8):1603–11.