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Executive summary on the use of ultrasound in the critically ill: consensus report from the 3rd Course on Acute Care Ultrasound (CACU)

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Abstract

Over the past decades, ultrasound (US) has gained its place in the armamentarium of monitoring tools in the intensive care unit (ICU). Critical care ultrasonography (CCUS) is the combination of general CCUS (lung and pleural, abdominal, vascular) and CC echocardiography, allowing prompt assessment and diagnosis in combination with vascular access and therapeutic intervention. This review summarises the findings, challenges lessons from the 3rd Course on Acute Care Ultrasound (CACU) held in November 2015, Antwerp, Belgium. It covers the different modalities of CCUS; touching on the various aspects of training, clinical benefits and potential benefits. Despite the benefits of CCUS, numerous challenges remain, including the delivery of CCUS training to future intensivists. Some of these are discussed along with potential solutions from a number of national European professional societies. There is a need for an international agreed consensus on what modalities are necessary and how best to deliver training in CCUS.

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Key words: fluid therapy, ultrasound, CCUS, critical care ultrasound, POCUS, point-of-care ultrasound, training, transthoracic, transesophageal, abdominal, lung, vascular, resuscitation, monitoring, fluid responsiveness

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Over the past decades, ultrasound (US) has gained its place in the armamentarium of monitoring tools in the intensive care unit (ICU) [1]. A greater understanding of lung, heart, abdominal and vascular US and improved access to portable machines have revolutionised ICU care, with CCUS playing an important role in bedside examination, potentially becoming the stethoscope of the 21st century [1]. Critical care ultrasonography (CCUS) is the combination of general CCUS (lung and pleural, abdominal, vascular) and CC echocardiography, allowing prompt assessment and diagnosis in combination with vascular access and therapeutic intervention [2]. Although it has been practiced by enthusiasts for over 30 years, CCUS is a relatively young but increasingly widespread discipline. In this review, summarising the last Course on Acute Care Ultrasound (3rd CACU) held in Antwerp, Belgium on November 26th 2015, the usefulness and advantages of US in the critical care setting are discussed.

DELIVERING US TRAINING

BACKGROUND

The use of ultrasound has expanded beyond the realms of radiologists and into many areas of healthcare. Although championed by enthusiasts, the use of ultrasound in intensive care unit (ICU) has lagged behind that of other specialties, including emergency medicine. The lack of a uniform formal training structure and programme is a recurring issue across Europe and, indeed, worldwide. Even in countries with national programmes, there are significant variations within them. It thus poses crucial questions of whether scans have been appropriately performed and reported, and whether there exists proper clinical governance to ensure a high standard of care.

CHALLENGES

Two international expert statements have acknowledged the challenges of obtaining appropriate training in CCUS and have aimed to describe the components of competence in order that clinicians may have specific goals of training while they develop their skills [2–4]. Although the framework defines the minimal requirements, it is by no means rigid; each training organization can be adapted according to resources available. The statements acknowledge the various processes of certification, accreditation, or delivery of a diploma when validating the acquisition of competence. Currently, certification is only recommended for advanced CC echocardiography. For basic CC echocardiography, as well as for general ultrasonography, no formal certification/diploma is required although training has to be included in the curriculum of all intensivists.

Despite the lack of agreement regarding the minimum number of scans, duration of training and lack of appropriate trainers (accessibility), several key themes are consistent. Competency in ultrasound examination requires a combination of theoretical knowledge and practical skills. The delivery of theoretical knowledge can be in the form of online resources, via face-to-face lectures at courses, or a hybrid of the two.

As it is a practical skill, the initial learning requires direct, hands-on supervision by an expert, usually at courses or in the learner's own ICU. It is imperative that such mentored learning occurs using the appropriate patient mix and not just normal volunteers.

THE UK SOLUTION — CUSIC

The Intensive Care Society (UK) recently introduced the Core US Skills in Intensive Care (CUSIC) in order to provide a formal and robust training structure to attain these competencies. The programme ensures the highest level of competency-based training with clear learning objectives and outcomes defined from the onset for both the trainer and trainee.

The modules encompass the areas covered in the above international statements – focussed echocardiography, pleural/lung US, vascular and abdominal US, with a minimum number of scans defined for each module. The modular system allows for a degree of flexibility and ensures that a balance is achieved between service-provision and training/learning periods.

Each 3-month module comprises of 4 phases:

- PHASE 1: Initial **theoretical** and practical training
  - E-learning
  - Course
- PHASE 2: **Supervised** practice until competence demonstrated in acquiring and saving images
- PHASE 3: **Mentored** practice with completion of logbook demonstrating knowledge of an appropriate range of pathology
- PHASE 4: Completion of **competency assessments** within the range of practice

The various modules equip the intensivist with the skills to deal with the range of clinical situations he/she is likely to encounter. The trainee is expected to keep a logbook of the scans and procedures performed; a summary of the training record (Fig. 1) is reviewed by a board of experts before accreditation is awarded. Robust clinical governance policies are maintained through formalised working practice with all stakeholders, including radiology and cardiology departments. This requires a considerable degree of preparation prior to commencement of the programme.

THE DUTCH SOLUTION — ICARUS CONSOLIDATION

The Dutch Society for Intensive Care recently adopted the Intensive Care Ultrasound (ICARUS) consolidation program that was initially developed at VU University Medical

Appendix 2: Summary Training Record

Core Ultrasound Intensive Care: Summary of training record (for submission to ICS)		
Critical Care Core Ultrasound Training Record		
Trainee name		
GMC number		
Confirmation of trainin completed		
	Date	Signature
The,oretical training		
Log book of cases		
.-		
Competency assessments	Date	Signature
Lung ultrasound		
Vascular access		
Abdominal ultrasound		
Lung ultrasound triggered assessment		
Date of completion of training		
Mentor name		
Mentor sign off	Date	
Supervisor name		
Supervisor sign off	Dato	

Figure 1. Summary of training record for UK CUSIC programme (Intensive Care Society UK CUSIC Accreditation — http://www.ics.ac.uk/ics-homepage/accreditation-modules/cusic-accreditation/)

Centre Amsterdam (http://echografie.nvic.nl/). It is intended as a consolidation course for those intensivists that have already completed a basic-level introductory course in CCUS. Similar to the UK solution, ICARUS relies heavily on mentorship.

ICARUS starts with a one-day course in a participating hospital. One of the instructors is then appointed as a mentor. A selection of 30 full ICARUS scans is then uploaded to the mentor who provides feedback. The course also includes a half-day bedside session at a later date with the mentor and a formal exam that consists of theoretical questions, interpretation of archived US examinations and demonstration of US skills. Upon successful completion, intensivists receive ICARUS certification, issued by the society.

The UK and Dutch programmes described are by no means the only method and a comparison is shown in Table 1.

THE FRENCH SOLUTION

France started to train intensivists and anaesthesiologist more than 15 years ago [5]. In contrast with all other countries, France started to train the trainers and develop a two-year specific diploma, including basic practice with TTE and TEE. For years, more than 100 intensivists and anaesthesiologists were trained every year and acquired high competency in echocardiography in the ICU. More than 5 years ago, France developed a one-year diploma for those who would like to reach an advanced level including 100 hours of didactics, 100 TTE, 25–50 TEE and 20–25 ultrasound examinations for abdominal, transcranial and lung ultrasound. Today, a large majority of intensivists, anaesthesiologists and emergency doctors are trained and are able to include ultrasounds in their daily practice. Also in France (Paris), there exists the "Cercle des Echographistes d'Urgence et de Réanimation Francophones" (called CEURF), that organizes training courses on ultrasound devoted to the critically ill, focusing on lung ultrasound and the BLUE-protocol. It is therefore a lung-centred training programme which integrates the lung, deep veins, combined with a simplified approach of the heart, as a first-line tool. CEURF teaches the users how to make use of a more sophisticated following of the rules of holistic ultrasound, when needed.

THE EUROPEAN SOLUTION

Recently a consensus statement was published through the European Society of Intensive Care Medicine (ESICM) by a group of international experts on training standards

Table 1. Comparisons of UK, Dutch and American accreditation programme

	UK CUSIC accreditation	Dutch NVIC ICARUS consolidation accreditation	American College of Chest Physicians accreditation*
Duration (recommended)	1 year	3-9 months	3 years
Online course	Yes	No	Yes
Face-to-face course	Yes — 1	Yes — 2	Yes — 2
Online portfolio	No	No	Yes
Supervision/Mentor	Direct	Distant	Variable
Echocardiography	50 studies	30 studies	10 studies
Lung/Pleural	50 studies	30 studies	4 studies
Abdominal	20 studies	n/a	4 studies
Vascular	Vascular access	n/a	Doppler/DVT
Assessment	Yes — at end of each module	Yes — at completion of 30 exams	Yes — at completion of entire portfolio

*American College of Chest Physicians Critical Care Ultrasonography accreditation - http://www.chestnet.org/Education/Advanced-Clinical-Training/Certificate-of-Completion-Program/Critical-Care-Ultrasonography

for advanced CCUS [2]. The aim was to provide guidance to critical care physicians and students involved in advanced CCUS training and teaching. The consensus statement establishes specific requirements to guide instructors involved with the development of structured training programs defining different goals such as image acquisition, image interpretation, and the cognitive base. This can be adapted in the future by national authorities or critical care medicine societies to establish their own certification process or when preparing for international exams (e.g., European Diploma in Echocardiography Care, EDEC)

KEY MESSAGES

- Competency in CCUS requires a combination of theoretical and practical training
- A clearly defined syllabus and competencies are paramount to a successful training programme
- There is significant variation in CCUS training programmes across the world

HOW TO CONSOLIDATE US IN YOUR UNIT

BACKGROUND

Distinct from the use of US in specialties outside the ICU, CCUS strongly focuses on cardiopulmonary interaction and bedside assessment with the aim to rapidly diagnose and treat patients with the ability to monitor response to treatment in real-time [6]. Image interpretation in the ICU setting is a holistic process, integrating all other available patient data, including those from haemodynamic monitoring and patient-ventilator interaction.

CHALLENGES

A first challenge is the person of contact. Whilst the unique applications and nature of CCUS place it squarely within the ICU domain, most US trainers are in reality located in non-ICU specialties e.g. Cardiology and Radiology. Well-rounded training in CCUS is, therefore, likely to require collaboration with these specialties; specific contact persons in these departments provide a valuable source of support when interpreting complex or unusual images [1]. In an ideal world, regular CCUS multidisciplinary meetings discussing cases of interest will enhance the intensivist's ongoing learning and practice.

A second challenge lies in defining the limits. It also follows that practical boundaries must be clearly defined for an intensivist using CCUS. For example, in some institutions, it is agreed among specialties that CCUS focuses on point-of-care US of heart and lungs, including global assessment of left and right heart systolic function and chamber sizes, pericardial and pleural effusions, lung and pleural artefacts. This implies that intensivists will not draw conclusions on other visualised abnormalities e.g. valvular pathology. Clearly defining both the possibilities and limitations of practicing CCUS in written protocols helps one to avoid medico-legal and inter-professional conflict.

Finally, there is ongoing debate on the minimum training requirements. Given the non-uniformity of CCUS training nationally and internationally, a minimum training standard must be outlined before introducing CCUS in any ICU. Current consensus is that a minimum of 30 fully supervised CCUS examinations are needed for an acceptable safe level of practice. This is mainly based on expert opinion, with support from a few studies [6]. For governance and educational purposes, all images should be stored preferably using the hospital picture archiving and communication system (PACS) to ensure accessibility for all healthcare professionals involved in the patient's care, and to facilitate review and feedback.

Table 2. Normal values of measurements and calculations that can be obtained with TCD

Measurement	Calculation	Normal Values (ACM)
Peak Systolic Velocity (PSV)	–	85 cm s^{-1}
End-Diastolic Velocity (EDV)	–	40 cm s^{-1}
Mean Velocity (Vm) = Time Averaged Peak Velocity (TAPV)	(PSV – EDV)/3 + EDV	55–60 cm s^{-1}
Pulsatility Index (PI)	(PSV – EDV)/Vm	0.6–1.0
Lindegaard Index (LI)	Vm ACM/Vm ACI	1.5

Table 3. Overview of the pathological values obtained with TCD

Measurement		
Peak Systolic Velocity (PSV)		Duration < 200 ms: poor prognosis
End-Diastolic Velocity (EDV)	> 20 cm s^{-1}: good prognosis	< 20 cm s^{-1}: poor prognosis
Mean Velocity (Vm) = Time Averaged Peak Velocity (TAPV)	> 120 cm s^{-1}: moderate vasospasm	> 180 cm s^{-1}: severe vasospasm
Pulsatility Index (PI)	> 1.4: ICP > 15 mm Hg	> 2: ICP > 20 mm Hg
Lindegaard Index (LI)	< 3: hyperaemia	> 6: vasospasm

Vm ACI — Mean Velocity in the Internal Carotid Artery

KEY MESSAGES

- The lack of sufficiently qualified trainers has been identified as a potential barrier to widespread dissemination of CCUS
- There is an urgent need for professional societies to develop a unified, competency-based training programme Transcranial Doppler

INDICATIONS

Transcranial Doppler (TCD) can be very useful in a limited number of indications including the detection of vasospasm in the presence of a subarachnoid haemorrhage, cerebral perfusion pressure (CPP) and intracranial pressure (ICP) evaluation and the screening for brain death [7, 8].

ANATOMY AND WINDOWS

The most important vessels for TCD are the middle cerebral artery (MCA) and the anterior cerebral artery (ACA). At the level of the temporal bone, antegrade flow measures flow within the MCA; retrograde flow represents flow within the ACA.

PROBE, POSITION AND MEASUREMENTS

Tables 2 and 3? lists the normal values of measurements and calculations that can be obtained with TCD. The Vm (mean velocity) is proportional to cerebral blood flow (high flow giving high velocities) and inversely proportional to vessel diameter, with vascular spasms resulting in high velocities (Fig. 2). TCD is an early screening tool for the detection of vasospasm, a Vm greater than 120 cm s^{-1} indicates 'moderate vasospasm' while a Vm larger than 180 cm s^{-1} suggests 'severe vasospasm'. The Pulsatility Index (PI), used in conjunction with waveform morphology, is indicative of cerebrovascular resistance; the Lindegaard Index (LI) can further differentiate between vasospasm and hyperaemia. A LI < 3, indicates hyperaemia, where a LI > 6, indicates vasospasm.

Whilst TCD provides an inexpensive, non-invasive screening tool for vasospasm (sensitivity of 0.99 at the level of the MCA), it only has a specificity of 0.66. TCD is a screening tool for raised ICP and diminished CPP [9]. When the ICP increases, the Vm will decrease. A PI > 1.4 correlates with an ICP > 15 mm Hg and a decreased CPP [10]. Although the formula 10.93 × PI) — 1.28 has been suggested for ICP measurement, TCD remains more useful in the monitoring of ICP changes rather than providing an exact value [11, 12]. Likewise, while TCD can screen for brain death, it is not definitive due to the inability to scan the posterior circulation. Important limitations include inter-operator variability and inadequacy of acoustic windows in a proportion of adults.

KEY MESSAGES

- TCD is an inexpensive, non-invasive, bedside tool to assess the CNS but has limitations that the operator must be aware of.
- TCD allows one to assess not only the anatomy but also other parameters like the pulsatility index, the presence of vasospasm or an estimation of ICP

LUNG ULTRASOUND

BLUE-PROTOCOL

The clinical data are usually sufficient for a diagnosis of respiratory failure in most patients, although the BLUE-(Bed-

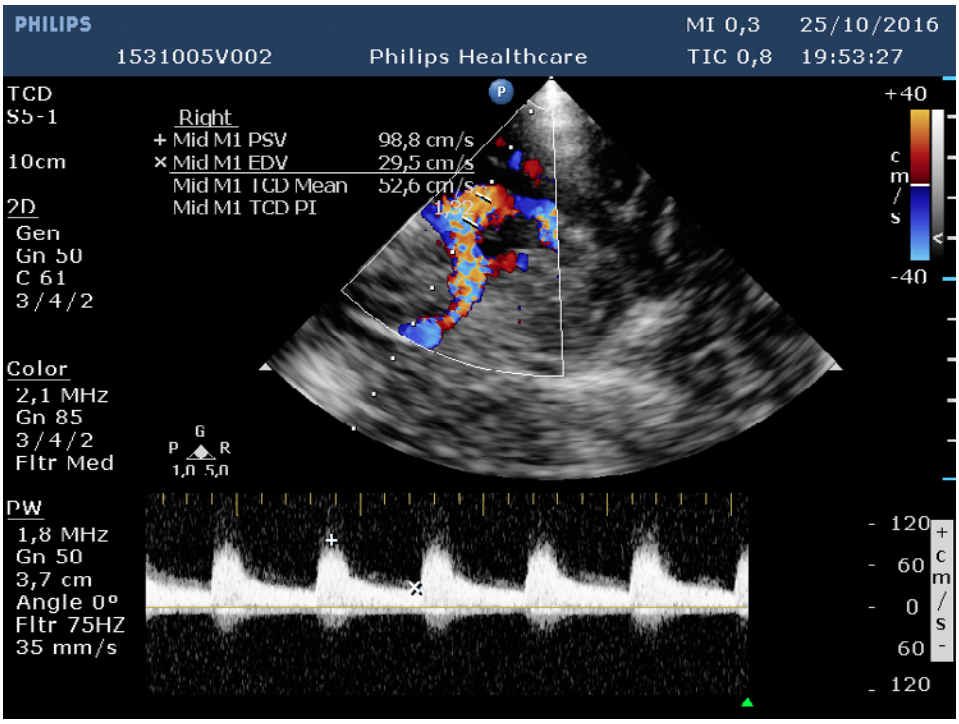


Figure 2. Transcranial Doppler image. The „+" indicates the Peak Systolic Velocity (PSV), while the „x" indicates the End Diastolic Velocity (EDV)

side Lung ultrasound in Emergency) protocol will help in difficult cases [1, 13]. The BLUE-protocol sequentially screens strategic areas (BLUE-points) and generates a profile based on the presence and characteristics of specific patterns/artefacts with an accuracy of > 90%. The BLUE-protocol is one application among many others, describing the clinical relevance of lung ultrasound in the critically ill, namely in the differential diagnosis of an acute respiratory failure with the identification of different signs: the bat sign (pleural line); lung sliding (seashore sign); the A-lines (horizontal artefact); the quad sign and sinusoid sign indicating pleural effusion; the fractal and lung sign indicating lung consolidation; the B-lines and lung rockets indicating interstitial syndromes, abolished lung sliding with the stratosphere sign suggesting pneumothorax; and the lung point indicating pneumothorax. Two more signs, the lung pulse and the dynamic air bronchogram are used to distinguish atelectasis from pneumonia.

With the BLUE-protocol one can identify 8 profiles by which it becomes possible to differentiate between 6 acute syndromes (Fig. 3) namely: pulmonary oedema; pulmonary embolism; pneumonia; chronic obstructive pulmonary disease; asthma; and pneumothorax, each showing specific US patterns and profiles.

KEY MESSAGES

- Lung ultrasound has a higher diagnostic sensitivity and specificity compared to plain chest radiographs
- The use of the BLUE protocol allows one to differentiate between distinct causes of respiratory failure: pulmonary oedema, pneumonia, pneumothorax, pulmonary embolism, chronic obstructive lung disease and asthma

CCUS DURING CIRCULATORY FAILURE

FALLS-PROTOCOL

The FALLS-protocol (Fluid Administration Limited by Lung Sonography) adapts the BLUE-protocol in acute circulatory failure, by combining basic CC echocardiography and lung US, with the appearance of B-lines considered the endpoint for fluid therapy [14, 15]. It is a decision tree used to sequentially search for obstructive, cardiogenic, hypovolaemic and distributive shock in the absence of an obvious clinical cause.

By firstly ruling out obstructive and cardiogenic causes, the remaining causes (hypovolaemic and distributive e.g. septic shock) usually require fluid therapy, which should lead to clinical improvement in hypovolaemic shock. Conversely, in distributive shock, the fluid will accumulate without clinical improvement, saturating the lung interstitial compartment, revealing a transformation from A-lines to B-lines (the FALLS-endpoint indicating clinically occult hypervolaemia) (Fig. 4). The FALLS-protocol aims to decrease the mortality of shock, mainly septic, by a prompt diagnosis. The main limitation here is that no study has been designed to prove the ability of such an approach to improve prognosis.

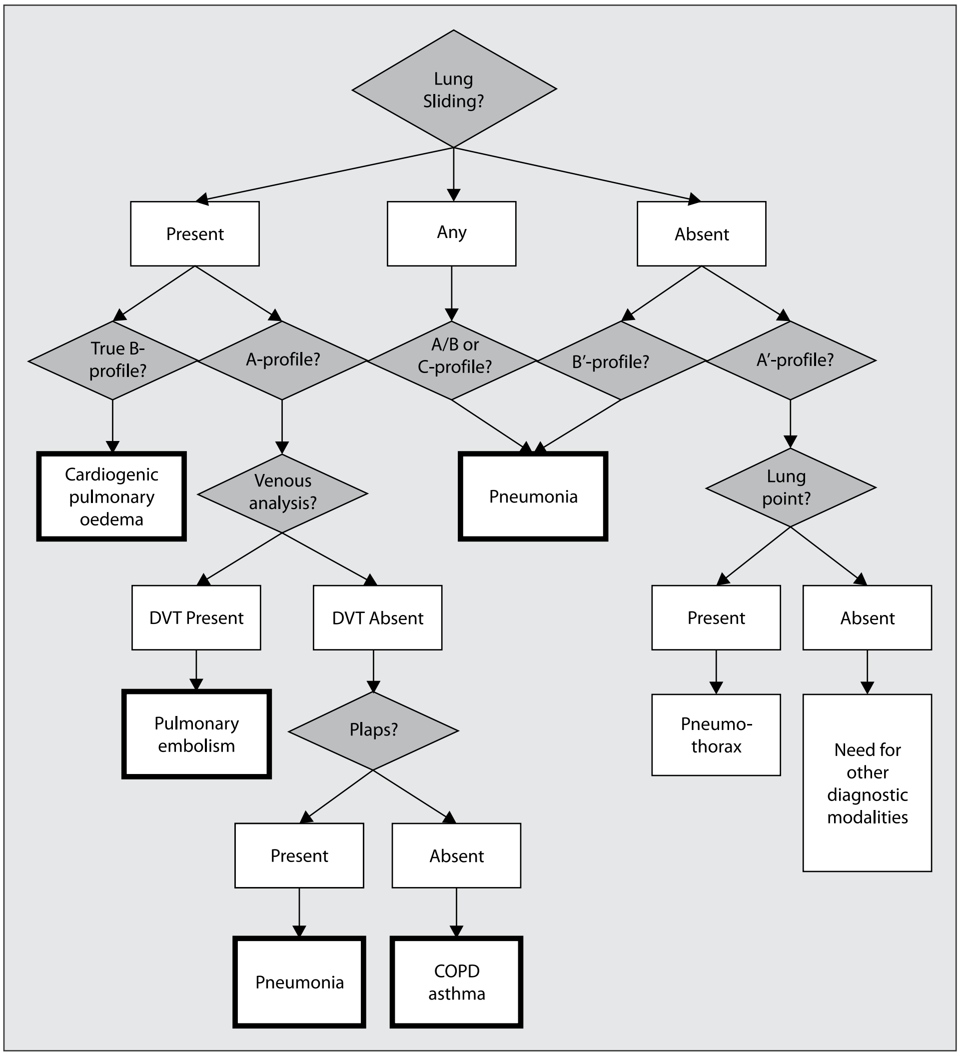


Figure 3. The modified BLUE-protocol starting at the upper and lower BLUE-points looking for lung sliding, and moving to the PLAPS-point, allows immediate differential diagnosis of the main causes of acute respiratory failure using lung and venous ultrasound. Adapted from Lichtenstein *et al.* [1] with permission. PLAPS — Postero Lateral Alveolar and/or Pleural Syndrome. See text for explanation. The **A-profile** defines a normal lung surface and correlates with severe asthma or COPD. Associated with a deep venous thrombosis, it leads to a diagnosis of pulmonary embolism. In combination with the presence of a postero-lateral alveolar and/or pleural syndrome (called PLAPS), it highly suggests the diagnosis of pneumonia. The **A'-profile**, defined as abolished lung sliding with exclusive A-lines, is suggestive of pneumothorax, and makes the detection of a lung point mandatory, a specific sign of pneumothorax. The **B-profile** associates anterior lung sliding with anterior lung rockets, and highly suggests acute cardiovascular pulmonary oedema (true B-profile) or other causes of lung oedema (e.g. hyper permeability). The **B'-profile** combines abolished lung sliding with lung rockets, and is also correlated with pneumonia. The **A/B-profile**, i.e., unilateral lung rockets, suggests pneumonia. The **C-profile** defines anterior lung consolidations (from large parenchymal volumes to a simple thickened, irregular pleural line) and again suggests pneumonia. When the anterior lung surface is normal, the detection of a DVT suggests the diagnosis of pulmonary embolism with a high specificity

SESAME-PROTOCOL, ULTRASOUND IN CARDIAC ARREST

The SESAME-protocol or "Sequential Echographic Scanning Assessing Mechanism Or Origin of Severe Shock of Indistinct Cause" involves a rapid, sequential assessment for shockable causes followed by an assessment of the presence or absence of pneumothorax, pulmonary embolism, hypovolaemia/haemorrhage finally followed by exclusion of pericardial tamponade, all highly reversible causes of shock [14]. The final step of the assessment, performed in the absence of the previous causes, focuses on the heart.

The main practical consideration in all these protocols is time-criticality. A compact US machine with a rapid start-up time allows for swift navigation around the bedspace. A universal long-range microconvex probe makes it possible to image the lungs, veins, abdomen and heart with a single probe. The absence of any software filter enables the user to start up the machine and scan with minimal delay.

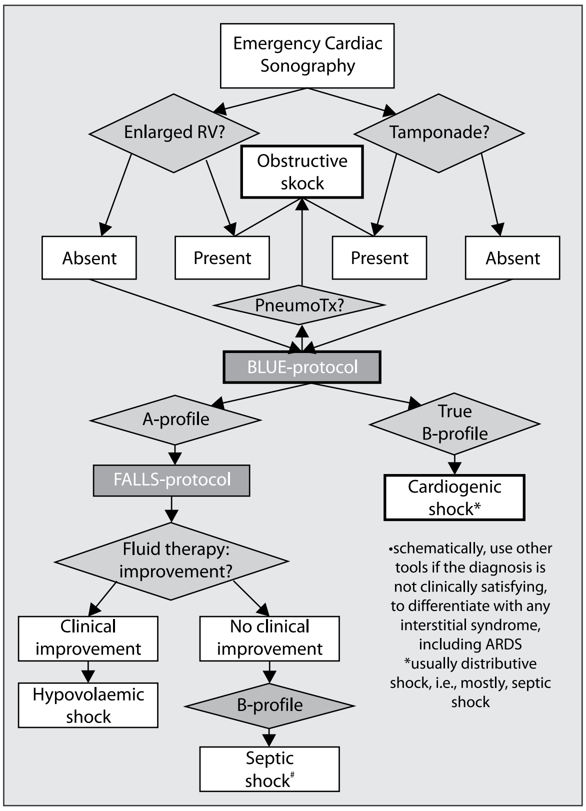


Figure 4. The FALLS protocol. A decision tree facilitating the understanding of the FALLS-protocol. According to Weil's classification, cardiac and lung ultrasound sequentially rule out obstructive, cardiogenic (from left heart), hypovolaemic and, finally, distributive shock, i.e. septic shock in current practice. Adapted from Lichtenstein *et al*. [1] with permission. FALLS-protocol — Fluid Administration Limited by Lung Sonography; BLUE-protocol — Bedside Lung Ultrasound in Emergency; RV — right ventricle; PneumoTx — pneumothorax

KEY MESSAGES

- The systematic (and holistic) use of CCUS in various protocols provides a comprehensive assessment of the patient's cardiovascular and respiratory system
- The SESAME protocol allows one to differentiate between reversible causes during cardiac arrest in the following sequence: first exclude pneumothorax, followed by pulmonary embolism, hypovolaemia (e.g. abdominal bleeding), cardiac tamponade, and finally cardiac disorders
- The FALLS protocol allows one to establish a sequential diagnosis in patients with shock: first exclusion of obstructive (pericardial tamponade, pulmonary embolism, pneumothorax), followed by cardiogenic, hypovolaemic and finally distributive (sepsis) causes of shock

THE ROLE FOR TRANSOESOPHAGEAL ECHOCARDIOGRAPHY

INVESTIGATING THROMBOEMBOLISM

TOE is an elegant tool providing both detailed diagnostic and monitoring information in critically ill patients but also intraoperatively [16–18]. TOE is useful in the bedside investigation of thromboembolic events through visualisation of thrombi involving the proximal pulmonary arteries, atheroma plaques (≥ 5 mm) in the thoracic aorta, patent foramen ovale and atrial septal aneurysm [19]. TOE may also visualize thrombi into the main or the right pulmonary artery, then allowing diagnosis of proximal pulmonary embolism at the bedside in a mechanically ventilated patient. However, apical thrombi can be better visualised with transthoracic imaging because of the location of the ventricular apex [20].

MONITORING VENTRICULAR FUNCTION

TOE is particularly useful in ventricular function monitoring in the ICU and during major surgery or interventional procedures. An initial TOE investigation after admission to ICU should highlight regional wall motion abnormalities. Any changes may be detected during a periodic assessment and related with perfusion alterations, or alteration in the patient's clinical state. Volumetric assessment of the left ventricle is facilitated by 3-D TOE because of improved spatial resolution, as well as more accurate and reproducible measurements [21], although a simple measurement of LV areas on a short axis view is usually adequate in the critically-ill patient. LV systolic function is very easily and accurately assessed by an eyeballing evaluation and simple graduation of systolic function in 4 categories, namely supranormal, normal, moderately and severely depressed, allows for treatment adaptation and shock classification. Furthermore, right ventricular dilation, associated or not with a paradoxical septal motion, must be regarded in view of the potential causes of right ventricular failure when a perfusion deficit is present (cardiogenic shock, ventilation-perfusion mismatch, ARDS etc.).

VALVULAR ASSESSMENT

Another advantage of TOE is the assessment of native or prosthetic valve dysfunction. Mitral and tricuspid valve issues can be captured by TOE with a combination of transverse and longitudinal planes in the multiplane facility. Assessment of aortic valve function is more difficult but possible using a deep transgastric view in a transverse plane (0°) in the stomach or a LAX view (120°) at the gastro-oesophageal transition [22]. This view, in fact, allows for the dynamic imaging of all four valves. The different views are summarized in Table 4.

Additionally, TOE is useful in early follow-up after mitral valve repair, in 2-D or 3-D [23]. Although the function of the repaired valvular apparatus, the presence of paravalvular leaks, an systolic motion of the anterior mitral leaflet may all be examined, the effects of anaesthetic/sedatives, and the altered preload and afterload conditions must be taken into account.

Table 4. Summary of different TOE views

View	To visualize	Indication
Transgastric		
SAX	LV, RV	Global function, RWMA, pericardial fluid, static evaluation of filling, LVH
MV	MV, LV	MV disease
ME		
4-chamber	4 chambers, MV, TV	Global function, RWMA
MV commissural	MV leaflets, scallops	MV disease
2-chamber	LV, MV scallops	MV disease
LVOT	LV, RV, AV, LVOT	Valve function, SAM, AI, AS
Upper mediastinal	AA, pulmonary arteries, AV	AS, AI, aneurysm, dissection, PA flow
Deep transgastric 0°	AV, LVOT, AA, MV	AV function, AS, AI
Clockwise rotation 0°	RV, TV	TI, RV function
120°	RV inflow, RA, RV outflow, PV	TI, PI, PS
Descending aorta	DA	Dissection, aneurysm, low flow state, pleural fluid, posterior pulmonary complications

AA — ascending aorta; AI — aortic valve insufficiency; AS — aortic stenosis; AV — aortic valve; DA — descending aorta; LV — left ventricle; LVH — left ventricular hypertrophy; LVOT — left ventricular outflow tract; MV — mitral valve; PI — pulmonary valve regurgitation; PS — pulmonary valve stenosis; PV — pulmonary valve; RV — right ventricle; RWMA — regional wall motion abnormalities; SAM — systolic anterior motion of the anterior MV leaflet; TI — tricuspid valve insufficiency; TV — tricuspid valve

MONITORING FLUID STATUS

A smaller TOE probe left *in situ* enables real-time examination of ventricular function and fluid responsiveness, particularly in patients with precarious haemodynamics. An extensive review of the assessment of loading conditions through echocardiography can be found elsewhere. Fluid responsiveness evaluation may be assessed by flow variation of aortic flow (transaortic valvular Doppler variation with mechanical ventilation) or cyclic changes of superior caval vein diameter, as assessed with M mode of the superior caval vein in a bicaval view. A large observational and prospective study performed in patients with shock has reported that the SVC collapsibility index has the best specificity, whereas respiratory variations of aortic blood flow possesses the best sensitivity [24].

Tissue Doppler adds important information, both on systolic and diastolic function of the LV; as all myocardial Doppler signals are load-dependent, care should be taken that ventilator settings, such as PEEP, can influence diastolic function parameters [25, 26].

KEY MESSAGES

- TEE has become a gold standard for haemodynamic monitoring in the ICU.
- TEE allows for the assessment of the presence or not of thromboembolism, pericardial fluid, fluid status, valvular and ventricular function.
- Although the advantage is that image quality is superior, compared to other haemodynamic monitoring techniques it is user dependent and semi-continuous (as the probe may heat with prolonged use)

THE ROLE FOR TRANSTHORACIC ECHOCARDIOGRAPHY

Transthoracic echocardiography (TTE) is non-invasive and easy test to perform at the bedside, and can diagnose the cause of shock or respiratory failure in more than 80% of cases, even in the presence of mechanical ventilation and pre-existing lung disease [27]. TTE can also guide the pericardiocentesis in the case of pericardial tamponade.

Assessment of the inferior vena cava can demonstrate fluid-responsiveness [28, 29]. However a recent study reported limited accuracy [24]. Respiratory variations of aortic blood flow recorded using a pulsed Doppler also reflect fluid-responsiveness [30]. Cardiac output can be estimated from the left ventricular outflow tract area, the aortic velocity time integral and the heart rate.

Pulmonary arterial pressures are easy to assess in ICU patients. Tricuspid regurgitation can be identified on an apical 4-chamber view using continuous wave Doppler [31], with the maximal velocity of the tricuspid regurgitation corresponding to the maximal systolic pressure gradient between the right ventricle and the right atrium. The sum of this measured pressure gradient with the right atrial pressure (central venous catheter reading) calculates the right ventricular systolic pressure, and subsequently the pulmonary systolic arterial pressure, with good correlation between pulmonary Doppler and invasive systolic arterial pressure [32]. Pulmonary artery occlusive pressure (PAOP) is a useful index in pulmonary oedema, with good correlation between invasively-measured PAOP and Doppler evaluation [33]. In patients with respiratory failure and cardiac failure, TTE can be used to assess the left ventricular ejection

Table 5. Evaluation of left ventricular ejection fraction

Measurement	View	Calculation	Limitations
Shortening Fraction	PLAX	(LVEDD – LVESD)/LVEDD	Not reliable when RWA at septal or posterior wall. Measurement needs to be perpendicular on the posterior wall
Shortening Fraction of the LV Area	PSAX	(LVEDD — LVESD)/LVEDD	Not reliable when RWA
True Ejection Fraction	A4C	Simpson Biplane Method	Most reliable method
E Point Septal Separation (EPSS) = Mitral Valve Opening	PLAX	M mode. Normal < 7–10 mm	
Eyeballing	PLAX/PSAX/A4C		Operator dependent. Reliable when experienced provider

PLAX — Parasternal Long Axis View; PSAX — Parasternal Short Axis View; A4C — Apical 4 Chamber View; RWA — Regional Wall Abnormalities; LVEDD — Left Ventricular End-Diastolic Diameter; LVESD — Left Ventricular End Systolic Diameter

fraction, differentiating between systolic or diastolic left ventricular dysfunction or severe valvular regurgitation.

KEY MESSAGES

- TTE has evolved as the modern stethoscope for the intensivist
- Similarly to TEE, TTE also allows for the assessment of presence, or not, of thromboembolism, pericardial fluid, fluid status, valvular and ventricular function
- Although compared to TEE it is readily available, the image quality in ICU patients is sometimes poor (e.g. in presence of subcutaneous emphysema, COPD, etc.)

ASSESSMENT OF THE LEFT VENTRICLE

The assessment of the left ventricle includes the measurements of the ejection fraction (EF), the cardiac output (CO) and the left ventricle filling pressure [34, 35].

EJECTION FRACTION

Ejection fraction does not equal contractility since it also takes afterload and preload into account (Table 5). If one increases the afterload, one will decrease the ejection fraction without a change in contractility.

CARDIAC OUTPUT

One measures the diameter (in cm) at the Left Ventricular Outflow Tract (LVOT) 0.5 cm before the aortic valve at the ventricular side in the PLAX. In a next step, the surface of the LVOT Area (in cm^2) is calculated. In the A5C or A3C view, the Aortic Blood Flow (ABF) with Pulse Wave (PW) Doppler is measured. One subsequently traces the edge of the ABF curve to calculate the Velocity Time Interval (VTI) which is the Area Under the Curve (AUC). A normal LVOT VTI is > 18 cm. If one multiplies this VTI with the LVOT Area, one gets the stroke volume (in cm^3 or mL). Finally, when one multiplies the stroke volume with the frequency one gets get the cardiac output. If one divides the cardiac output by the Body Surface Area (BSA) one gets the Cardiac Index (CI). This method is very accurate and can be considered as gold standard function [36].

DIASTOLIC FUNCTION

Diastolic Dysfunction shifts the LV end-diastolic pressure (LVEDP)/ LV end-diastolic volume (LVEDV) curve to the left and narrows the therapeutic range for safe intravenous fluid administration. The LV Pressure Gradient will decrease and the flow over the mitral valve will decrease. It will cause A (Late Filling over the Mitral Valve) to be larger than E (Early Filling over the Mitral Valve) in a Pulse Wave (PW) Measurement just behind the mitral valve. It must be noted that mitral flow largely depends on age, heart rate, preload and afterload and, as such, this flow cannot be used to assess diastolic function of the LV. The measurement of the movement of the mitral valve annulus at the lateral wall in Tissue Doppler Imaging (TDI) is not dependent on preload, which we call E′ and A′. E′ velocity can be used to assess diastolic dysfunction, where an E′ lower than 8–10 usually corresponds to a diastolic dysfunction. The third part of the assessment is the measurement of the size of the left atrium (LA). If the LA has a normal size, there is no diastolic dysfunction (Table 6). However, one has to keep in mind that the size of the LA may change during preload changes.

PAOP

The E/E′ ratio correlates very well with Pulmonary Artery Occlusion Pressure (PAOP or wedge pressure) since the E′ is independent of the preload (and only dependent on the LV relaxation) while the mitral flow (E) is dependent on the PAOP and on the LV relaxation. The cut-off for a raised PAOP is 18 mm Hg. An E/E′ ratio below 8 is usually associated with low or normal PAOP while above 12 corresponds to PAOP > 18 mm Hg, with a grey zone between 8 and 12. However, the accuracy of this parameter to assess PAOP was recently discussed with only extreme values corresponding to a low or high PAOP.

KEY MESSAGES

- Assessment of the left ventricle provides important information for the ICU physician
- LV assessment includes cardiac output, LV ejection fraction, diastolic function and estimation of PAOP

Table 6. Diastolic function

Measurements	Diagnosis
E′ Lateral > 10 cm s^{-1}, E′ Septal > 8 cm s^{-1} LA Volume < 34 mL m^{-2}	Normal Left Ventricular Relaxation
E′ Lateral > 10 cm s^{-1}, E′ Septal > 8 cm s^{-1} LA Volume > 34 mL m^{-2}	Athlete's heart
E′ Lateral < 10 cm s^{-1}, E′ Septal < 8 cm s^{-1} LA Volume > 34 mL m^{-2}	Left Ventricular Dysfunction

ASSESSMENT OF THE RIGHT HEART

In the statement of the American College of Chest Physicians and of the French Society of Intensive Care, which defined for the first time critical care echocardiography (CCE), it is recommended to intensivists to be competent in evaluating RV function [3]. At the advanced level of CCE, intensivists have to accurately detect RV dilatation and paradoxical septal movement, in order to diagnose acute cor pulmonale (ACP), to evaluate the impact of mechanical ventilation and respiratory settings on RV function. For such goals, different echo parameters have been proposed.

EVALUATION OF RV SIZE

Moderate RV dilatation is defined as a ratio between RV end-diastolic area (RVEDA) and left ventricular end-diastolic area (LVEDA) greater than 0.6, whereas a severe dilatation is defined when this ratio is greater than 1, the RV being bigger than the LV [37]. This can be evaluated by transthoracic echocardiography (TTE) on an apical 4-chamber view or by a transoesophageal echocardiography (TOE) on a transverse mid-esophageal view. We have suggested that this can be qualitatively done just by visualizing the view on the screen of the echo machine [37]. Very frequently, in case of RV dilatation, the inferior vena cava also appears on a subcostal view as dilated and congestive without any respiratory movement. This reflects a high right atrial pressure [38].

INTERVENTRICULAR SEPTAL MOVEMENT

In some very abnormal situations, when the pressure into the RV becomes higher than the pressure into the LV, a paradoxical septal movement can be diagnosed. When occurring at end-diastole, this reflects a huge RV diastolic overload. When occurring at end-systole early diastole, this reflects RV systolic overload. While this pattern is usually qualitatively evaluated (it is present or not), it can also be quantified using the eccentricity index of the LV [39]. This index is the ratio between the antero-posterior diameter of the LV and the septo-lateral one. In a normal situation, as the LV is purely spherical, the eccentricity index in diastole and in systole is 1, whereas in case of RV overload, the LV is compressed due to which the eccentricity index is greater than 1. The movement of the interventricular septum may be evaluated either using TTE on a parasternal short-axis view or using TOE on a transgastric short-axis view. The association of RV dilatation and paradoxical septal motion at end-systole defines cor pulmonale.

DOPPLER EVALUATION OF RV EJECTION FLOW

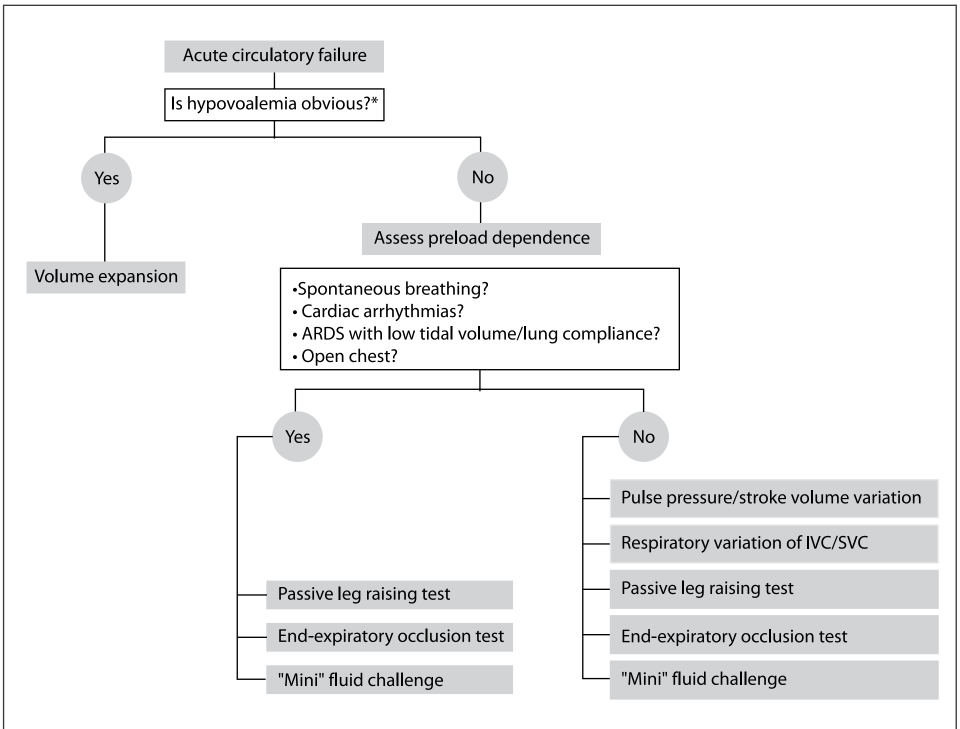
The use of the pulsed-wave Doppler (PWD) in the RV outflow track allows for analyzing whether there are respiratory variations of RV ejection during tidal ventilation. When occurring, it always reflects a significant impact of tidal ventilation on RV function, either due to a preload effect (usually corrected by fluid expansion) or due to an afterload effect (fluid expansion is useless, even deleterious and changes in respiratory settings have to be considered).

From the RV ejection flow recorded by the PWD at end-expiration, some information on the status of the pulmonary circulation may be obtained. When the acceleration time, which is the time between the beginning and the peak of the ejection, is below 100 ms, it reflects some degree of pulmonary artery pressure elevation. When the flow is biphasic, this is very suggestive that a significant obstruction of the pulmonary circulation is present, either due to a massive pulmonary embolism (proximal obstruction) or to a severe acute respiratory distress syndrome (ARDS) (distal obstruction).

MORE "ADVANCED" ECHO PARAMETERS OF RV FUNCTION

Study of the lateral part of the tricuspid annulus during systole has been proposed to evaluate RV systolic function. Tricuspid annular plane systolic excursion (TAPSE) with the time-motion mode evaluates the amount of movement; an S-wave using the tissue Doppler imaging (TDI) evaluated the maximal velocity. The larger the movement or higher the velocity, the better the RV systolic function. Although different cut-off values have been proposed to define RV systolic dysfunction, usually an S-wave below 11.5 cm s^{-1} [40] and a TAPSE below 12 mm [41] are considered as significantly abnormal.

It has also been proposed to use the mean acceleration of the RV ejection flow in mechanically ventilated patients for ARDS [42]. The mean acceleration is the ratio between the maximal velocity of the RV ejection flow and the acceleration time. This is correlated to RV systolic function and inversely correlated to RV afterload. Consequently, a decrease in the mean acceleration time is suggestive of a decrease in RV systolic function and an increase in RV afterload, as observed during tidal volume in some patients. Although new ultrasound techniques (speckle tracking) may analyse



Very initial phase of septic shock, when no fluid has been already administered, in case of haemorrhagic shock or in case of hypovolaemic shock due to diarrhoea, vomiting or ketoacidosis for instance

Figure 5. Decisional algorithm for the prediction of fluid responsiveness. Adapted (with permission) from [47]. ARDS — acute respiratory distress syndrome; IVC — inferior vena cava; SVC— superior vena cava

much more accurately the systolic function of the RV, this technique is still under evaluation [42].

INTEREST OF TOE-FOCUS IN SPECIFIC SITUATIONS

TOE may be very useful and is safe in mechanically ventilated patients. In case of clinical suspicion of pulmonary embolism, in a patient who had a cardiac arrest following by circulatory failure, it may provide a diagnosis in a few minutes at the bedside by visualizing a clot in the pulmonary arteries [43]. In severe ARDS patients, this is the gold standard approach in order to diagnose ACP [44] and open formaen ovale which occurs in 20–22% of patients [45].

KEY MESSAGES

- Assessment of the right ventricle provides important information for the ICU physician.
- RV assessment includes RV anatomy and function, RV dimensions, presence of pulmonary hypertension.

ASSESSMENT OF FLUID RESPONSIVENESS

Concept of fluid responsiveness

When making the decision to infuse fluids in a patient with acute circulatory failure, the clinician has to face a therapeutic dilemma. On the one hand, the fluid-induced increase in cardiac preload may increase cardiac output and, eventually, oxygen delivery to the tissues. On the other hand, volume expansion may contribute to fluid overload, a condition that has been clearly demonstrated to be associated with poor outcome, especially in patients with sepsis and acute respiratory distress syndrome (ARDS). Moreover, due to the shape of the Frank-Starling relationship, the fluid-induced increase in preload leads to a significant increase in cardiac output only in cases of fluid responsiveness. This corresponds to around 50% of cases in patients with acute circulatory failure who are hospitalised in the intensive care unit [46].

This is the reason why some methods have been investigated in order to assess fluid responsiveness at the bedside. All these methods can be used with echocardiography, which may be especially useful when no other measurement of cardiac output is available.

Before describing these indices, one must emphasise two major points. Firstly, the question whether to assess fluid responsiveness only arises in case of acute circulatory failure, e.g. when one has decided to increase cardiac output because of inadequacy between oxygen demand and supply. Secondly, the indices described below are useless when fluid responsiveness is extremely likely, as for example in a patient with unresuscitated haemorrhagic shock or during the initial, unresuscitated phase of septic shock (Fig. 5).

STATIC INDICES OF CARDIAC PRELOAD

It has been clearly demonstrated that no static measure of cardiac preload reliably predicts fluid responsiveness in most situations. The main reason is physiological. As the slope of the Frank-Starling relationship depends on ventricular systolic function, a given value of preload may correspond either to the steep or the flat part of the curve [46].

Echocardiographic static measures of preload include the left end-diastolic volume and area, as well as all indices derived from the mitral flow and mitral annulus motion Doppler analysis. Although these indices estimate left ventricular preload, they do not indicate preload dependence of stroke volume except for very low values [46]. For basic CCUS, a few echo parameters are very likely associated with fluid-responsiveness, as a small IVC and a small hyperkinetic left ventricle, possibly associated with a dynamic obstruction, whereas it is very unlikely to have a fluid responsiveness status when the mitral inflow is restrictive.

RESPIRATORY VARIATION OF STROKE VOLUME

The relationship between respiratory cycle and cardiac preload is a complex one. Under positive pressure ventilation, each respiratory cycle induces changes in cardiac preload. This results in greater variation of stroke volume if both ventricles are operating on the steep portion rather than on the plateau of the Frank-Starling relationship.

Echocardiography estimates the left ventricular stroke volume through the velocity-time integral (VTI) of the systolic Doppler signal when the sampling window of pulsed Doppler is placed in the outflow tract of the left ventricle. Variability in stroke volume can be assessed simply by measuring changes in aortic peak velocity (rather than VTI itself). It has been shown that when the respiratory variation of the aortic peak velocity is greater than 12% or VTI variations of more than 20%, fluid responsiveness is likely [46].

The primary limitation regarding the use of respiratory variation of LVOT velocity is that it is sometimes difficult to keep the Doppler sample window in the left ventricular outflow tract during breathing movements. In this regard, if an arterial catheter is in place, the respiratory variation of pulse pressure is much easier to assess. Moreover, this method cannot be used in cases of cardiac arrhythmias or spontaneous breathing (even in patients receiving intubation) (Fig. 5). Indeed, in such cases, changes in stroke volume primarily reflect the irregularities of the cardiac or respiratory cycles rather than preload dependence (false positives). Right ventricular dysfunction and or dilation may also induce a false positive due to an afterload effect of the mechanical ventilation rather than a preload effect. Moreover, when tidal volume is low and/or when lung compliance is low, as during ARDS, changes in right ventricular preload induced by mechanical ventilation may be too low to generate significant variations of stroke volume, even if the patient is preload dependent (false negatives) (Fig. 5). Finally, when the thorax and/or the pericardium are open, respiratory variability indices may be unreliable [46].

RESPIRATORY VARIATION IN THE DIAMETER OF THE VENA CAVA

The diameter of the vena cava depends on the intramural pressure (which itself depends on the circulating blood volume) and the extramural pressure (intra-abdominal pressure for the inferior vena cava, intrathoracic pressure for the superior vena cava). Significant respiratory changes in the diameter of the vena cava indicate that positive pressure ventilation affects systemic venous return, suggesting preload dependence.

Fluid responsiveness was found to be predicted by a respiratory variation of the inferior vena cava ([maximum diameter – minimum diameter] / minimum diameter or [maximum diameter – minimum diameter] / mean of maximum and minimum diameters) higher than 18% or 13%, respectively, and a superior vena cava collapsibility index ([maximum diameter – minimum diameter] / maximum diameter) greater than 36% in mechanically ventilated patients.

In some critically ill patients with poor subcostal windows, the inferior vena cava may be difficult to image. Superior vena cava collapsibility can only be measured with a transesophageal echocardiography, which requires special expertise. Unlike the respiratory variability of aortic velocity, respiratory variability of diameter of the vena cava can be used in patients with cardiac arrhythmias but is invalid in the case of spontaneous breathing and, likely, in case of low tidal volume and low lung compliance (Fig. 5). Finally, intra-abdominal hypertension might invalidate inferior vena cava variability measurements. The accuracy of IVC and SVC variations to assess fluid-responsiveness were recently discussed in a large prospective study in which it was demonstrated that IVC is a poor predictor and the cut-off values are different than those previously published [24].

THE PASSIVE LEG RAISING TEST

The elevation of the lower extremities relative to the horizontal position provokes the transfer of a volume of venous blood into the thorax. The resultant increase in right and left ventricular preload can be used to evaluate preload dependence. As the PLR-induced increase in cardiac preload does not depend on cardiac rhythm or intrathoracic pressure variations, PLR is an alternative to indices based on respiratory variability where they are not valid [48] (Fig. 6).

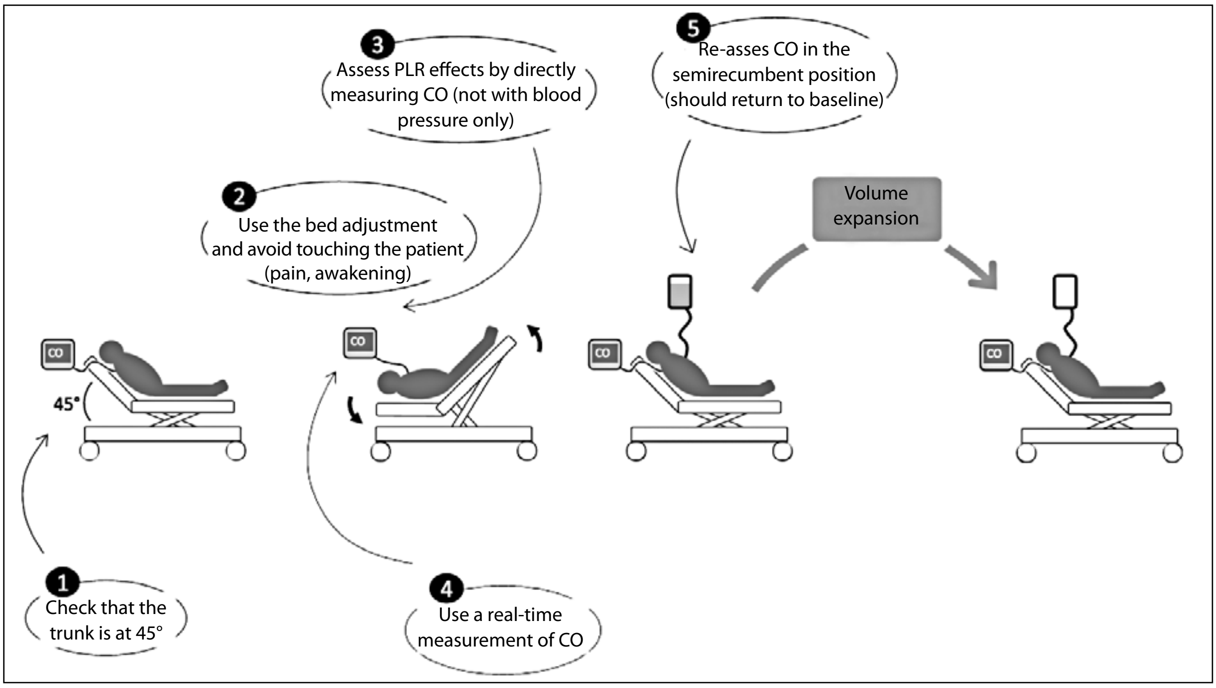


Figure 6. The best method for passive leg raising, indicating the five rules to be followed. Adapted from Monnet *et al.*, [48] with permission. CO — cardiac output; PLR — passive leg raising

Several studies have demonstrated that an increase in stroke volume by more than 10% during PLR predicts fluid responsiveness with good diagnostic accuracy, even in patients with cardiac arrhythmias, spontaneous ventilation, or ARDS. With echocardiography, an increase in the VTI of the left ventricular outflow tract of more than 10% during PLR predicts the response to volume expansion with good results [49]. The test is more sensitive when the manoeuvre is started from the semi-recumbent position as it allows the mobilization of the large abdominal venous blood volume, in addition to the volume of blood contained in the lower extremities [48].

The first limitation of the method is that it is sometimes difficult to maintain the probe in a stationary position relative to the thorax during postural change. The test is much easier to perform in cases of continuous monitoring of cardiac output with a specific device. The second limitation is that the PLR test often cannot be used during active surgery and is contraindicated in intracranial hypertension and unstable pelvic fractures. Finally, whether intra-abdominal hypertension is a condition where PLR may be unreliable has been suggested but is not certain [48].

THE END-EXPIRATORY AND END-INSPIRATORY OCCLUSION TESTS

During mechanical ventilation, inspiration cyclically increases the backward pressure of venous return, thus reducing the cardiac preload. Stopping mechanical ventilation at end-expiration for a few seconds interrupts this cyclic reduction: end-expiratory occlusion (EEO) induces a transient increase in cardiac preload. Observing the resulting effects on stroke volume allows one to assess preload dependence. If cardiac output increases by more than 5% during a 15-second EEO, the presence of fluid responsiveness is likely [48]. The test is very easy to perform with a continuous measurement of cardiac output, such as pulse contour analysis. Furthermore, adding the effects on the LVOT blood flow of a 15-sec end-inspiratory occlusion, which decreases cardiac output in case of preload responsiveness, increases the test's sensitivity. If the addition (in absolute values) of the changes in VTI during a 15-sec EEO and during a 15-sec end-inspiratory occlusion is more than 13%, fluid responsiveness is very likely.

The EEO test can be used in patients with cardiac arrhythmias and with ARDS, regardless of the level of positive end-expiratory pressure. Although it can be used in patients with mild spontaneous breathing activity, it cannot be performed if the spontaneous breathing interrupts the inspiratory hold. When US is used to perform the test, another limitation is that it requires the very precise measurement of VTI, a task which is difficult for non-experts.

FLUID CHALLENGE

When no other index is available, it may be best to test fluid responsiveness by administering a small quantity of fluid, observe its effects on cardiac output, and expect that a larger volume of fluid will exert similar effects. This can be performed serially, stopping volume expansion when fluid no longer increases cardiac output. Nevertheless, since this fluid challenge usually consists of infusing 300-500 mL of fluid, the method would inherently induce fluid overload.

A new method called "mini fluid challenge" has been proposed. The effects of 100 mL of colloid (given in a speedy manner) on stroke volume were shown to predict the response of cardiac output to a subsequent 500 mL volume expansion [50]. These changes in stroke volume were estimated with echocardiography [50].

Nevertheless, small amounts of fluid only induce small changes in stroke volume and cardiac output. Whether echocardiography is precise enough in non-expert hands to detect these changes is far from certain.

CONCLUSION

Several tests have been developed to detect preload responsiveness and to guide decision making regarding volume expansion. This avoids unnecessary fluid administration and harmful volume overload. Many of these tests can be performed with the help of echocardiography. This may be particularly useful when cardiac output monitoring is absent, either because it is not indicated or it has not been installed yet. In particular, US can be used for measuring the respiratory variations of the velocity of the aortic flow and of the diameter of the vena cava and for assessing the effects of a PLR test or, in ventilated patients, of 15-sec end-inspiratory and end-expiratory occlusions.

KEY MESSAGES

- Dynamic measures outperform static measures in the determination of fluid responsiveness in patients
- Various bedside tests, such as the PLR and the end-inspiratory/expiratory occlusion hold, have been advocated as a test of fluid responsiveness without actual fluid administration
- All tests need to be interpreted in the context of the individual patient, especially with regards to respiratory parameters

ABDOMINAL ULTRASOUND

Abdominal US on ICU can be performed for diagnostic and therapeutic purposes. Several free open-access medical educational (FOAM) resources are available on the internet (Table 7). In experienced hands, bedside abdominal US is focused on the aim of answering a specific clinical question e.g. presence of free intraabdominal fluid, urinary tract obstruction (hydronephrosis), hydrops of the gall bladder, bladder or stomach distension, increased renal resistive index, portal vein thrombosis etc.

FAST SCAN

The most established focused abdominal US examination is the FAST (Focused Assessment with Sonography for Trauma). The goal is the identification of free intraabdominal fluid/blood using 4 standard views, namely: subcostal, right and left upper quadrant and suprapubic.

EFAST SCAN

This combines a FAST scan with a lung US in order to identify pneumothoraces.

RUSH SCAN

The RUSH scan (Rapid US for Shock and Hypotension) is an examination designed to be rapid and easy to perform in the emergency department. In addition to abdominal and lung US, it also includes views of the heart (parasternal long axis and apical 4-chamber), inferior vena cava and aorta.

Other diagnoses that are amenable to the point-of-care US include liver/gallbladder abnormalities e.g. acute cholecystitis, abscess, biliary obstruction and renal abnormalities e.g. atrophy, abscess, cysts.

KEY MESSAGES

- The detection of free fluid in the abdomen is a simple skill to acquire.
- In experienced hands, abdominal ultrasound can provide other useful information, such as gastric distension, hydrops of the gall bladder, bladder distension, hydronephrosis, renal resistive index and much more.

VASCULAR ACCESS

Using the traditional 'landmark approach', placement of vascular catheters such as central venous catheters (CVC), peripherally inserted central catheters (PICC) and arterial catheters carries risks e.g. arterial puncture, pneumothorax. Direct visualisation using real-time US guidance allows for the identification of the target vessel and optimal insertion site, thereby reducing the incidence of complications. Furthermore, by avoiding the Trendelenburg position, patient comfort is improved. Guidelines and recommendations advocate the introduction of US for vascular access in clinical practice [51].

GENERAL PRINCIPLES

In most patients, the target vessels can be visualised using a linear high-frequency probe. US may be performed either in static (considered the absolute minimum for vascular access) or dynamic mode. Dynamic, or real-time US guidance is performed under sterile conditions. The choice of an in-plane or out-of-plane approach is usually based on operator preference, with no general recommendations made, even though a recent randomized study between

Table 7. FOAM resources on ultrasound

Abdominal US		
	FAST scan in trauma	http://www.sonoguide.com/FAST.html
	RUSH protocol and discussion	http://emcrit.org/rush-exam/
	Indications for FAST	http://www.trauma.org/archive/radiology/FASTindications.html
Miscellaneous Resources and links		
	Sonosite Education	http://www.sonositeeducation.com
	Ultrasound training solutions	http://www.UStraining.com.au/information/medical-education-links
	Bedside US iBook by @USpod	https://itunes.apple.com/us/book/introduction-to-bedside-US/id554196012?mt=13

both approaches seems to favour the short axis for the sub-clavian access.

CENTRAL VENOUS ACCESS

Internal jugular vein (IJV): The IJV is the most straightforward to approach by US and the easiest for novices to access. The IJV can be easily identified in the neck, usually lateral or superior to the carotid artery (Fig. 7) and demonstrates good compressibility.

Subclavian vein (SV): The SV is traditionally shunned by clinicians using the landmark approach due to the higher risk of complications. In a recent publication, SV catheterization was associated with a lower risk of bloodstream infection and symptomatic thrombosis but a higher risk of pneumothorax than jugular or femoral vein catheterisation [52]. Whilst US-guided SV catheterisation largely avoids the risks of pneumothorax and arterial puncture, it requires more skill and training than the jugular approach by virtue of its anatomical location. The preferred approach is a longitudinal visualisation of the vessel with an in-plane approach, with the necessity of seeing "tenting" of the vessel "roof" just prior to vascular puncture (Fig. 8).

Femoral vein (FV): The femoral vein, though not a preferred vessel, can be easily identified and cannulated. Cannulation of the superficial femoral vein in the mid-thigh is an alternative approach when one wants to avoid the groin area.

PICC and Midline catheters (ML): PICC and ML catheters avoid central structures and are ideal for patients receiving ambulatory care. The target vein (basilic vein for PICC and ML or cephalic vein for ML) should be screened for patency and size (diameter up to 3 times that of the catheter), which is essential to avoid vein thrombosis. Although this technique requires a lot of experience and practice, once mastered, it will prove very valuable for many patients.

ARTERIAL CANNULATION

Arterial cannulation is commonly performed in critically ill patients. US guidance allows alternative approaches, such as cannulation of the radial artery in the mid fore-arm,

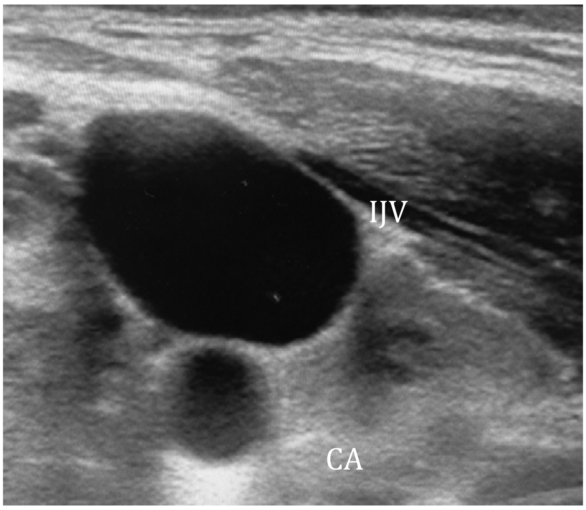


Figure 7. Vascular access. Internal jugular vein (IJV) lying on top of carotid artery (CA)

Figure 8. Vascular access. Longitudinal visualization in an in-plane approach of the subclavian vein with typical "tenting" of the vein, confirming correct entry

thereby avoiding the problem of catheter kinking when inserted over joints.

TRAINING AND EDUCATION

Several training methods for US-guided catheter placement have been described. Although approaches can be trained practiced on training gels and other devices, this is not a substitute for supervised bedside training. It usually takes 10 one-to-one supervised procedures before a trainee can work more independently.

KEY MESSAGES

- The use of real-time, US guidance for vascular access is rapidly becoming normal practice.
- Various professional bodies, although advocating the use of US, differ with regards to whether the in- or out-of plane approach should be the default position.

DISCUSSION

Ultrasound has evolved beyond just being the remit of radiologists and has become an important tool in the armamentarium of the intensivists.

This review has highlighted the various aspects of CCUS and its place in modern intensive care unit. It summarises key learning points, as well as challenges for the practicing clinician. CCUS is not meant to replace traditional clinical examination but rather enhances it by improving diagnostic expertise. Although by no means can ultrasound replace clinical examination, classic physical examination in combination with holistic ultrasound will provide the clinician with a full physiological examination. Hence, the ultrasound may become the modern stethoscope for the ICU physician. However, CCUS scans do not represent comprehensive imaging studies and should never replace studies performed by our specialist colleagues, such as radiologists, radiographers or cardiologists.

Of the various modalities of CCUS, echocardiography is the most established, both in terms of clinical practice and training delivery. The European Diploma in Echocardiography (EDEC) established by the European Society of Intensive Care Medicine is a testament of this. Whilst this advanced-level qualification has been clearly defined, that which constitutes basic competencies is lacking across Europe. Programmes, such as CUSIC and ICARUS, mentioned above form the framework of future work. Despite the landmark expert consensus statement published in 2011, there remains a void in competencies and, hence, how best to train future colleagues in this field. The lack of qualified trainers is often highlighted as the biggest stumbling block in the introduction of a standardised training programme. There is an urgent need for professional organisations to first address the lack of guidance in training before the issue of trainers can be addressed.

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Manu Malbrain is founding President of WSACS (The Abdominal Compartment Society) and current Treasurer, he is also member of the medical advisory Board of Pulsion Medical Systems (part of Maquet Getinge group) and consults for ConvaTec, Acelity, Spiegelberg and Holtech Medical. He is co-founder of the International Fluid Academy (IFA). This article is endorsed by the IFA. The mission statement of the IFA is to foster education, promote research on fluid management and hemodynamic monitoring, and thereby improve the survival of the critically ill by bringing together physicians, nurses, and others from throughout the world and from a variety of clinical disciplines. The IFA is integrated within the not-for-profit charitable organization iMERiT, International Medical Education and Research Initiative, under Belgian law. The IFA website (http://www.fluidacademy.org) is now an official SMACC affiliated site (Social Media and Critical Care) and its content is based on the philosophy of FOAM (Free Open Access Medical education — #FOAMed). The site recently received the HONcode quality label for medical education

(https://www.healthonnet.org/HONcode/Conduct.html?HONConduct519739).

Xavier MONNET is a member of the medical advisory board of Pulsion Medical Systems (part of Maquet Getinge group).

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References:

1. Lichtenstein D, van Hooland S, Elbers P, et al. Ten good reasons to practice ultrasound in critical care. Anaesthesiol Intensive Ther. 2014; 46(5): 323–335, doi: 10.5603/AIT.2014.0056, indexed in Pubmed: 25432552.
2. Expert Round Table on Echocardiography in ICU. International consensus statement on training standards for advanced critical care echocardiography. Intensive Care Med. 2014; 40(5): 654–666, doi: 10.1007/s00134-014-3228-5, indexed in Pubmed: 24615559.
3. Mayo PH, Beaulieu Y, Doelken P, et al. American College of Chest Physicians/La Société de Réanimation de Langue Française statement on competence in critical care ultrasonography. Chest. 2009; 135(4): 1050–1060, doi: 10.1378/chest.08-2305, indexed in Pubmed: 19188546.
4. Expert Round Table on Ultrasound in ICU. International expert statement on training standards for critical care ultrasonography. Intensive Care Med. 2011; 37(7): 1077–1083, doi: 10.1007/s00134-011-2246-9, indexed in Pubmed: 21614639.
5. Vieillard-Baron A, Caille V, Charron C, et al. Actual incidence of global left ventricular hypokinesia in adult septic shock. Crit Care Med. 2008; 36(6): 1701–1706, doi: 10.1097/CCM.0b013e318174db05, indexed in Pubmed: 18496368.
6. Touw HRW, Tuinman PR, Gelissen HP, et al. Lung ultrasound: routine practice for the next generation of internists. Neth J Med. 2015; 73(3): 100–107, indexed in Pubmed: 25852109.
7. Lysakowski C, Walder B, Costanza MC, et al. Transcranial Doppler versus angiography in patients with vasospasm due to a ruptured cerebral aneurysm: A systematic review. Stroke. 2001; 32(10): 2292–2298, indexed in Pubmed: 11588316.

8. Lee Y, Zuckerman SL, Mocco J. Current controversies in the prediction, diagnosis, and management of cerebral vasospasm: where do we stand? Neurol Res Int. 2013; 2013: 373458, doi: 10.1155/2013/373458, indexed in Pubmed: 24228177.
9. Brandi G, Béchir M, Sailer S, et al. Transcranial color-coded duplex sonography allows to assess cerebral perfusion pressure noninvasively following severe traumatic brain injury. Acta Neurochir (Wien). 2010; 152(6): 965–972, doi: 10.1007/s00701-010-0643-4, indexed in Pubmed: 20379747.
10. Chan KH, Miller JD, Dearden NM, et al. The effect of changes in cerebral perfusion pressure upon middle cerebral artery blood flow velocity and jugular bulb venous oxygen saturation after severe brain injury. J Neurosurg. 1992; 77(1): 55–61, doi: 10.3171/jns.1992.77.1.0055, indexed in Pubmed: 1607972.
11. Gura M, Elmaci I, Sari R, et al. Correlation of pulsatility index with intracranial pressure in traumatic brain injury. Turk Neurosurg. 2011; 21(2): 210–215, doi: 10.5137/1019-5149.JTN.3574-10.1, indexed in Pubmed: 21534204.
12. Bellner J, Romner B, Reinstrup P, et al. Transcranial Doppler sonography pulsatility index (PI) reflects intracranial pressure (ICP). Surg Neurol. 2004; 62(1): 45–51; discussion 51, doi: 10.1016/j.surneu.2003.12.007, indexed in Pubmed: 15226070.
13. Lichtenstein DA, Mezière GA. Relevance of lung ultrasound in the diagnosis of acute respiratory failure: the BLUE protocol. Chest. 2008; 134(1): 117–125, doi: 10.1378/chest.07-2800, indexed in Pubmed: 18403664.
14. Lichtenstein D, Malbrain ML. Critical care ultrasound in cardiac arrest. Technological requirements for performing the SESAME-protocol--a holistic approach. Anaesthesiol Intensive Ther. 2015; 47(5): 471–481, doi: 10.5603/AIT.a2015.0072, indexed in Pubmed: 26578398.
15. Lichtenstein DA. BLUE-protocol and FALLS-protocol: two applications of lung ultrasound in the critically ill. Chest. 2015; 147(6): 1659–1670, doi: 10.1378/chest.14-1313, indexed in Pubmed: 26033127.
16. Colreavy FB, Donovan K, Lee KY, et al. Transesophageal echocardiography in critically ill patients. Crit Care Med. 2002; 30(5): 989–996, indexed in Pubmed: 12006793.
17. Guarracino F, Baldassarri R. Transesophageal echocardiography in the OR and ICU. Minerva Anestesiol. 2009; 75(9): 518–529, indexed in Pubmed: 19396054.
18. Poelaert JI, Schüpfer G. Hemodynamic monitoring utilizing transesophageal echocardiography: the relationships among pressure, flow, and function. Chest. 2005; 127(1): 379–390, doi: 10.1378/chest.127.1.379, indexed in Pubmed: 15654003.
19. Maltagliati A, Galli CA, Tamborini G, et al. Usefulness of transoesophageal echocardiography before cardioversion in patients with atrial fibrillation and different anticoagulant regimens. Heart. 2006; 92(7): 933–938, doi: 10.1136/hrt.2005.071860, indexed in Pubmed: 16284221.
20. Maron MS, Finley JJ, Bos JM, et al. Prevalence, clinical significance, and natural history of left ventricular apical aneurysms in hypertrophic cardiomyopathy. Circulation. 2008; 118(15): 1541–1549, doi: 10.1161/CIRCULATIONAHA.108.781401, indexed in Pubmed: 18809796.
21. Lang RM, Badano LP, Tsang W, et al. American Society of Echocardiography, European Association of Echocardiography. EAE/ASE recommendations for image acquisition and display using three-dimensional echocardiography. Eur Heart J Cardiovasc Imaging. 2012; 13(1): 1–46, doi: 10.1093/ehjci/jer316, indexed in Pubmed: 22275509.
22. Poelaert J, Schmidt C, Van Aken H, et al. A comparison of transoesophageal echocardiographic Doppler across the aortic valve and the thermodilution technique for estimating cardiac output. Anaesthesia. 1999; 54(2): 128–136, indexed in Pubmed: 10215707.
23. Maslow A, Mahmood F, Poppas A, et al. Three-dimensional echocardiographic assessment of the repaired mitral valve. J Cardiothorac Vasc Anesth. 2014; 28(1): 11–17, doi: 10.1053/j.jvca.2013.05.007, indexed in Pubmed: 24075641.
24. Vignon P, Repessé X, Bégot E, et al. Comparison of Echocardiographic Indices Used to Predict Fluid Responsiveness in Ventilated Patients. Am J Respir Crit Care Med. 2017; 195(8): 1022–1032, doi: 10.1164/rccm.201604-0844OC, indexed in Pubmed: 27653798.
25. Jacques DC, Pinsky MR, Severyn D, et al. Influence of alterations in loading on mitral annular velocity by tissue Doppler echocardiography and its associated ability to predict filling pressures. Chest. 2004; 126(6): 1910–1918, doi: 10.1378/chest.126.6.1910, indexed in Pubmed: 15596692.
26. Amà R, Segers P, Roosens C, et al. The effects of load on systolic mitral annular velocity by tissue Doppler imaging. Anesth Analg. 2004; 99(2): 332–8, table of contents, doi: 10.1213/01.ANE.0000131972.99804.28, indexed in Pubmed: 15271700.
27. Maizel J, Salhi A, Tribouilloy C, et al. The subxiphoid view cannot replace the apical view for transthoracic echocardiographic assessment of hemodynamic status. Crit Care. 2013; 17(5): R186, doi: 10.1186/cc12869, indexed in Pubmed: 24004960.
28. Feissel M, Michard F, Faller JP, et al. The respiratory variation in inferior vena cava diameter as a guide to fluid therapy. Intensive Care Med. 2004; 30(9): 1834–1837, doi: 10.1007/s00134-004-2233-5, indexed in Pubmed: 15045170.
29. Airapetian N, Maizel J, Alyamani O, et al. Does inferior vena cava respiratory variability predict fluid responsiveness in spontaneously breathing patients? Crit Care. 2015; 19: 400, doi: 10.1186/s13054-015-1100-9, indexed in Pubmed: 26563768.
30. Slama M, Masson H, Teboul JL, et al. Respiratory variations of aortic VTI: a new index of hypovolemia and fluid responsiveness. Am J Physiol Heart Circ Physiol. 2002; 283(4): H1729–H1733, doi: 10.1152/ajpheart.00308.2002, indexed in Pubmed: 12234829.
31. Jobic Y, Slama M, Tribouilloy C, et al. Doppler echocardiographic evaluation of valve regurgitation in healthy volunteers. Br Heart J. 1993; 69(2): 109–113, indexed in Pubmed: 8435234.
32. Berger M, Haimowitz A, Van Tosh A, et al. Quantitative assessment of pulmonary hypertension in patients with tricuspid regurgitation using continuous wave Doppler ultrasound. J Am Coll Cardiol. 1985; 6(2): 359–365, indexed in Pubmed: 4019921.
33. Combes A, Arnoult F, Trouillet JL. Tissue Doppler imaging estimation of pulmonary artery occlusion pressure in ICU patients. Intensive Care Med. 2004; 30(1): 75–81, doi: 10.1007/s00134-003-2039-x, indexed in Pubmed: 14634723.
34. Vermeiren GLJ, Malbrain ML, Walpot JM. Cardiac Ultrasonography in the critical care setting: a practical approach to asses cardiac function and preload for the "non-cardiologist". Anaesthesiol Intensive Ther. 2015; 47 Spec No: s89–104, doi: 10.5603/AIT.a2015.0074, indexed in Pubmed: 26588484.
35. Schiller NB, Foster E. Analysis of left ventricular systolic function. Heart. 1996; 75(6 Suppl 2): 17–26, indexed in Pubmed: 8785699.
36. Mercado P, Maizel J, Beyls C, et al. Transthoracic echocardiography: an accurate and precise method for estimating cardiac output in the critically ill patient. Crit Care. 2017; 21(1): 136, doi: 10.1186/s13054-017-1737-7, indexed in Pubmed: 28595621.
37. Vieillard-Baron A, Page B, Augarde R, et al. Echocardiographic pattern of acute cor pulmonale. Chest. 1997; 111(1): 209–217, indexed in Pubmed: 8996019.
38. Pepi M, Tamborini G, Galli C, et al. A new formula for echo-Doppler estimation of right ventricular systolic pressure. J Am Soc Echocardiogr. 1994; 7(1): 20–26, indexed in Pubmed: 8155330.
39. Ryan T, Petrovic O, Dillon JC, et al. An echocardiographic index for separation of right ventricular volume and pressure overload. J Am Coll Cardiol. 1985; 5(4): 918–927, indexed in Pubmed: 3973294.
40. Rydman R, Söderberg M, Larsen F, et al. Echocardiographic evaluation of right ventricular function in patients with acute pulmonary embolism: a study using tricuspid annular motion. Echocardiography. 2010; 27(3): 286–293, doi: 10.1111/j.1540-8175.2009.01015.x, indexed in Pubmed: 20113327.
41. Ghio S, Recusani F, Klersy C, et al. Prognostic usefulness of the tricuspid annular plane systolic excursion in patients with congestive heart failure secondary to idiopathic or ischemic dilated cardiomyopathy. Am J Cardiol. 2000; 85(7): 837–842, indexed in Pubmed: 10758923.
42. Vieillard-Baron A, Loubieres Y, Schmitt JM, et al. Cyclic changes in right ventricular output impedance during mechanical ventilation. J Appl Physiol (1985). 1999; 87(5): 1644–1650, indexed in Pubmed: 10562603.
43. Vieillard-Baron A, Qanadli SD, Antakly Y, et al. Transesophageal echocardiography for the diagnosis of pulmonary embolism with acute cor pulmonale: a comparison with radiological procedures. Intensive Care Med. 1998; 24(5): 429–433, indexed in Pubmed: 9660256.
44. Lhéritier G, Legras A, Caille A, et al. Prevalence and prognostic value of acute cor pulmonale and patent foramen ovale in ventilated patients with early acute respiratory distress syndrome: a multicenter study. Intensive Care Med. 2013; 39(10): 1734–1742, doi: 10.1007/s00134-013-3017-6, indexed in Pubmed: 23860806.

45. Mekontso Dessap A, Boissier F, Charron C, et al. Acute cor pulmonale during protective ventilation for acute respiratory distress syndrome: prevalence, predictors, and clinical impact. Intensive Care Med. 2016; 42(5): 862–870, doi: 10.1007/s00134-015-4141-2, indexed in Pubmed: 26650055.
46. Monnet X, Pinsky MR. Predicting the determinants of volume responsiveness. Intensive Care Med. 2015; 41(2): 354–356, doi: 10.1007/s00134-014-3637-5, indexed in Pubmed: 25649527.
47. Monnet X, Teboul JL. Volume expansion and fluid responsiveness. In: Brown S, Blaivas M, Hirshberg E, Kasal J, Pustavoitau A. ed. Comprehensive Critical Care US. Springer 2016.
48. Monnet X, Teboul JL. Passive leg raising: five rules, not a drop of fluid! Crit Care. 2015; 19: 18, doi: 10.1186/s13054-014-0708-5, indexed in Pubmed: 25658678.
49. Monnet X, Marik P, Teboul JL. Passive leg raising for predicting fluid responsiveness: a systematic review and meta-analysis. Intensive Care Med. 2016; 42(12): 1935–1947, doi: 10.1007/s00134-015-4134-1, indexed in Pubmed: 26825952.
50. Muller L, Toumi M, Bousquet PJ, et al. AzuRéa Group. An increase in aortic blood flow after an infusion of 100 ml colloid over 1 minute can predict fluid responsiveness: the mini-fluid challenge study. Anesthesiology. 2011; 115(3): 541–547, doi: 10.1097/ALN.0b013e318229a500, indexed in Pubmed: 21792056.
51. Lamperti M, Bodenham AR, Pittiruti M, et al. International evidence-based recommendations on ultrasound-guided vascular access. Intensive Care Med. 2012; 38(7): 1105–1117, doi: 10.1007/s00134-012-2597-x, indexed in Pubmed: 22614241.
52. Parienti JJ, Mongardon N, Mégarbane B, et al. 3SITES Study Group. Intravascular Complications of Central Venous Catheterization by Insertion Site. N Engl J Med. 2015; 373(13): 1220–1229, doi: 10.1056/NEJMoa1500964, indexed in Pubmed: 26398070.

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