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Title Page

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Perioperative ultrasound-assisted clinical evaluation

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The authorship listing conforms with the journal's authorship policy, and all authors are in agreement with the content of the submitted manuscript.

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Title

Perioperative ultrasound-assisted clinical evaluation – a case based review

Abstract

Ultrasound is increasingly being adopted into anaesthesia and intensive care practice. The range of ultrasound examination has also increased from transoesophageal echocardiography in cardiac surgery and ultrasound guided nerve blocks and vascular access, to examination of the heart, lungs, abdomen and deep veins. Typically, the use of ultrasound is focused or basic, designed to be performed by the anaesthetist at the patient's bedside in real time, in order to answer clinical question s and to direct therapy. Ultrasound is not performed in isolation, but used to complement clinical evaluation, and accordingly can be considered as "ultrasound assisted perioperative evaluation". Whilst there is good evidence that ultrasound improved diagnostic accuracy and that in turn leads to altered management, there are few data examining whether ultrasound will lead to improved clinical outcomes. This review will examine multiple uses of perioperative ultrasound with case studies to illustrate potential utility.

Keywords

Ultrasound, perioperative, preoperative assessment

Main text

Introduction

Ultrasound has been used in anaesthesia for more than 20 years, primarily transoesophageal echocardiography by cardiovascular anaesthetists, and more recently for guiding vascular access and regional blocks. There has recently been a concerted effort to increase the use of ultrasound to guide acute decision-making[1] which includes transthoracic echocardiography, lung ultrasound, abdominal and gastric ultrasound, and screening for deep vein thrombosis.[2-4] Collectively, these uses are referred to as "perioperative ultrasound" and they will be the focus of our review.

Ultrasound use is too often separated by body regions and medical disciplines. Specialty groups use clinical ultrasound differently, but use can be broadly divided by whether the treating physician performs the ultrasound (point-of-care), or whether the physician is part of a third-party provider of clinical ultrasound services (such as cardiology or radiology). Third-party providers typically perform comprehensive examinations, usually of a single organ system. The resulting diagnostic information is subsequently integrated into a comprehensive clinical evaluation that includes other patient-specific information.

Point-of-care ultrasound differs in being an extension of routine clinical evaluation in which treating physicians use ultrasound to examine organ systems relevant to the clinical question, guided by the patient history and physical examination. An increasingly popular example is focused cardiac ultrasound, which is a goal-directed form of transthoracic echocardiography[5]. This sort of focused examination typically relies on a two-dimensional and color-flow Doppler examination and uses pattern recognition for qualitative rather than quantitative interpretation. However, with further training, selected quantification techniques (such as spectral Doppler assessment of pulmonary hypertension and aortic stenosis) can still be incorporated into the point of care examination to increase diagnostic accuracy. Importantly, additional information from the ultrasound examination is used to guide medical decision making in real time.

The term “perioperative ultrasound” is now taken to include ultrasonic examination of various body regions and organ systems as clinically indicated. Here we will focus on bedside ultrasound diagnosis, where focused surface ultrasound applications are performed by anaesthetists and used to complement clinical evaluation in real time. We will illustrate the concept with a series of case studies (which are modified to assist illustration).

Case example 1

A 78-year-old female suffered a fractured hip 24-hours ago after a fall. Surgery was scheduled for the following morning. She had a prior history of well-treated hypertension, type II diabetes, was a smoker, but did not have known cardiac disease. She lived independently, had normal cognition, but required assistance around the house and with shopping because of hip and knee osteoarthritis. She denied shortness of breath on exertion but did not exert herself because of arthritic pain. She had falls previously and attributed the falls to tripping on the carpets in her home.

The patient's electrocardiogram (ECG) showed left ventricular hypertrophy and sinus rhythm, and her chest x-ray was unremarkable. On auscultation, she had two heart sounds without murmur or added sounds, and her lung fields had scattered crepitations most noticeable in the basal segments.

The anaesthetist elected to proceed, and planned a general anaesthetic with intravenous induction using propofol, oscillometric blood pressure monitoring, and multimodal analgesia for post-operative care. Anticipated disposition was to a surgical ward rather than to a high-dependency unit. Shortly after induction of anaesthesia, the patient suffered profound hypotension which was difficult to treat even with aggressive vasopressor therapy and fluid infusion. Her blood pressure continued to decrease, leading to cardiac arrest and death.

The anaesthetist was left wondering what went wrong, and what may have been missed with their clinical evaluation. Did the patient have an undiagnosed cardiac condition such as severe left or right heart failure, pulmonary hypertension, or aortic stenosis? Was the hypotension caused by anaphylaxis to the muscle relaxant? Now

consider what might have happened if focused cardiopulmonary ultrasound had been used. Key ultrasound features are shown in figure 1, and video S1.

The aortic valve leaflets are heavily calcified and severely restricted consistent with haemodynamically important aortic stenosis, which has been long standing as evidenced by the left ventricular hypertrophy. The left atrial pressure is apparently raised because the atrium is enlarged and there is a fixed left-to-right curvature of the interatrial septum[6]. The lung basal segments demonstrate multiple B lines representing alveolar interstitial syndrome, likely from pulmonary venous congestion. The raised left atrial pressure and pulmonary venous congestion are sinister signs that the aortic stenosis has resulted in left ventricular failure, which places the patient at extreme risk of haemodynamic compromise from induction of anaesthesia.

Using the diagnostic information from the perioperative ultrasound examination, the anaesthetist might have decided to refer the patient for cardiology assessment prior to surgery, as if the focused cardiac ultrasound findings are verified then surgery may be deemed futile. If surgery was to proceed then the anaesthetist might have decided to take proactive measures aimed at preventing haemodynamic collapse, including insertion an arterial catheter for continuous blood pressure monitoring, starting a vasopressor infusion before induction of anesthesia to counter-act anaesthetic-induced vasodilation, optimise fluid administration, and organise postoperative admission to a surgical intensive care unit. Hypotension might then have been prevented, and the patient's surgical course uneventful.

Our point is that substantial cardiopulmonary pathology can be missed even with a careful history and physical examination, and that perioperative ultrasound can enhance clinical management and thus improve outcomes. It is not too difficult to understand how an ejection systolic murmur may go undetected in a busy operating room environment. A subtle but important behavioral change occurs when focused ultrasound is incorporated into the diagnostic process. When critical new information emerges, it allows anaesthetists to be proactive rather than reactive. The first scenario represents a reactive approach to an unexpected intraoperative event, with cardiovascular management being instituted after critical hypotension developed. In

the alternative scenario, the diagnosis of aortic stenosis, diastolic failure, and pulmonary venous congestion alerted the anaesthetist to the high risk of cardiovascular collapse, thus allowing proactive measures including invasive monitoring and a vasopressor infusion.

Airway management is a good analogy. The reactive approach is to induce anaesthesia, paralyze patients, and then try to intubate. But when a difficult intubation is suspected preoperatively, anaesthetists proactively maintain control of the airway by instituting proactive measures to maximize the chances of intubation and have sequential plans for maintaining oxygenation even if intubation fails. Perioperative ultrasound can provide information about various body systems that is analogous to having advance knowledge of a difficult airway — thus permitting comparable proactive management.

Improvements in diagnostic accuracy

One driver for clinical ultrasound use is increasing recognition of just how poor the diagnostic fidelity of stethoscopes is.[7,8] Compared to clinical evaluation alone, clinical ultrasound distinctly improves diagnostic accuracy.[7-9] The largest body of evidence is in the comparison of cardiovascular clinical examination and focused cardiac ultrasound.[10] A summary of the literature investigating the impact of point-of-care focused cardiac ultrasound on diagnosis, management and outcomes in the anesthesia and intensive care setting is shown in table 1

A recent systematic review[9] examined the impact of focused cardiac ultrasound on perioperative management for non-cardiac surgery. It found that clinically important cardiac pathology was missed by clinical evaluation in 17 to 78% of cases. Unsurprisingly, diagnostic advantage was most evident when focused cardiac ultrasound was performed to evaluate a clinical suspicion[8,11-13] rather than routinely.[14]

Amongst asymptomatic patients aged ≥65 years and younger symptomatic patients who were evaluated in preoperative clinic, new cardiac pathology was diagnosed in 10% of the time.[15] However in patients with suspected cardiac disease, focused cardiac ultrasound detected significant pathology in a third and, equally importantly,

ruled out clinically important cardiac pathology in the remainder. A similar study of focused ultrasound in elderly patients scheduled for emergency non-cardiac surgery showed that focused ultrasound was most likely to reveal new diagnoses and influence management when patients were considered to be at cardiovascular risk (74%) than when there was no specific indication for echocardiography (29%).[12] The agreement between clinical evaluation and focused cardiac ultrasound was only 39%, with the divergence resulting largely from important disease being missed on routine clinical examinations. The impact on diagnosis is similar in the critical care setting, with clinically important new diagnoses being identify in 33 to 37% of cases.[16-19]

Case example 2.

An anaesthetist was asked to care for a patient who presented with chest pain and cardiogenic shock requiring urgent cardiac catheterization and potential angioplasty. The patient was in the intensive care unit with the provisional diagnosis of acute myocardial infarction after collapsing on the ward several days after knee surgery. The patient was mechanically ventilated, required high-dose vasopressor and inotrope infusions, with a tachycardia, and was mildly hypotensive. The ECG was non-diagnostic due to the presence of left bundle branch block, and the chest x-ray suggested pulmonary venous congestion. During the cardiac catheterization, which showed normal coronary vessels, the patient had a cardiac arrest and could not be resuscitated. What happened?

Now consider what might have happened if the anaesthetist had supplemented the history and a physical examination with perioperative ultrasound. Key transthoracic images are shown in figure 2 and in video S2. Within seconds, the true diagnosis was apparent. The cardiac ultrasound shows a right ventricular failure pattern with severe right ventricular dilation causing septal shift and compression of the left ventricle, and severe tricuspid regurgitation. The left pulmonary artery is occluded with an echogenic mass consistent with thrombus, and the diagnosis of pulmonary embolism is apparent. Instead of an unnecessary cardiac catheterisation, the patients could have been referred for confirmatory computerized tomography and then pulmonary thrombectomy. Although pulmonary embolus is rarely visualised with TTE as in this case, an embolus causing haemodynamic compromise usually results in the

characteristic TTE appearance of severe dilation and hypokinesis of the right ventricle. The addition of a bedside DVT ultrasound exam may clinch the diagnosis.

Perioperative ultrasound changes management

Changes in diagnosis often changes patient management, sometimes leading to a step-up in treatment intensity when new pathology is diagnosed, and sometimes to a step-down when normal or unremarkable findings provide reassurance that suspected pathology is lacking. A summary of the impact of management changes with focused cardiac ultrasound is shown in table 1, and for non-cardiac ultrasound is shown in table 2. Changes in planned treatments include fluid therapy, vasoactive drugs, type of anesthesia, surgical management, and postoperative admission to critical care. There is evidence that lung ultrasound improves decision-making in emergency departments[20] and intensive care settings,[21] but there remains a paucity of reports on the influence of ultrasound on decision-making for lung,[22] gastric, and deep vein thrombosis in the perioperative setting.

Case 3.

A 25-year-old man presented for surgical fixation of a tibial fracture from a motor vehicle accident. He was previously well, but sustained a seatbelt injury causing rib fractures and abdominal contusion. A chest x-ray at hospital admission showed rib fractures, but no evidence of consolidation or pleural effusion. He was aggressively resuscitated with fluids in the emergency department for hypotension before being transferred to the intensive care unit where he remained normotensive but required supplemental oxygen to prevent hypoxemia.

After induction of general anesthesia, the patient was persistently hypotensive and hypoxemic, requiring 100% oxygen, aggressive fluid resuscitation, and blood transfusion. Postoperatively, the patient was taken for an urgent computerized tomographic scan that showed right upper lobe consolidation, a right pleural effusion, peritoneal free fluid, and signs of splenic rupture. Further hypotension led to emergency reoperation and splenectomy.

Management of this trauma victim might have differed considerably had an ultrasound examination been performed preoperatively, for example a cadiac, lung

and FAST exam. Images are shown in figure 3 and video S3. The cardiac ultrasound demonstrated hypovolemia, with an under-filled and hyperdynamic heart, a small left atrium with normal interatrial septum motion, and a small inferior vena cava. The lung ultrasound demonstrated a normal left lung, a right basal pleural effusion, and consolidation consistent with a contusion or aspiration. The abdominal ultrasound revealed free fluid in the abdomen, and solid gastric contents.

With this knowledge, a laparotomy might have been performed instead of an internal fixation of the tibia, with special care taken during intubation to prevent pulmonary aspiration. An acute pleural effusion in the setting of trauma is likely to be a haemothorax, and the patient could also have been evaluated by thoracic surgery to consider the necessity for a chest tube or thoracoscopy. Ultrasound might also have been used therapeutically as well as diagnostically to guide vascular access and paravertebral blocks for postoperative pain management.

The breadth of perioperative ultrasound.

Perioperative ultrasound is a broad term and suggests that anaesthetists can examine most organ systems at a basic level using ultrasound. It does not imply that the whole body should be examined every time, but rather that ultrasound can be used to complement clinical evaluation where indicated. The heart, lungs, abdomen, and femoral deep veins are relatively easy to examine and interpret at a basic level. A summary of perioperative ultrasound applications and indications is shown in table 3.

Ultrasound is sensitive and specific for pleural effusion, interstitial alveolar syndrome, consolidation, atelectasis, and pneumothorax.[23] Lung ultrasound is easier to learn than focused cardiac ultrasound and has become common practice in emergency medicine and intensive care, where it is effective in bedside diagnosis of respiratory failure.[21] As with focused cardiac ultrasound, lung ultrasound improves diagnostic accuracy when performed as a screening tool in both the cardiac surgical ICU[24] and non-cardiac surgery ICU.[25] Lung ultrasound has additive value when combined with focused cardiac ultrasound, especially for confirmation or detection of pleural effusion. In Australia, lung ultrasound is now more common than transthoracic echocardiography.[26] However, perioperative lung ultrasound remains uncommon.

Ford et al.[22] compared lung ultrasound to clinical evaluation and chest X-rays in patients before and after cardiac and thoracic surgery. For pathologies such as interstitial edema, pleural effusion, pneumothorax, lung atelectasis or consolidation, ultrasound was the superior diagnostic approach. Ultrasound identified important lung pathology that was missed by conventional assessment in 20% of patients, with the largest difference being in detection of interstitial alveolar syndrome and the smallest difference being in detection of pleural effusion. Amir et al.[27] also demonstrated that during central venous catheter insertion, TTE and lung ultrasound could substitute chest radiography for identifying the central venous catheter tip and excluding pneumothorax.

Focused lung ultrasound can be used to identify the etiologies of preoperative or postoperative dyspnea, hypoxaemia,[28] and ventilatory problems. Potential ultrasound-guided thoracic procedures may include confirmation of correct endotracheal tube position,[29] predicting the suitable tube size[30-32] and in facilitating percutaneous subglottic airway cannulation[33-36] and tracheostomy.[37-39]

Other diagnostic uses of clinical ultrasound include examination for gastric contents. It is not possible to clinically examine the abdomen for gastric contents, whereas gastric ultrasound can reliable identify the presence and volume of liquid and solid contents as well as identify an empty stomach[40-42] and is simple to perform and learn[43]. This may assist in avoiding pulmonary aspiration of gastric contents, however neither a change in airway management or reduction in aspiration has yet been demonstrated. Detection of free fluid in the abdomen in the acute trauma setting has been incorporated widely to assist in the acute management of hemodynamically stable and unstable patients.[44] More recently this has been extended to identification of other acute abdominal pathology that could cause shock, making it a worthy addition to focused cardiac and lung ultrasound assessment of peri-arrest and acute abdominal pain[45]. Some examples include identification of abdominal aortic aneurysm, ruptured ectopic pregnancy, identification of fetal heart beat in the gravid uterus.

The femoral veins are readily visualized with ultrasound and assessment for deep vein thrombosis can be performed using a combination of 2-dimensional, color flow

Doppler, and pulsed wave Doppler modalities to identify or exclude proximal and therefore life-threatening thrombus.[46] Ultrasonic evaluation of deep veins can be performed before, during, or after surgery in patients at increased risk for thrombosis.[47]

Perioperative ultrasound may improve outcome

Although it is logical that improved diagnosis leads to better management decisions, which in turn may affect outcome, the evidence for this sequence is weak.[48] The best current evidence in the perioperative setting is restricted to a retrospective cohort study and a small pilot study, both of which evaluated the impact of focused cardiac ultrasound on clinical outcomes after surgery for hip fracture.

The retrospective cohort study reported a lower 30 day mortality (3/64 = 4.7% vs. 10/66 = 15.2%, log rank P = 0.047), and 12-month mortality (11/64 = 17% vs. 22/66 = 33%, log rank P = 0.031) in participants who received focused cardiac ultrasound prior to surgery compared to historical controls with similar risk factors who did not receive focused cardiac ultrasound before surgery.[12] The randomized pilot study of 100 participants reported group separation favoring the ultrasound group for the 30-day primary composite outcome of all cause death, acute kidney injury, non-fatal cardiac arrest, myocardial infarction, stroke, or pulmonary embolism of 14% vs. 24% (OR 0.54, 0.19–1.52).[49] Obviously, large robust trials are needed to confirm that focused ultrasound not only improves diagnosis and alters management, but also improves substantive patient outcomes.

Training anaesthetists in perioperative ultrasound

Many medical schools are now incorporating clinical ultrasound into their programs.[50] These young graduates will have basic ultrasound skills before they enter anaesthesia training. The next decade of training will thus presumably focus on training existing specialists and residents, along with providing more advanced anaesthesia-specific training for recent medical school graduates.

Most non-cardiac anaesthetists will use perioperative ultrasound in a goal-directed manner, relying on basic imaging with two-dimensional and color-flow Doppler. Some anaesthetists will elect to increase their knowledge base to a diagnostic level (as

occurs with cardiac anaesthesia), but for most the additional skills will be unnecessary. This is illustrated in figure 4 where the expertise pyramid in clinical ultrasound shows that the broad base of use will be "ultrasound assisted examination" and ultrasound guided procedures". It is also the "getting started" point for all anaesthetists and maps out a logical progression to increased competency over time.

Clinical ultrasound is a practical skill, training must therefore satisfy three core components of learning: knowledge (image interpretation), hands-on learning (image acquisition), and practice (clinical experience). The challenge is to provide education that is easy to acquire, sufficient equipment for everyday use, and societal leadership within anesthesiology. The Society of Cardiovascular Anaesthesiologists has produced a course on perioperative ultrasound that includes the three core components to learning: knowledge base via online learning, practical training workshops, and supervised logbook of practice cases (www.scahq.org/Education/ContinuingMedicalEducation/PerioperativeUltrasound.aspx). The Association of Anaesthetists of Great Britain and Ireland promote practical ultrasound training workshops and online learning programs in basic transthoracic echocardiography. Simulators have the potential to accelerate learning point-of-care ultrasound. Simulators are becoming available for most types of perioperative ultrasound for procedures and diagnosis. Newer high-fidelity cardiac and lung simulators now mimic commonly (and uncommonly) encountered perioperative pathology to facilitate learning of image acquisition, interpretation, and anatomy. They also provide metrics to track learning progress. Existing workshop based and peer to peer learning is used to facilitate uptake of perioperative ultrasound, those learning modalities remain difficult to scale as expansion to meet the rise in demand for training remains restricted by availability of trainers. Ultrasound simulators may be used for self-directed training without the use of supervised trainers. A scalable education program has been developed by the University of Melbourne (FCU TTE Course[51]) that is based on an almost entirely automated and self-directed course using eLearning (knowledge base), simulators (hands on learning), and an electronic logbook (practice) that is administered with an on-line platform. This model also works for other diagnostic ultrasound (lung and abdominal) and ultrasound-guided procedures.

Availability of ultrasound equipment is rapidly increasing in anaesthesia. The same ultrasound machines used for vascular access or regional anesthesia can be equipped with transthoracic or abdominal ultrasound probes facilitating the breadth of perioperative ultrasound examination. But perhaps the most disruptive change is the proliferation of hand-held ultrasound machines which can be individually owned and are highly transportable. These devices are small enough to fit inside a coat pocket or handbag, and therefore routinely be available when physicians evaluate patients.

Conclusion

Anaesthesia practice is undergoing a transition from stethoscope-based clinical evaluation to ultrasound-assisted examination and ultrasound-guided procedures. Perioperative ultrasound examinations improve diagnostic accuracy and alter management. Large trials are still needed to determine whether patient outcomes are substantively improved by ultrasound-assisted diagnoses. Much work is also required in ensuring patient safety during the learning curve of point of care ultrasound so as to limit the consequences of false positives and negatives in ultrasound trainees. But in the meantime, physicians are already increasingly incorporating ultrasound into clinical evaluations — a trend that seems unlikely to abate.

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Table 1 Impact of point of care focused cardiac ultrasound (FCU) on diagnosis, management and outcome of patients in the anaesthesia and intensive care setting

Reference	Methodology	Indication for FCU	Cohort	Summary
Impact of FCU on diagnosis and management				
Heiberg 2016[9]	Systematic review: 5 prospective observational studies (2009-2014)	Anaesthesia setting. Screening (age>18 or >65y), or as requested by attending anaesthesiologist, or suspected cardiac disease or abnormal hemodynamic state, or hemodynamic instability	568 patients undergoing elective or urgent non-cardiac surgery. FCU performed preoperatively (546) or postoperatively (22) by anaesthesthetists	Changed diagnosis in 17-78% Changed management in 12-82% including surgical workflow, intraoperative monitoring, hemodynamic management and level of postoperative care.
Heiberg 2016[9]	Systematic review: 6 prospective observational	Intensive care setting. Suspected cardiac disease or abnormal	1318 patients from 6 prospective observational studies in patients admitted to	Changed diagnosis in 8-84% Changed management in 16-49% including changes to fluid administration, inotrope

	studies (2004-2009)	hemodynamic state or hemodynamic instability	intensive care. FCU was performed by intensivists, cardiac sonographers or cardiologists.	or drug therapy, and treatment limitation.
Heiberg 2016[9]	Systematic review: 3 prospective observational studies (2007-2015)	Intensive care setting - after cardiac surgery. Screening, suspected cardiac tamponade, or suspected cardiac dysfunction	206 patients. FCU was performed by intensivists, cardiac sonographers or cardiologists.	Changed diagnosis in 13-51%. Changed management in 13% (surgery for cardiac tamponade).
Haji 2017[25]	Prospective observational study	Intensive care setting. Patients admitted <24h to intensive care were screened with FCU and lung ultrasound.	93 patients	Changed cardiac diagnosis in 67%. Changed cardiac management in 60 included increased (12%) or decreased (23%) fluid therapy, and commencing (10%), changing

				(7%) or cessation (9%) of inotropic, vasoactive or diuretic drug infusions. Changed lung diagnosis in 59%. Changed lung management in 5% including increased ventilatory support in 3% and pleural tap in 2%
Joseph 2004[18]	Prospective observational study	Shock (systolic BP < 100 mm Hg or fall in BP >=25% and inotrope use or evidence of low output or pulmonary/venous congestion)	100 patients admitted to intensive care. FCU was performed by cardiac sonographers.	Cardiac shock identified in 63%. Sensitivity of FCU for cardiac cause of shock was 100%, specifity 95%, positive predictive value 97%, and negative predictive value 100%. There were relative contraindications to TEE in 15% of cases.
Impact of FCU on outcome				

Canty 2017[49]	Pilot randomised controlled trial	Anaesthesia setting. Hip fracture surgery, Age>65y, no TTE<1 month prior to surgery	100 patients (49 received FCU, 51 controls). The primary composite outcome was any death, acute kidney injury, non-fatal myocardial infarction, stroke, pulmonary embolism or cardiac arrest within 30 days of surgery. FCU was performed by anaesthesiologists.	The 30-day primary composite outcome occurred in 7 of the FCU group patients and 12 of the control group patients (group separation 39.3%). Number needed to treat (NNT) 10.9.
Canty 2012[12]	Retrospective cohort study	Anaesthesia setting. Hip fracture surgery, Age>65y, ASA 3, no TTE<6 months prior to surgery	64 patients who received preoperative FCU were compared with 66 patients who did not receive preoperative FCU who had similar risk factors. FCU was	Preoperative FCU was associated with lower mortality at 30 days (4.7% v 15.2%, p=0.047, NNT 9.5) and 12 months after surgery (17.1% v 33.3%, p=0.031, NNT 6.2).

			performed by anaesthesiologists		
Reference	**Ultrasound modality**	**Methodology**	**Indication for ultrasound**	**Cohort**	**Summary**
Kanji 2014[48]	Retrospective cohort study	Intensive care setting. Shock	110 patients admitted to intensive care received	Patients receiving FCU received less fluids (49 {33-	
Lichtenstetin	Lung ultrasound	Prospective (despite vasopressor	Intensive care FCU and outcome	260 patients who had a	Lung ultrasound could determine the definitive
		infusion and intravenous fluid challenge achieving a CVP of at least 8 mm Hg)	compared to 110 matched retrospective controls. FCU was performed by intensivists.	74} vs 66 {42-100} mL/kg, P = .01), more dobutamine infusions (22% vs 12%, P = .01). FCU was associated with less mortality at 28-days (34% vs 44%, P = .04, NNT 9.1), less stage 3 acute kidney injury (20% vs 39%), and more days alive and free of renal support (28 {9.7-28} vs 25 {5-28}, P = .04).	

Table 2 Impact of point of care non-cardiac ultrasound on diagnosis, management and outcome of patients in the anaesthesia and intensive care setting

2008[21]		observational study	setting. Patients admitted to intensive care with acute respiratory failure.	definite diagnosis.	diagnosis of respiratory failure in - asthma or COPD (sensitivity 89%, specifity 97%) - pulmonary edema (sensitivity 97%, specifity 95%) - pulmonary embolism (sensitivity 81%, specifity 99%) - pneumothorax (sensitivity 81%, specifity 100%) - consolidation (sensitivity 89%, specifity 94%) Lung ultrasound can help the clinician make a bed-side diagnosis in patients with acute respiratory failure.
Volpicelli 2012[23]	Lung ultrasound	International consensus conference on evidence base for bed-side lung	Emergency and intensive care setting.	Literature reviewed from 1966 to 2011	Lung ultrasound is more accurate than chest x-ray in diagnosis of pneumothorax, interstitial syndrome, consolidation and pleural effusion. Lung ultrasound is recommended for diagnosis of pulmonary embolism if CT is not available.

		ultrasound			
Ford 2017[22]	Lung ultrasound	Prospective observational study	Anaesthesia setting. Patients undergoing either cardiac or thoracic surgery either before surgery or after surgery when on the ward and who had received a chest x-ray within 24 hours and age>18y.	78 patients of whom 42 were assessed before surgery and 36 after surgery.	Lung ultrasound identified lung pathology that was missed by clinical assessment and chest x-ray in 20% of patients. Lung ultrasound detected lung pathology in 10 of 42 (24%) patients before surgery in the preoperative clinic and in 34 of 36 (94%) patients after surgery.
Haji 2017[25]	Lung ultrasound	Prospective observational study	Intensive care setting. Patients admitted <24h to intensive care were screened with FCU and lung ultrasound.	93 patients	Changed lung diagnosis in 59%. Changed lung management in 5% including increased ventilatory support in 3% and pleural tap in 2%. Changed cardiac diagnosis in 67%. Changed cardiac management in 60 included increased (12%) or decreased (23%) fluid therapy, and

					commencing (10%), changing (7%) or cessation (9%) of inotropic, vasoactive or diuretic drug infusions.
Alsaddique 2015[25]	Lung ultrasound	Prospective observational study	Intensive care and cardiac surgery ward setting. Patients admitted to intensive care after open cardiac surgery were screened with FCU and lung ultrasound at three time-points: on the first postoperative day, after extubation and removal of chest drains, and when ready for discharge from the ward. FCU	91 patients	FCU and/or lung ultrasound changed the diagnosis of important cardiac and/or respiratory disorders in 61patients (67%). New cardiac findings included cardiac dysfunction (38 patients), pericardial effusion(5), mitral regurgitation(2), and hypovolemia(1). New respiratory findings included pleural effusion(30), pneumothorax(4), alveolarinterstitial syndrome (3) and consolidation (1).

			was performed by cardiac technicians.		
Perlas 2009[41]	Gastric ultrasound	Prospective observational study	Anaesthesia setting.	18 healthy volunteers ingested 0 to 500mL fluid and solid meal and underwent gastric ultrasound.	The gastric antrum provided the most reliable quantitative information for gastric volume. The antral cross-sectional area correlated with volumes of up to 300 mL in a close to-linear fashion, particularly when subjects were in the right lateral decubitus position. Sonographic assessment of the gastric antrum and body provides qualitative information about gastric content (empty or not empty) and its nature (gas, fluid, or solid). The fundus was the gastric area least amenable to image and measure.
Perlas 2011[42]	Gastric ultrasound	Prospective observational study	Anaesthesia setting.	200 patients fasted for elective surgery	Eighty-six patients were classified as grade 0 (empty antrum); 107 patients as grade 1 (minimal fluid volume detected only in the right lateral decubitus position); and 7 patients were classified as grade 2 (antrum clearly

					distended with fluid visible in both supine and lateral positions).
Perlas 2013[43]	Gastric ultrasound	Prospective observational study	Anaesthesia setting. Patients undergoing upper gastrointestinal endoscopy.	108 patients were randomly assigned to ingest 0, 50, 100, 200 or 400mL apple juice. After gastric ultrasound gastric fluid was aspirated by endoscopy and measured and compared to estimated volume from ultrasound.	Gastric ultrasound volume assessment correlated to gastric volume of aspirated fluid.
Burnside 2008[47]	Deep venous thrombosis (DVT) ultrasound	Systematic review: 6 relevant publications identified.	Emergency medicine setting. Patients presenting with clinical suspicion of DVT.	936 patients received DVT ultrasound assessment by an emergency medicine physician and then by a radiologist (reference	Overall sensitivity of emergency physician diagnosis of DVT was 0.95 (0.87 to 0.99) and specificity of 0.96 (0.87 to 0.99) and hence may be accurate for the diagnosis of DVT compared with radiology-performed ultrasound.

		method).
Ultrasound Type	**Indications**	**Clinical examples**

Table 3 Applications of perioperative ultrasound

Transthoracic Echocardiography	Hypotension Shortness of breath Peri-arrest Age > 65 years Unable to exercise Known cardiac disease Unstable symptoms or signs consistent with heart disease	A 70-year-old patient for total hip replacement who cannot exercise due to osteoarthritis – unidentified aortic stenosis Undiagnosed hypotension in the PACU – a vasodilated state During trauma resuscitation – hypovolemia consistent with blood loss 55-year-old patient with ischemic heart disease and cardiomyopathy undergoing major surgery – mild systolic failure only and valves normal – proceed as planned 80 year-old patient is short of breath and hypotensive after hip fracture surgery – severe right heart failure – decision to palliate
Lung ultrasound	Tachypnea or shortness of breath Suspected pleural effusion or pneumonia Screen for pneumothorax after central line insertion Any cause of hypoxia Peri-arrest to rule out pneumothorax Chest trauma to identify hemothorax or pneumothorax	A 27-year-old lady has shortness of breath after emergency Cesarean section – right upper lobe consolidation - consistent with aspiration Routine chest examination on an ICU ward round – more than half the patients will have some pathology Examination for pneumothorax after a difficult central line insertion A cardiac arrest call with pulseless electrical activity – pneumothorax identified A 24-year-old man with seatbelt injury is short of breath and hypoxic – a large hemothorax with lung consolidation (contusion)

	Undiagnosed fever Possible gastric contents aspiration	
Abdominal ultrasound	Peri-arrest Bladder scan Suspected abdominal aortic aneurism Foetal viability (heart beat)	A 45-year-old trauma victim with abdominal injury and severe hypotension – free peritoneal fluid identified An elderly patient is anuric after a prolonged operation without a catheter- a bladder scan to identify whether the bladder is full (obstruction) versus empty (renal failure). An elderly patient with flank pain and hypotension - possible aneurysm A 26-year-old pregnant patient has the vaginal bleeding - fetal heartbeat is seen demonstrating fetal viability
Gastric Ultrasound	Screening for gastric contents	A 55-year-old diabetic patient for emergency surgery has full stomach with solid contents
Venous Ultrasound	Screening for deep vein thrombosis	A patient presenting for multiple repeated skin grafts has a swollen let – ultrasound reveals a femoral DVT
Procedural Ultrasound	Ultrasound guided regional anaesthesia Ultrasound-guided venous access Ultrasound-guided intercostal catheter	A 45-year-old motor vehicle accident patient has limb fractures, shortness of breath and hypotension, and venous access is not successful. Ultrasound used to locate veins and guide access, femoral nerve block under ultrasound

	insertion Ultrasound-guided pericardial effusion drain insertion	guidance inserted for post-operative pain relief and an ultrasound-guided intercostal catheter inserted to manage pneumothorax.

Figure legends

Figure 1

Parasternal transthoracic echocardiography images during mid-systole are shown in panel A (parasternal long axis), B (parasternal short axis) and C (apical long axis) demonstrating a heavily calcified and severely restricted aortic valve (AV), and a dilated left atrium (LA), and color flow turbulence in the ascending aorta consistent with post stenotic flow acceleration (Acc). A lung ultrasound image of the left posterior lower zone (LPL) is shown in Panel D, demonstrating multiple B lines, representing alveolar interstitial syndrome that could be from heart failure.

Figure 2

Panel A is a parasternal long axis view showing a dilated right ventricular (RV) outflow tract, and a small left atrium (LA). Panel B is a parasternal short axis view showing a dilated right ventricle and a small left ventricle (LV) with a D-shaped interventricular septum consistent with right ventricular failure. Panel C is a parasternal short axis view angled up to see the pulmonary artery. The right pulmonary artery (RPA) appears normal, but the left pulmonary artery (LPA) is occluded by an echogenic mass consistent with thrombus. Panel D is an apical four-chamber view showing the dilated RV and severe tricuspid regurgitation (TR).

Figure 3

Panel A is a parasternal short axis view of the mid left ventricle showing a small end diastolic cavity size. Panel B right posterior lung showing a pleural effusion and consolidated lung. Panel C shows the gastric antrum containing both fluid and solid contents. Panel D is the left upper abdominal quadrant showing free fluid between the spleen and the peritoneum

Figure 4

The expertise pyramid demonstrating the progression from basic ultrasound use to expert use

Online supporting information

Video S1

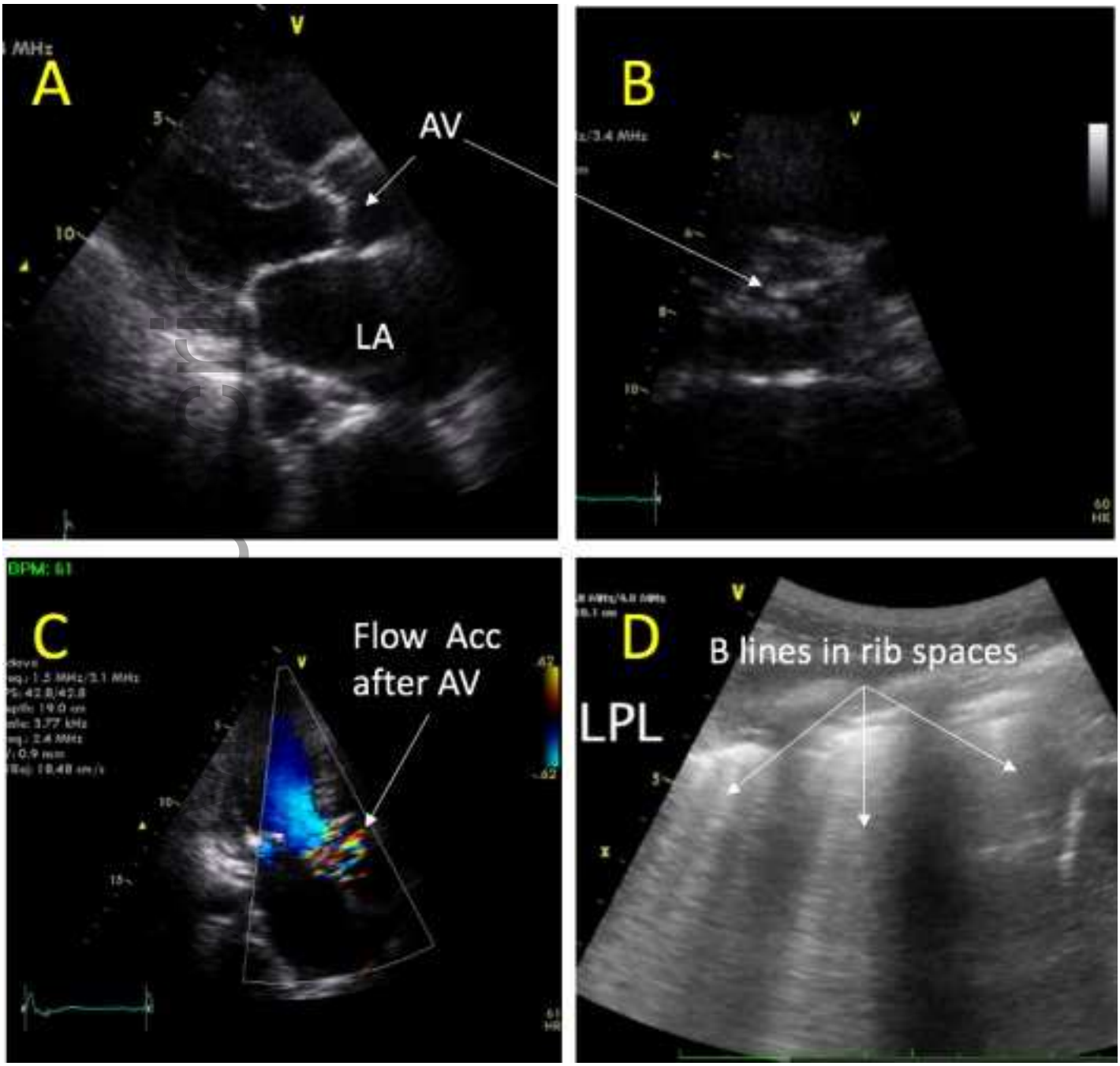
Focused transthoracic echocardiography and lung ultrasound for case study 1. Key features include aortic stenosis; and high left atrial pressure and interstitial edema pattern consistent with diastolic failure

Video S2

Focused transthoracic echocardiography for case study 2. Key features include a right ventricular failure pattern and severe tricuspid regurgitation along with an occluded left pulmonary artery consistent with pulmonary embolus

Video S3

Focused transthoracic, abdominal and lung ultrasound examination for case study 3. Key features show a hypovolemic left ventricle, full stomach, free fluid in the abdomen near the spleen and a pleural effusion.



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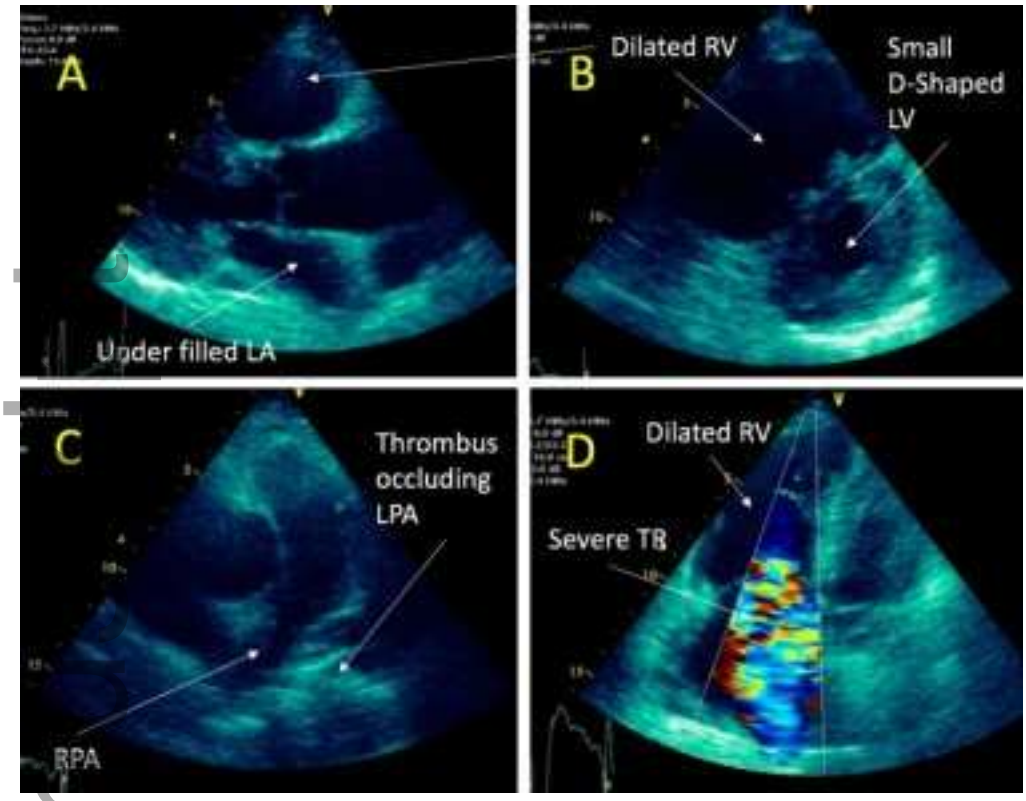

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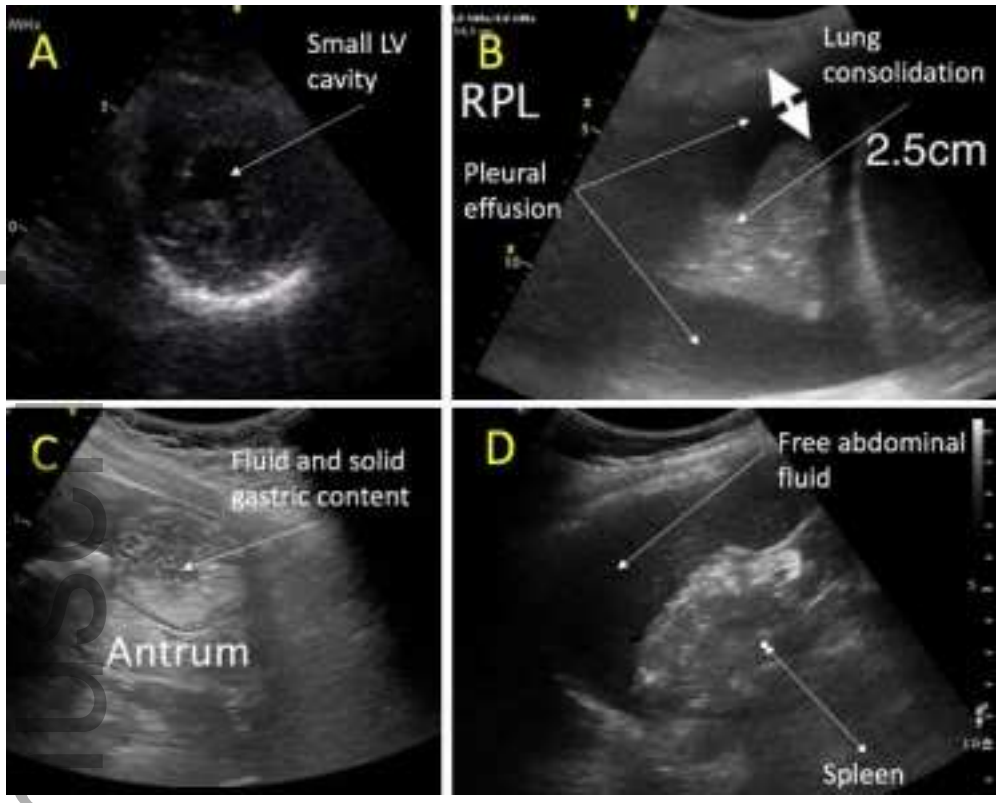

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