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ORIGINAL ARTICLE

Ultrasound-guided placement of central venous catheters: a comprehensive guide for the clinician

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Abstract

Background: Using ultrasound as a guidance tool during central venous catheter placement has repeatedly been shown to improve procedural safety. More recent evidence has shown its potential as a diagnostic modality to detect placement-associated complications. A protocol combining these modalities is lacking. This article uses the Indication, Acquisition, Interpretation and Medical decision-making (I-AIM) model, common to other ultrasound protocols, to provide a systematic ultrasound approach to guide central venous catheter placement and assess potential related complications. It is part of a larger series published in this journal.

Methods: Relevant articles were found in a thorough search in PubMed using the MeSH terms: “diagnostic imaging” or “ultrasonography” or “sonography” and “central venous catheter” or “central venous cannulation” and “complications” or “placement procedure”. Studies conducted on patients younger than 18 years and studies conducted in animals were excluded. Two independent researchers evaluated the articles for relevance and quality. The results of the various studies were used to create the following structured ultrasound approach.

Recommended approach: Following the I-AIM model, acquiring the most valuable images is subdivided into patient, probe, picture and protocol considerations. Ultrasound guidance during central venous catheter placement should be conducted in four steps: pre-cannulation, confirming patency, dynamic guidance during insertion, and confirmation of intravenous central venous catheter position. After these steps, ultrasound should be used in the diagnostic evaluation of malposition and iatrogenic pneumothorax.

Conclusions: This model provides a comprehensive and ready to use ultrasound approach to guide central venous catheter placement and assess potential placement associated complications.

Introduction

The use of central venous catheters (CVCs) is of vital importance in treating and stabilising most patients admitted to the intensive care unit (ICU).[1] However, CVC placement can lead to mechanical, infectious and thrombotic complications, with a total complication rate of around 5%.[2] In the case of mechanical complications, serious situations such as iatrogenic pneumothorax and CVC malposition are the most common. As these complications are potentially of great detriment to patient health, the current guidelines require that a chest X-ray is routinely performed after CVC placement. This is, however, cost-ineffective, time consuming and exposes the patient to additional ionising radiation.[3]

To decrease the risk of mechanical complications, ultrasound imaging is already routinely used to guide the needle and guidewire during CVC placement. So called dynamic guidance is nowadays even considered best practice.[4] Besides insertion guidance, ultrasound imaging has the potential to be used in a broader sense with regard to CVC placement. An additional view of the right atrium potentially increases the safety of the procedure because it decreases the likelihood of malposition.[5-7] In addition, evaluation of mechanical complications using ultrasound might also be adequate; ultrasound imaging is known to be an acceptable method in ruling out iatrogenic pneumothorax.[8] More recently, its ability to detect pneumothorax has been attributed a higher sensitivity than chest X-ray.[9] In addition, ultrasound is likely to be a feasible diagnostic modality for other complications of CVC placement such as malposition.[10,11] Even if visualisation of the CVC itself is not possible due to high positioning in the superior vena cava (SVC), malposition can be evaluated using microbubbles (bubble test).[10,12] Taking all these benefits into account, creating a structured ultrasound procedure combining the guidance and diagnostic potential of ultrasound would be worthwhile.

We suggest that proper CVC placement and evaluation of its position and mechanical complications using ultrasound can be structured using the Indication, Acquisition, Interpretation and Medical decision-making (I-AIM) framework for ultrasound imaging.[13] This framework was especially designed as a mnemonic for ultrasound imaging and to provide structure in teaching ultrasound techniques, and has been used in other point-of-care ultrasound (POCUS) protocols.[13-15] The core principle is the subdivision of the procedure into the aforementioned four components. This model can be used for a wide variety of ultrasound examinations and is tailor-made for articles such as this one, especially because it is part of a series in this journal on ultrasound indications beyond heart and lungs.[16-18]

Methods

Relevant articles were found in a thorough search in PubMed using the MeSH terms: ("diagnostic imaging" or "ultrasonography" or "sonography") and ("central venous catheter" or "central venous cannulation") and ("complications" or "placement procedure"). Studies conducted on patients younger than 18 years and studies conducted in animals were excluded. Two independent researchers evaluated articles for relevance and quality (TSS and PRT).

The results of these studies were used in the writing of an I-AIM structured recommendation for departmental implementation of ultrasound as both a guidance and diagnostic modality in periprocedural CVC placement. The first step of this model is indication, in which the medical necessity for the use of ultrasound as a guidance tool during placement and as diagnostic modality for the evaluation of mechanical complications is addressed. In the second step – acquisition – patient characteristics are assessed and a description is given of how the right probe, machine settings and scanning technique can be used to acquire high-quality pictures. A structured protocol of the placement and diagnostic procedure is also part of this second step. The third step is interpretation of the images, which is conducted through evaluation of anatomic structures and artefact recognition. The fourth and final step, medical decision-making, encompasses follow-up based on the ultrasound findings and clinical context, pre-test probability and physician interpretation of these parameters.[13]

Indication

The two indications for the use of ultrasound in the CVC placement procedure that are supported by the literature are: 1) use as a guidance tool and 2) as a diagnostic tool for mechanical complications. Ultrasound guidance of CVCs lowers the risk of mechanical complications and increases the chance of successful placement.[4,19,20] Therefore, the general sentiment is that ultrasound should always be preferred over non-ultrasound-guided placement.[4,19,20] It is also a relatively simple procedure that can easily and rapidly be taught to both inexperienced and experienced physicians.[21] Using a dynamic scanning technique is favoured over a static technique for it provides continuous insight and helps to manage anatomical variance.[22] Thus, dynamic ultrasound guidance of CVCs forms the first part of the proposed structured approach.
In recent research, ultrasound imaging as a diagnostic tool is shown to be a feasible alternative to chest X-ray, with non-inferior reliability in the detection of both iatrogenic pneumothorax and CVC malposition.[10,11] In addition, ultrasound examination is superior to chest X-ray with regard to time efficiency and comes without harmful radiation.[10-12] Despite the fact that a final conclusion on the topic has yet to be drawn, this protocol includes diagnostic follow-up as a second indication for the use of ultrasound in CVC placement.

Acquisition

Following the I-AIM model, acquiring the most valuable images is sub-divided into probe (choosing the right probe for each procedure), patient (characteristics and pre-cannulation), picture (using the various settings of the ultrasound machine to produce high-quality images) and protocol considerations (procedure explained step by step); each of these subdivisions will be discussed.[13] Ultrasound evaluation of CVC placement can be conducted in five steps: pre-cannulation, confirming patency, dynamic guidance during insertion, confirmation of CVC position and diagnostic evaluation of complications. The first two steps are discussed in the 'patient' paragraph, the following three steps will be discussed in the 'protocol' paragraph. These steps provide a clear structure to the procedure. When encountering difficulties in one of these steps, going back to the previous step can help adherence to this structure. A quick overview of these steps is provided in *figure 1.*

Probe

A high frequency (10-12 MHz) linear probe is best suited for imaging the entry vein, needle introduction and ruling out pneumothorax. For the view of the guidewire in the right atrium, a lower frequency (1-5 MHz) phased array probe should be used for adequate depth penetration. A sterile drape should be used to cover the probe when used near the entry site. Assistance is needed when switching probes in order to maintain sterility.

I. Prescanning

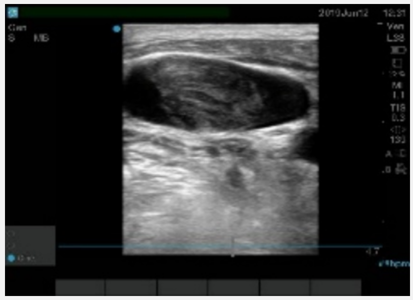
a. Scanning for entry-vein

- Identify relevant anatomic structures (vein, artery, muscle)
- Alternate between a longitudinal- and transverse view

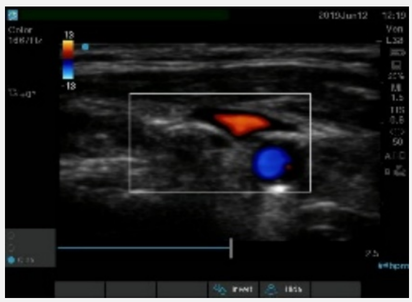
Suitable entry vein

b. Confirming patency

- Un-thrombosed veins collapse when pressure is applied
- Use Doppler to assess flow



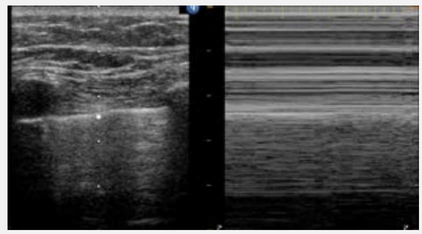
Non-collapsing thrombosed vein



Doppler flow through artery and collapsing vein

c. Confirm lung sliding

- Midclavicular in the 2nd intercostal space on the ipsilateral side of the entry vein



Lungsliding in B- and M-mode

II. Dynamic needle-guidance

- Use a transverse view of the entry vein
- Introduce the needle under continuous ultrasound guidance

Needle in entry vein

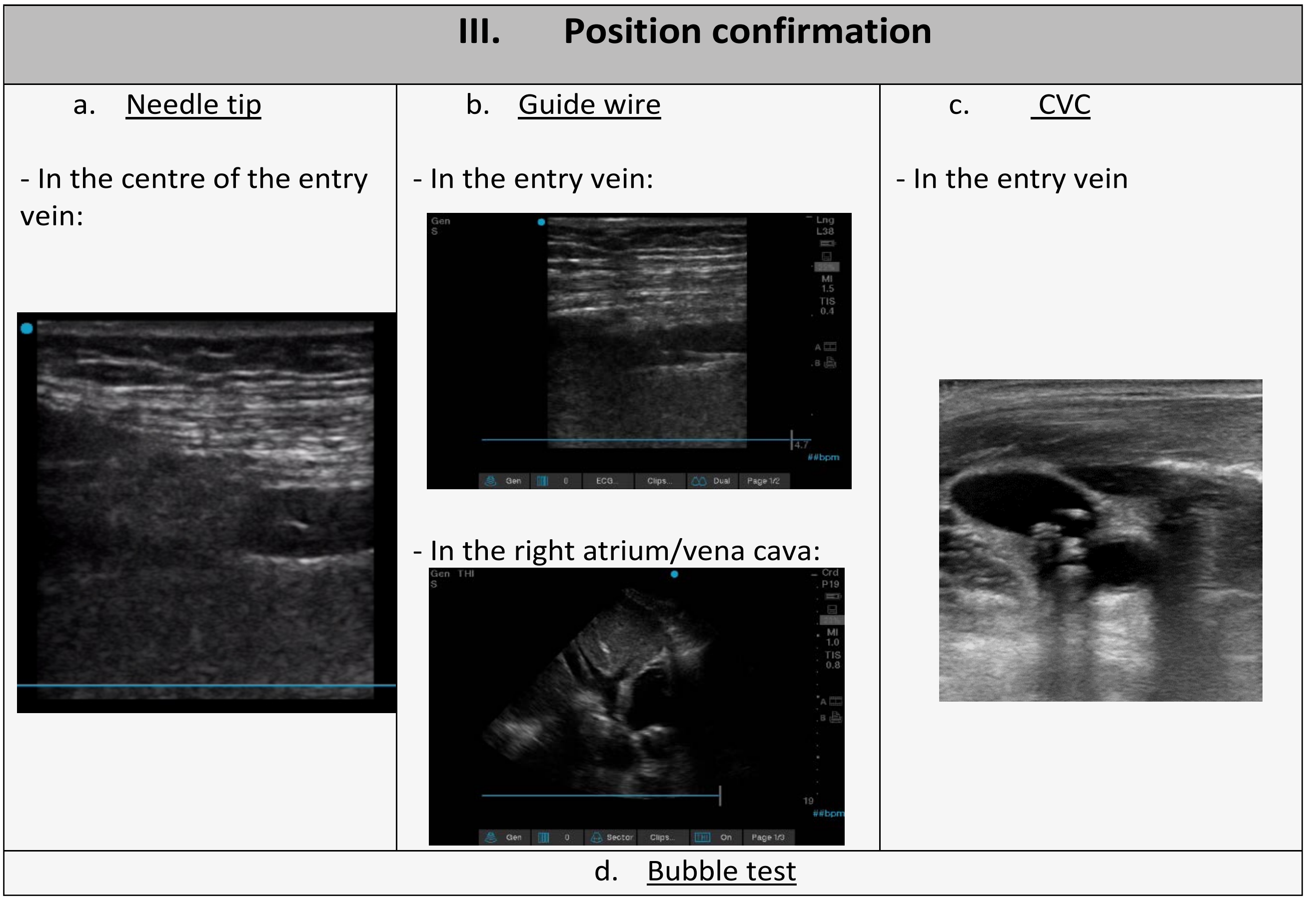


Figure 1. I-V Complete protocol diagram with images depicting ultrasound guidance of CVC insertion and evaluation of pneumothorax and malposition. CVC: central venous catheter; CXR: chest X-ray.

Patient

Pre-cannulation and confirming patency: In order to provide the best care, several steps should be taken before inserting the CVC. Initially, clinical pre-scanning should be conducted. Start by choosing the entry site, then identify the surrounding anatomic landmarks. Central venous access can be acquired through CVC insertion into the internal-jugular vein (IJV), subclavian vein (SV) or the femoral vein. Cannulation through the right IJV is preferred for quick access due to a lower risk for iatrogenic pneumothorax than CVCs placed in the SV, a close proximity to the heart and the fact that the CVC does not have to curve around corners to reach its desired position.[2] For long-term treatment, e.g. treatment with intravenous antibiotics or chemotherapy, subclavian access might be preferable due to lower risk of infection and thrombosis.[2]

Choosing a Trendelenburg position significantly increases vein diameter; however, there are contraindications to moving patients into this position, e.g. increased intracranial pressure or severe peripheral oedema. It is advised to judge each situation individually and adjust accordingly. For subclavian and jugular access the patient should ideally be in the Trendelenburg position. For femoral access reverse Trendelenburg or supine position is best suited. In both cases a 10% tilt provides sufficient increase in vein diameter.[23-25] Before proceeding, confirm lung sliding on the side of the proposed CVC insertion (*figure 1, Ic*). Then distinguish veins from arteries in order to prevent accidental arterial puncture by applying pressure to the skin with the probe; veins will easily collapse whereas arteries will not. Doppler may be used at this stage to assess flow to or away from the probe, if necessary. Check that the entry vein is wide enough to facilitate a CVC and that it is free of thrombosis (*figure 1, Ib*). Finally, evaluate the distance between the vein and the artery and adjust angle and depth of needle insertion accordingly.

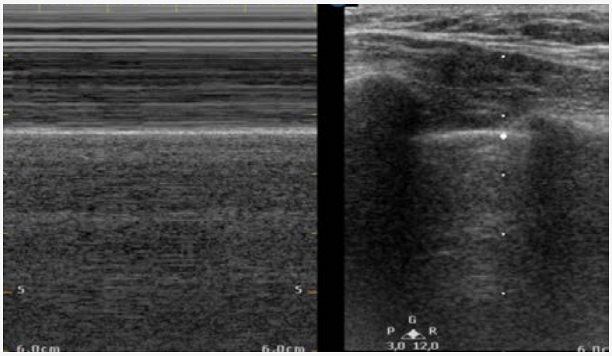
Picture

There are two main modes in which to acquire images on the ultrasound machine: brightness mode (B-mode), and motion mode (M-mode). Using these two modes can aid accurate assessment of anatomical structures. B-mode shows a two-dimensional representation of structures. M-mode shows movement of anatomical structures in a specific, single line plotted over time. B-mode is used for the identification of bodily structures, e.g. pleural lining, lung artefacts and the right ventricle. B-mode should also be used to locate the needle

IV. Diagnostic evaluation of pneumothorax

a. Healthy lung

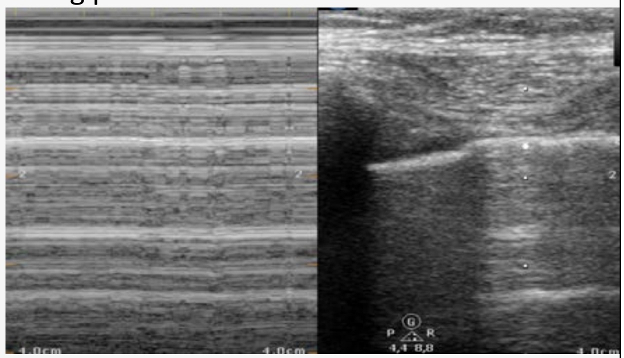
- A-lines
- Some B-lines or comet tails
- Lung sliding/lung pulse



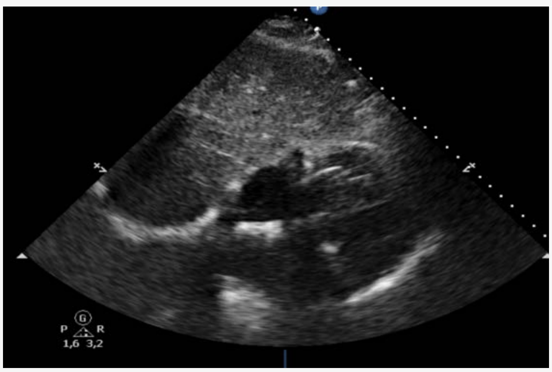
M-mode and B-mode of healthy lung

b. Collapsed lung

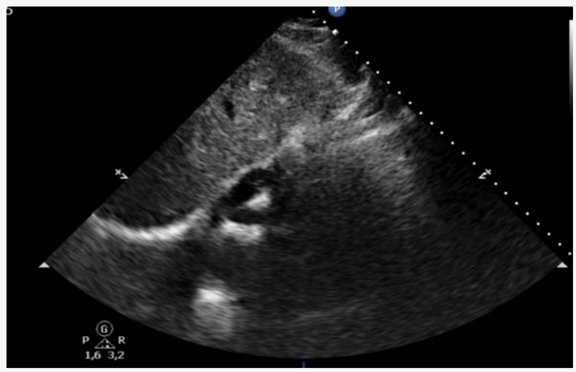
- A-lines
- No B-lines or comet tails
- Absent lung sliding
- Lung point



M-mode and B-mode of pneumothorax



No contrast



With contrast

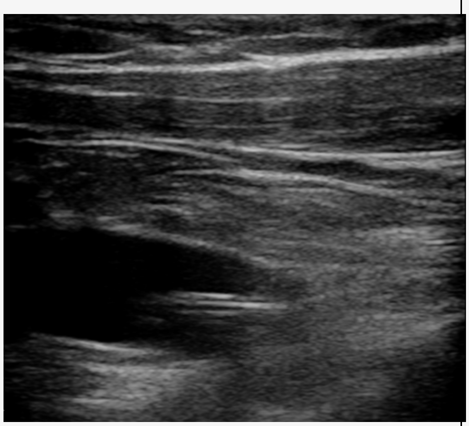
V. Diagnostic evaluation of malposition

a. Malposition unlikely

- Guide wire confirmed in right atrium
- CVC not visible in ipsi- or contralateral veins
- Asymptomatic patient
- Length of CVC corresponding with assumed depth

b. Malposition confirmed

- CVC visible in ipsi- or contralateral vein



Malposition in contralateral SV

c. Malposition suspected

- CVC not visible in ipsi- or contralateral veins
- Length of CVC not corresponding with assumed depth
- Symptomatic patient

INDICATION FOR CXR

tip and guidewire in the entry vein and to evaluate aberrant CVC migration into ipsilateral or contralateral veins. For the assessment of malposition, the 'vein' setting should be selected on the ultrasound machine. The 'lung' (tissue harmonics should be turned off) and 'cardiac' settings should be used for assessing the presence of iatrogenic pneumothorax and the visualisation of the guidewire in the right atrium, respectively. Adjustment of depth, gain and focus to optimise image quality should be adjusted to patient anatomy. Choosing the ideal acoustic windows will be discussed in the next section called: 'protocol'.

Movement of the pleural lining (lung sliding) can be observed in B-mode ; however, this can sometimes be difficult. To increase reliable assessment, M-mode can also be used to assess lung sliding. A more detailed discussion of lung ultrasound will follow under 'Diagnostic evaluation', which is part of the next section on 'Protocol'; this to ensure that a clear overview of all necessary steps can be found in one place.

Protocol

The following section describing the protocol for ultrasound-guided CVC placement is divided into two subparagraphs. First the necessary steps for CVC placement will be discussed, followed by the diagnostic evaluation of possible complications after placement. All the steps of the protocol and the related ultrasound images can be reviewed in the flow chart in *figure 1*.

To reduce CVC-related bloodstream infections, proper sterility measures should be taken before starting the procedures. This includes sheathing the probe and cable with a sterile cover before starting the procedure.[20] Other more general sterility measures are also indicated, but are beyond the scope of this article.

Placement

Dynamic guidance during insertion: Needle introduction into the entry vein should be done under ultrasound guidance using either an oblique or transverse view. An oblique view of the entry vein is optimal for needle insertion and is associated with reduced posterior vessel wall puncture when compared with the short-axis view.[26] In the transverse view, the probe can be tilted and slid upwards or downwards to continue the trajectory and follow the needle tip. Switching to a longitudinal view can help to obtain more detailed images of the vein and nearby artery. This view is not recommended during introduction of the needle into the vein because the view of the skin will be restricted by the probe and visualisation of the needle is more difficult (*figure 1, Ia)*.[26]

After analgesia, introduce the needle into the skin above the entry vein. The needle can be visualised as a hyperechogenic line within the hypoechoic vein on the ultrasound image (*figure 1, II*). Note that tissue is moved by insertion of the needle; this can be appreciated on the ultrasound monitor. Jiggling the needle may improve its visibility. It is important to be aware of the fact that the tip of the needle cannot be visualised. Proceed until the needle penetrates the vein on the ultrasound image and blood is aspirated. Confirm needle position on the ultrasound image (*figure 1, IIIa*).

After having introduced the guidewire, confirm its position in the entry vein, still using the linear probe (*figure 1, IIIb*). Position confirmation of the guidewire in the entry vein should be conducted for all CVCs.

Procedural steps specific to CVC placement in the SV and IJV: Ask an assistant to switch to the phased array probe and place the probe a few centimetres caudally to the xyphoid, apply some pressure to guide the probe underneath the ribs and point it cranially (the subcostal view point) to visualise the heart. If the heart cannot be visualised subcostally, obtain alternative views, for example an apical view of the heart or using the liver as an acoustic window. To obtain an apical view place the probe in a mid-clavicular position on the left hemithorax just below the nipple. Special attention should be paid to visualise the right atrium. Introduce the guidewire further until it can be visualised as a hyperechogenic line or point in the view of the right atrium.

Diagnostic evaluation

Evaluating position of CVCs placed in the SV or IJV: Previous research has shown that correct adherence to the CVC placement protocol makes malposition very unlikely.[5-7] Correct adherence, however, is not always possible. In the event that the cardiac view could not be properly obtained, the catheter position can only be confirmed in the entry vein (*figure 1, IIIc*). Other major neighbouring veins, the contralateral or ipsilateral IJV and/or SV, should be brought into view as well; aberrant migration of the CVC into either of these veins can be evaluated with these views (*figure 1, IV*). Contrast enhanced ultrasound is a helpful tool to assess whether the tip of the CVC has correctly protruded into the superior vena cava (SVC). For this step no special contrast fluid is needed. Two 10 ml syringes, one filled with 9 ml of NaCl 0.9% solution and one with 1 ml of air - joined with a stopcock - are required. Mixing the contents of these syringes rigorously will create microbubbles that, when injected through the distal port of the CVC, can be visualised as hyperechogenic artefacts in the right atrium (*figure 1, IIId*). If the microbubbles appear in view within two seconds, the tip of the CVC is most likely to be located in the SVC or right atrium.[27] If their appearance is delayed (>5 seconds) malposition is very likely.[28] This a very low risk procedure that has been used in echocardiography for over 50 years; side effects (gas embolism) have only been reported incidentally and have not been reported as a major problem in larger series of patients.[29,30]

Following placement of CVCs in the SV or IJV, iatrogenic pneumothorax should be ruled out by checking for lung sliding in the ipsilateral lung apex. An overview of common lung ultrasound findings is presented in *table 1*. Hold the phased array probe with the marker turned cranially, in a midclavicular position on the second intercostal space. Look for the pleural line (hyperechoic line) between two ribs (*figure 1, IVa*) and assess for the presence of lung sliding. This can be appreciated as horizontal movement or a 'flickering' motion of the pleural line. M-mode may be used to further evaluate lung sliding when in doubt. This mode shows the 'seashore sign' in a normal situation and the 'barcode sign' in case of absent lung sliding (*figure 1, IVb*). The presence of lung sliding or B-lines excludes a pneumothorax. If neither are visible, the ultrasound operator should actively search for the 'lung point' to confirm pneumothorax.[31-33] If lung sliding is absent or diminished in case of, for example, pleurodesis or atelectasis, the presence of a 'lung pulse' (the movement of lung tissue due to the movement of the heart) can be used to rule out pneumothorax.[8]

Routine diagnostic evaluation of CVCs placed in the femoral vein using ultrasound is not recommended because mechanical complications have been reported with a much lower frequency than in the IJV or SV. Signs of thrombosis and bloodstream infection should, however, be monitored even more closely due to the higher infection rates.[1]

Medical decision-making

If ultrasound evaluation after CVC placement shows either malposition or pneumothorax, the first thing that should be considered is the clinical relevance of the complication. Not all CVC malpositioning requires re-intervention. Beside the SVC, other veins are also suitable for intravenous administration of medication.[34] Parameters of the patient's health should be used as an indication for intervention when dealing with iatrogenic pneumothorax. If an asymptomatic pneumothorax is discovered, the patient O2 saturation and haemodynamics should be monitored. Progression or spontaneous recovery can be monitored using ultrasound.[35]

Limitations and pitfalls

Using ultrasound as a tool to improve CVC placement offers many advantages; however, the technique has some limitations and its standard use in emergency and intensive care departments is debated by some.[36] The use of ultrasound guidance of CVCs is sometimes met with some resistance, especially from more senior physicians.[21] They are often worried that its use will give a false sense of safety or pose a threat to sterility.[36] These are, however, not limitations inherently related to use of ultrasound but to user competence and to our knowledge are not supported by evidence. A potential actual limitation of ultrasound is posed by its restricted availability caused by the high costs of initial investment in ultrasound machines. Another limitation is caused by obstructive anatomical features such as the clavicle. Ultrasound guidance is therefore best suited for placement in the IJV. Furthermore, diagnostics of post-procedural complications using ultrasound are also influenced by anatomical limitations. For example: ultrasound cannot bring the whole course of the CVC into view, potentially missing migration into an aberrant position.[36] In addition, not all departments have paramedics sufficiently skilled in the use of ultrasound. This limits the possible implementation of a view of the right atrium during CVC placement.

These limitations do not outweigh the benefits of the use of ultrasound. The price of ultrasound machines is steadily decreasing; recently introduced and more affordable hand-held scanners are available and have already been shown to be a feasible alternative in echocardiography.([37,38] The cost of initial investment is further reduced by the potential decrease in radiography expenses when chest X-ray is no longer necessary.[3] Furthermore, when taking into account the recent research on peripheral administration of vasoactive drugs, retrosternal malposition might be of little clinical relevance.[34] Finally, cardiac view, including the bubble test, can still be conducted during diagnostic evaluation. In this case the saline solution should be administered by an assistant. This suggests that ultrasound has no known clinically relevant limitations when used in CVC placement.

Implementation

When implementing this structured approach, it is advised to focus teaching of the two main aspects: ultrasound guided placement and lung ultrasound. Both have a steep learning curve and can be taught to users of all levels of experience. Research shows that inexperienced users can become proficient in ultrasound guidance of CVCs after around eight

Table 1. Patient position, probe selection, protocol selection, and picture optimisation

	Dynamic guidance	Diagnostic evaluation	
		Malpositioning	Pneumothorax
Patient position	Ideally slight (reverse) Trendelenburg	Ideally supine	Ideally supine
Probe selection	High frequency- (venous) and low-frequency (cardiac) probe	High frequency probe	High frequency probe
Protocol selection	Look for the entry vein and later for the right atrium	Bring relevant veins into view using B-mode	Use B-mode and M-mode to assess movement of pleural lining
Picture optimisation	Use local (oblique) view for the entry vein and subcostal view for the right atrium	Switch between short and long axis	Second intercostal space on side of entry

Table 2. Artifact explanation

Lung artefact	Ultrasound characteristics	Clinical relevance
A-line (B-mode)	- Repetition of pleural lining - Horizontal - Hyperechoic - Parallel to pleural lining - Distance between pleural lining and A-line equals distance between skin an pleural lining	- Normal finding
B-line (B-mode)	- Comet-tail artifact, arises - From the pleural line - Moves in concert with lung-sliding - Long, well-defined, laser-like - Hyperechoic - Erasing A-lines	- ≥3 B-lines per view indicate interstitial syndrome
Lung sliding (B-mode)	- Hyperechoic horizontal line (pleural lining) - Glittering/sparkling	- Unrestricted movement of lung, normal finding - Rules out pneumothorax
Seashore sign (M-mode)	- Parietal tissue unmoving (striped aspect) - Visceral pleura moving - Proximal tissue striped aspect, distal tissue grainy aspect	- Normal finding - Lung sliding present - Rules out pneumothorax
Stratosphere sign (M-mode)	- Parietal tissue unmoving - Visceral pleura unmoving - All tissue striped "Barcode-like" aspect	- Lung sliding absent - Lung movement restricted - Pneumothorax
Lung point (B-mode and M-mode)	- B-mode: healthy lung moves into view at edge of pneumothorax - M-mode: sea-shore sign and stratosphere sign alternating	- Pathognomonic for pneumothorax

examinations[21] and can interpret lung sliding after only five.[39] This guideline uses the I-AIM model which makes it suitable as both a guide for teaching and routine use of ultrasound.

Conclusion

This article provides the I-AIM model as an intuitive structure for the use of ultrasound as a guidance and diagnostic tool in CVC placement. This structured approach ensures that the use of ultrasound to improve periprocedural safety and accurate diagnosis of associated complications can be easily adopted by physicians. Ultrasound-guided placement should always be preferred over non- ultrasound-guided placement, except in specific cases were ultrasound is not possible . Post-placement diagnostic evaluation using ultrasound adds very little time to the procedure and has shown to be reliable. Therefore, it should be considered mandatory after CVC placement.

Disclosures

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