Anaesthesia
Journal of the Association of Anaesthetists of Great Britain and Ireland

Anaesthesia, 2008, **63**, pages 806–813 doi:10.1111/j.1365-2044.2008.05513.x

Pitfalls of ultrasound guided vascular access: the use of three/four-dimensional ultrasound

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Summary
The use of ultrasound guidance for central venous access is widespread and was recommended as the technique of choice by The National Institute of Clinical Excellence in the UK in 2002. However, complications have been reported using this technique. In this article we review the technique of two-dimensional ultrasound needle guidance and the errors that can occur. We then discuss the development of three- and four-dimensional ultrasound and describe our experiences using this imaging modality in simulated and actual needle-guidance. We discuss the potential advantages for clinicians utilising this newer form of ultrasound imaging for central venous access.

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Accepted: 29 January 2008

Ultrasound guided central venous access has become a standard technique since the National Institute for (Health and) Clinical Excellence issued guidelines in 2002 [1]. The guidelines recommended the use of two-dimensional (2D) ultrasound guidance for elective central venous cannulation in both adults and children and suggested considering its use in all situations including emergency cannulation. They stated that appropriate training should be undertaken to achieve competence in the technique, although what that training should entail was not discussed. Complications have been reported with this technique [2, 3], although their incidence may be reduced compared with the landmark technique [4]. In this article we review the causative mechanisms of complications using 2D ultrasound needle guidance and how the use of three/four-dimensional (3D/4D) ultrasound may address these issues.

Two-dimensional ultrasound

Structures are viewed using ultrasound transversely (short axis view) or longitudinally (long axis view). The cannulating needle may be seen along its full length (long axis or in-plane) or transversely (short axis or out-of-plane). During ultrasound guided central venous cannulation, the short axis view allows a simultaneous view of both the artery and the vein, but insertion of the needle is then only seen transversely (out-of-plane needle approach). The needle will then appear only as a point on the ultrasound image and may only be implied by tissue movement [5]. On occasions the needle may be unintentionally passed across the ultrasound beam and through the vessel using this approach (Fig. 1). This may be avoided by observing the needle and vein in their longitudinal axes (in-plane needle approach), allowing the

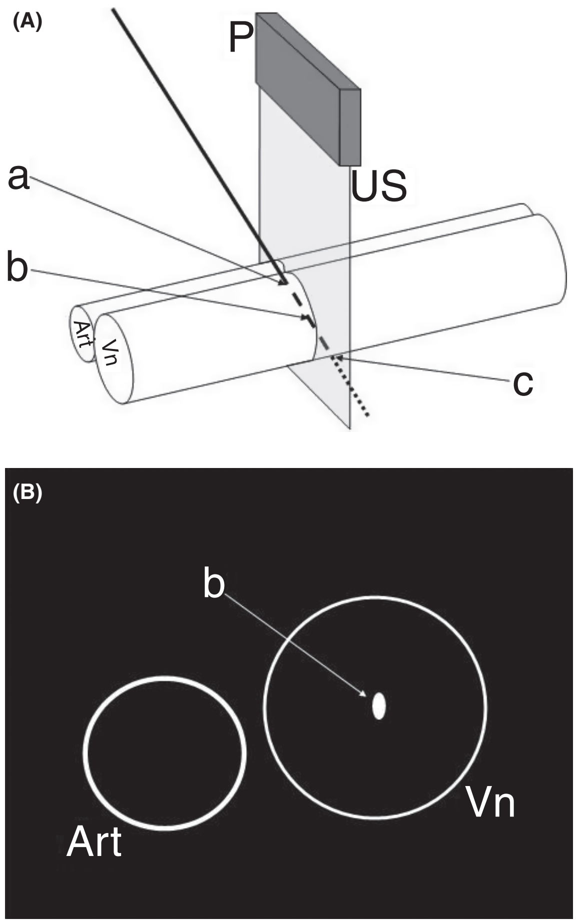

Figure 1 Short axis view of vessels with the out-of-plane needle approach showing overshoot: (A) alignment of the probe, vessel and needle; (B) ultrasound screen view. Art = artery; Vn = vein; P = probe; US = plane of the ultrasound beam; a = needle enters the vein; b = needle shaft crosses the plane of the ultrasound; c = needle exits the vein (overshoot).

operator to view the passage of the needle all the way to the centre of the vessel [6]. The artery and vein will now no longer be viewed simultaneously during passage of the needle (unless they lie directly underneath each other). If the operator strays medially or laterally he or she may accidentally cannulate the artery (Fig. 2). If an in-plane needle approach is to be employed for central venous cannulation, we would suggest that after identifying the vein in the longitudinal axis, the position of the adjacent artery should again be confirmed (utilising colour Doppler and compression of the vessel) by moving the probe in a medial-lateral direction before cannulation. Caution should also be taken to avoid partial line-up of the needle and probe; if this occurs the display may only show the proximal needle shaft whilst the distal shaft lies outside the beam. This gives the impression of the needle's position being more proximal than is actually the case. This scenario produces similar overshoots to the out-of-plane approach described above (Fig. 3). When using either approach the needle's tip should be visible at all times during advancement. Veins (as opposed to arteries) are usually identified using ultrasound by their nonpulsatile and easily compressible nature. This difference is not always pronounced, especially in the acute setting, in paediatric practice or with older ultrasound machines (because of the inferior quality of the images).

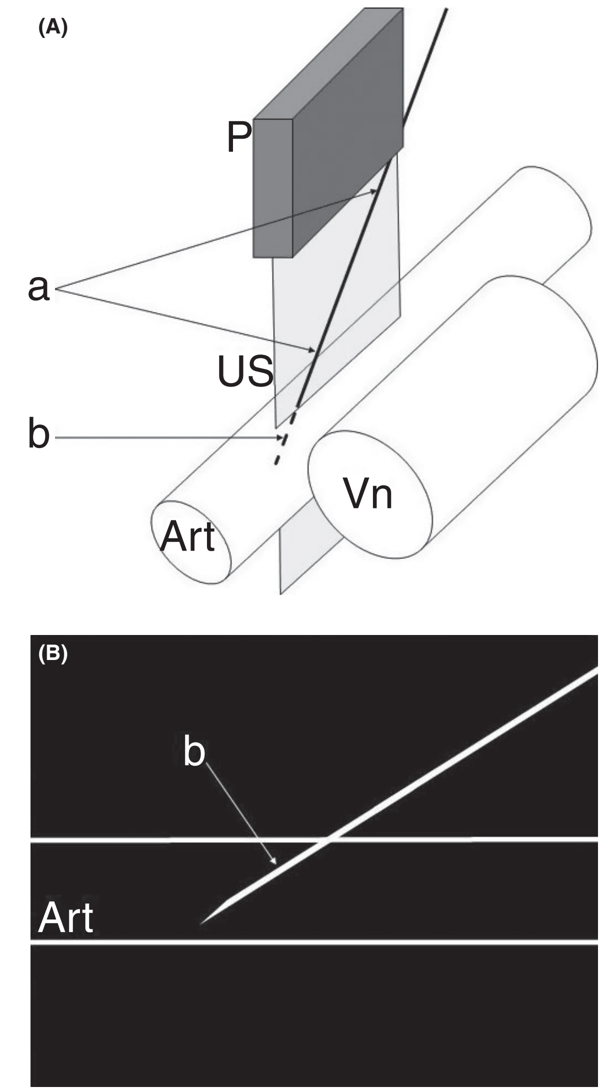

Figure 2 Long axis view of vessels with the in-plane needle approach showing incorrect identification of the vessel: (A) alignment of the probe, vessel and needle; (B) ultrasound screen view. Art = artery; Vn = vein; P = probe; US = plane of ultrasound beam; a = needle within the plane of the ultrasound beam; b = needle inserted into the incorrectly identified vessel.

Those new to ultrasound guidance may have higher complication rates; Sites et al. [7] found that trainees

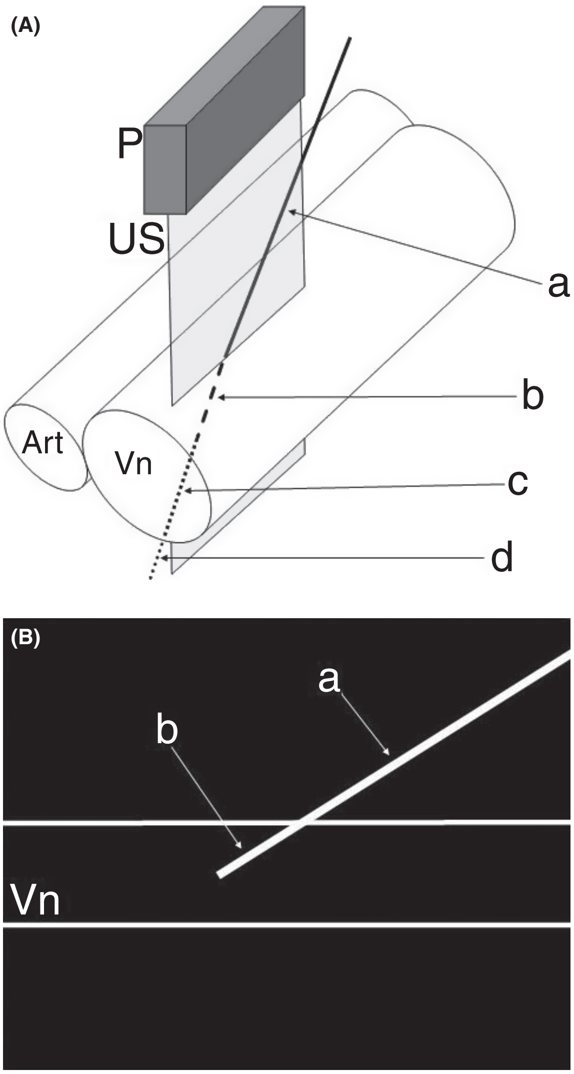

Figure 3 Long axis view of vessels with the in-plane needle approach showing overshoot with partial line-up of the needle and probe: (A) alignment of the probe, vessel and needle; (B) ultrasound screen view. Art = artery; Vn = vein; P = probe; US = plane of ultrasound beam; a = needle shaft in the plane of the ultrasound beam outside the vein; b = needle shaft in the plane of the ultrasound beam inside the vein; c = needle shaft outside the plane of the ultrasound; d = needle exits the vein (overshoot).

regularly over-inserted needles when attempting to target an olive using ultrasound guidance. We agree with Bodenham [8] that formal competencies in ultrasound guided needle techniques need to be developed and included as part of basic training.

Three/four-dimensional ultrasound

Three-dimensional (3D) ultrasound imaging refers to the static acquisition of a volume of data that can then be reviewed and manipulated later. The same technology can also be used in real time. This has been given a number of terms; in this article we refer to real time 3D imaging as four-dimensional (4D) imaging, to differentiate it clearly from static 3D imaging. Three/four-dimensional ultrasound images can be produced using either a mechanically steered array or a matrix array probe. Mechanically steered arrays produce still and real time images. The scan head is moved back and forth through an arc, thus scanning in two planes simultaneously. These transducers operate at high frequencies and therefore produce high resolution images. During 4D scanning the display frame rate is approximately half that of current 2D systems, resulting in visible pauses between displayed frames on the screen. Matrix arrays scan and generate images simultaneously in multiple planes. The images are generated electronically, so the scanning head is not required to move. As a result these probes are smaller and lighter and therefore ergonomically superior. The display frame rate is three times greater than a mechanically steered array, producing a smoother image on screen. Matrix array probes were designed for echocardiography, and operate at frequencies in the range 2-7 MHz, producing lower resolution images but enabling deeper penetration of tissue. They produce a sector-type image on the screen (the ultrasound beam spreads out rather than passing linearly from the probe's surface which would produce a smaller image) rather than a square-shaped linear image.

Four-dimensional multiplanar ultrasound

Four-dimensional multiplanar imaging provides simultaneous ultrasound images in up to three orthogonal (perpendicular) planes (Fig. 4). The first two of these views, the transverse (X or short axis) and longitudinal (Y or long axis), can be obtained using 2D ultrasound by rotating the probe through 90°. The third view, unobtainable using conventional 2D ultrasound, is parallel to the probe's surface. This view has also been termed the Z-axis or coronal view, although the view obtained will differ from the true anatomical coronal plane depending on where the probe is placed on the body. We therefore refer to this view as the 'plan view' due to the similarity with the architectural term showing the layouts of buildings from the overhead viewpoint. The point of intersection of the three planes is often marked on each image by a marker dot (seen on Figs 5 and 6). The dot can be steered to differing depths and can therefore function as a target during insertion of the needle.

Volumetric imaging

The 'rendered' image is a 3D volume representation of the scanned area and is produced from the orthogonal

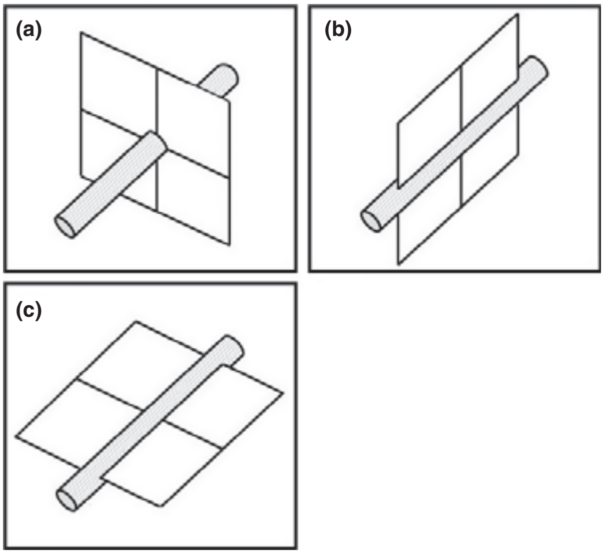

Figure 4 Diagram showing three orthogonal planes used in multiplanar ultrasound, with reference to a vessel. (a) Transverse view (X or short axis); (b) longitudinal view (Y or long axis); (c) plan view (Z-axis or coronal plane).

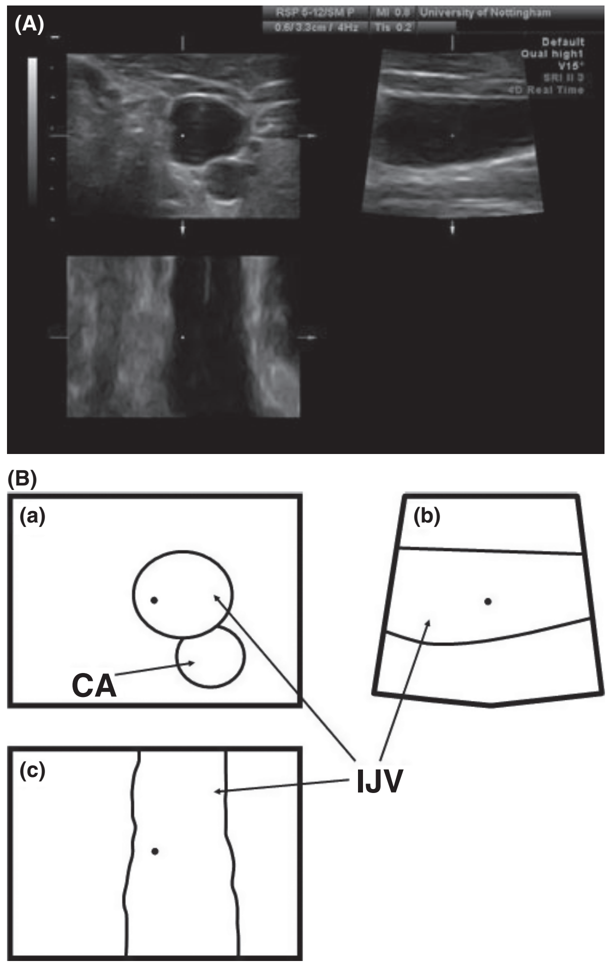

Figure 5 Three plane (mechanically steered array) multiplanar ultrasound image showing the left internal jugular vein and surrounding structures: (A) screen image; (B) reference diagram. (a–c) Multiplanar views as in Fig. 4; IJV = internal jugular vein; CA = common carotid artery. The marker dot is visible in the centre of each view. (Note that in this case the internal jugular vein overlies the common carotid artery; overshoot would result in arterial puncture).

planes. The image is then displayed as a cube or pyramid (depending on the type of probe). This is commonly used in obstetric practice to produce an image of the fetus in utero. Both multiplanar and volumetric images can be recorded and presented for viewing as a 'data set' (termed 3D imaging as mentioned above). The views can also be presented in 4D. This type of live imaging (4D) has already been used for needle placement in regional anaesthesia [9, 10], and to guide a number of interventional radiological procedures in various specialties [11–14]. This technology has the potential to improve accuracy of central venous cannulation.

Four-dimensional ultrasound guidance for vascular access

We subjectively assessed the two types of probe described above to examine their utility for central venous cannulation.

Mechanically steered array

Using a Voluson 730 Expert™ (GE Healthcare, Kretz, Zipf, Austria) ultrasound machine and 5.6-18.4 MHz small-parts probe (mechanically steered array), we produced multiplanar (three planes) and volumetric 4D images of the right internal jugular vein and surrounding anatomy in two volunteers (Fig. 5; see Supplementary material). The volumetric image was more difficult to interpret than the multiplanar views; this may be because we are more used to interpreting these types of images from our background in 2D imaging. We then modelled central venous cannulation using a simulator (Central Venous Catheterisation Simulator (CVC 200™), Pharmabotics Ltd, Hampshire, UK) and the needle of a 14-G Abbocath®-T (Hospira, Donegal Town, Ireland). We modelled both needle insertion and vessel overshoot. Vessels were initially identified using standard 2D imaging and then 4D imaging was used to guide insertion of the needle. The needle was successfully guided into the correct vessel using both out-of-plane and in-plane needle views simultaneously (Fig. 6). Purposeful overshoot was clearly seen in all three views. With the marker dot set in the centre of the vessel on the

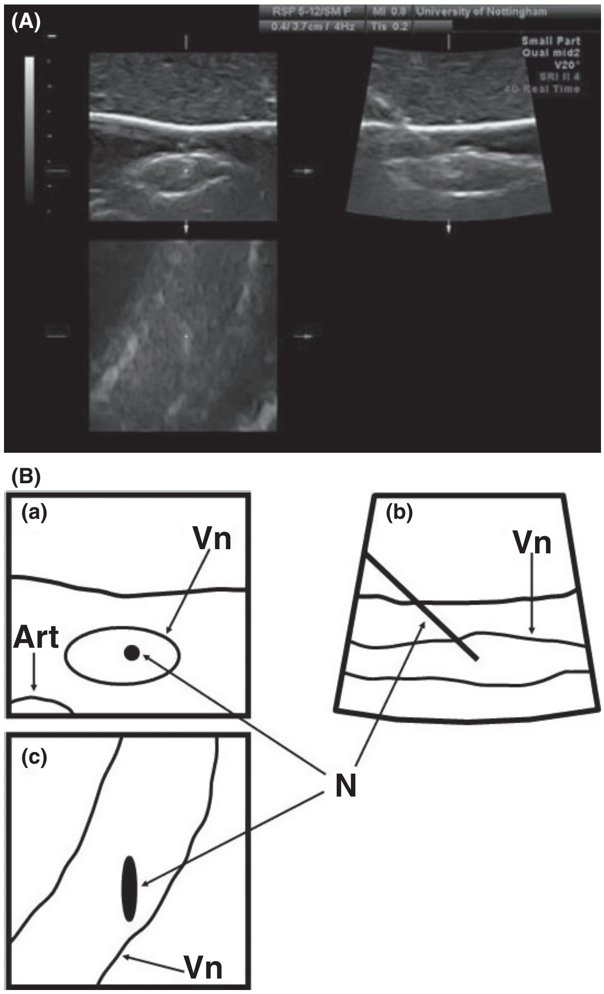

Figure 6 Three plane (mechanically-steered array) multiplanar ultrasound image showing insertion of the needle into a vascular access simulator: (A) screen image; (B) reference diagram. (a–c) Multiplanar views as in Fig. 4; Vn = simulated internal jugular vein; Art = simulated common carotid artery; N = needle. The marker dot overlies the needle in the centre of each view.

transverse view, the needle became visible in the plan view only when passing the depth of the marker dot, thereby providing extra confirmation of the needle's reaching the vessel centre (see Supplementary material). Seeing the needle within the model using volumetric imaging was difficult, and we chose not to evaluate this modality further. Future experience may enable us better to utilise this modality.

A number of practical difficulties were encountered with the mechanically steered array probe. The probe is much larger than standard 2D ultrasound probes used for central venous cannulation, making the handling of the probe and insertion of the needle more difficult (Fig. 7). Maintaining a view of the needle in all planes, to produce simultaneous in- and out-of-plane views of the needle, is

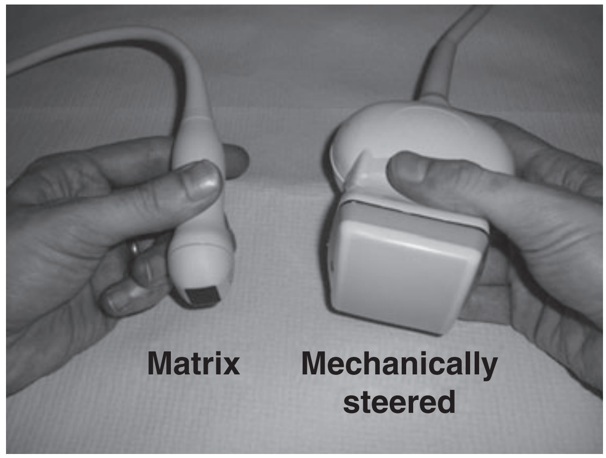

Figure 7 Matrix array (left) and mechanically steered array (right) 3D and 4D ultrasound probes.

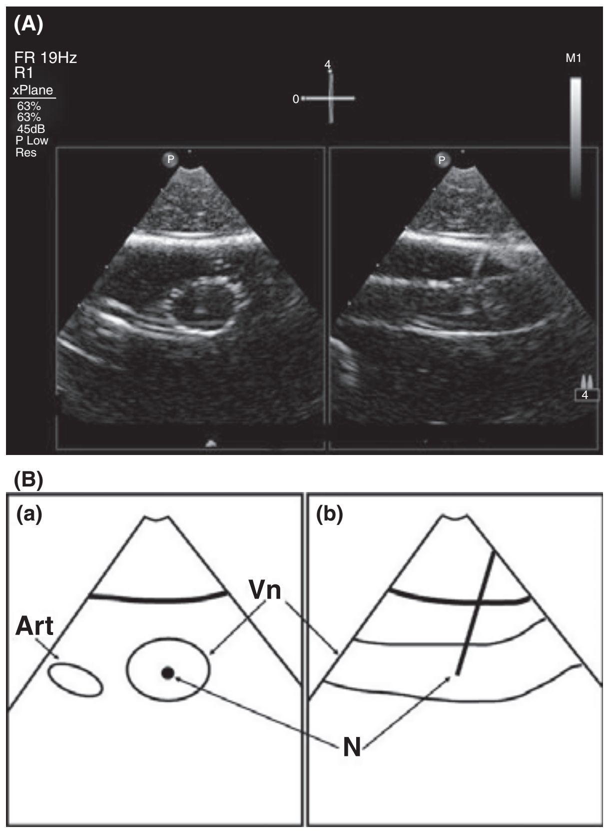

Figure 8 Two-plane (matrix probe) multiplanar ultrasound image showing insertion of the needle into a vascular access simulator: (A) screen image; (B) reference diagram. (a, b) Multiplanar views as in Fig. 4 (no plan view with this system); Vn = simulated internal jugular vein; Art = simulated common carotid artery; N = needle.

more difficult than with the standard 2D approach, though this improved with practice. The low display frame rate (highest at 7 Hz) made insertion of the needle appear jerky; this could lead to accidental advancement of the needle beyond a target. However, the plan view did display overshoot beyond the marker dot.

Matrix array

Using an iE22^{TM} ultrasound machine (Philips Medical Systems, Bothell, WA, USA) with an xMATRIX^{TM} (matrix array) 2-7 MHz transducer, we produced real time 3D images of the right internal jugular vein and surrounding anatomy in two volunteers, then modelled insertion of the needle using the simulator (Fig. 8; see Supplementary material). This machine produces the three plane views (described above) only as a data set for review, with 4D multiplanar imaging only shown as two planes. The first plane is fixed, with a second perpendicular plane that can be angled electronically without moving the probe. These views are obtained with standard 2D machines but not simultaneously. We were able to demonstrate the anatomy clearly using volumetric imaging (unlike with the mechanically steered array), probably due to the high display frame rate. This rendered image could be rotated in the three planes allowing observation of any part of the volume image. The volume image could also be cropped to allow demonstration of internal parts of the image. The vessels were easily observed in the two orthogonal planes and a display frame rate of approximately 19 Hz produced a smooth on-screen image. The matrix array probe was smaller and lighter than the mechanically steered array probe (Fig. 7). Images of the needle and simulated vessels were obtained in two planes and the correct vessel was successfully cannulated. The lack of the third orthogonal

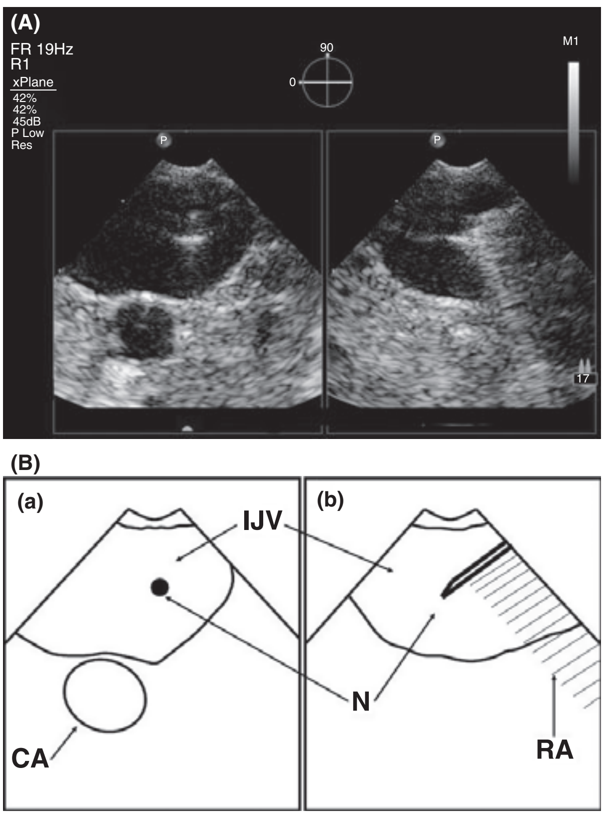

Figure 9 Two-plane (matrix probe) multiplanar ultrasound image showing the cannulating needle inside the right internal jugular vein in an adult: (A) screen image; (B) reference diagram. (a, b) Multiplanar views as in Fig. 4 (no plan view with this system); IJV = internal jugular vein; CA = carotid artery; N = cannulating needle; RA = reverberation artefact deep to the needle.

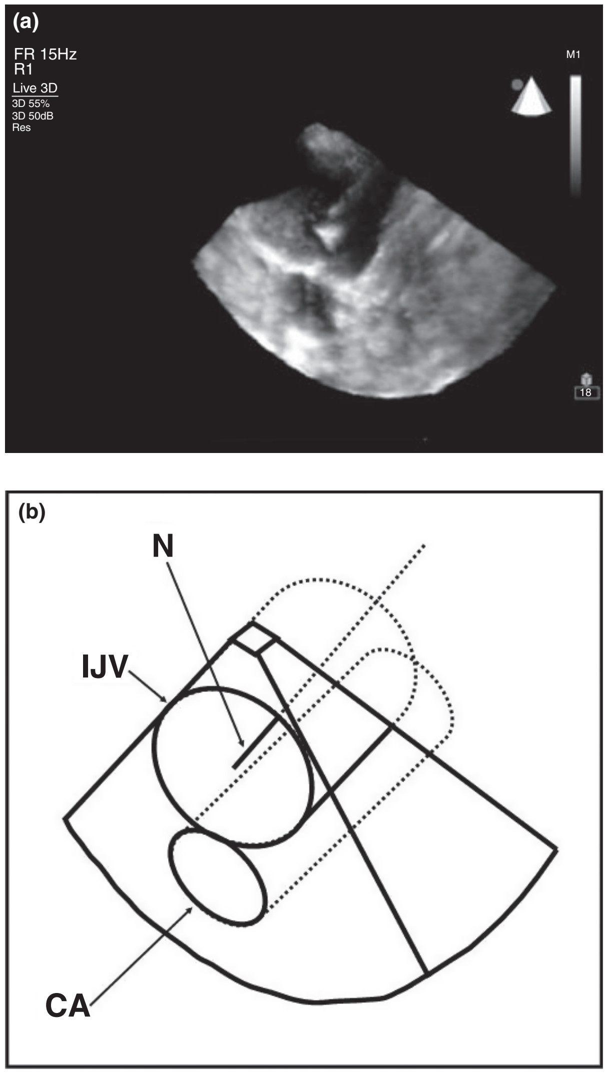

Figure 10 Volumetric ultrasound image (matrix probe) showing the cannulating needle inside the right internal jugular vein in an adult: (a) screen image; (b) reference diagram. IJV = internal jugular vein; CA = carotid artery; N = cannulating needle (dotted lines signify structures not seen on the ultrasound image).

plane (plan view) meant that the extra information regarding overshoot present with the first machine was not available.

Use of volumetric imaging gave a smooth on-screen image and allowed successful cannulation but visibility of the needle was again poor. Again, further experience may enable us better to utilise this modality. The matrix array probe allowed demonstration of the long and transverse axes of the vein and transverse axis of the artery to facilitate venous cannulation and avoidance of arterial puncture.

We then used the matrix array probe to guide central venous cannulation in two patients, after informed consent. Views of the neck vessels were obtained, and the cannulating needle was guided under 4D imaging (two planes as described above). The short-axis view simultaneously identified the carotid artery and internal jugular vein. The needle was inserted, viewing it in-plane in the longitudinal vessel view. The needle was clearly seen to enter the vein in both the short axis and long axis views (Fig. 9; see Supplementary material). The two-plane imaging helped us to avoid lateral deviation and also pass the needle into the centre of the vessel. The guidewire and catheter could also be seen in both views allowing us to confirm successful insertion by observing its longitudinal passage down the vessel. After successful insertion a volumetric image was obtained (Fig. 10; see Supplementary material). The small and light design of the matrix array probe did not hinder insertion of the needle and made for easy handling. The probe area (footprint) is small as it produces a sector type image (described above). The curved image produced is more difficult to interpret than a linear image. The maximum operating frequency of this matrix array probe was 7 MHz which limits the resolution of the image; however we found the resolution to be adequate for obtaining a view of the neck vessels.

Conclusion

Ultrasound guidance is the recommended technique for central venous cannulation; however reports do exist of complications during insertion of the needle. Having modelled the use of 4D ultrasound imaging for cannulating vessels, we have successfully performed central venous cannulation using 4D ultrasound guidance. Compared to mechanically steered probes, matrix arrays are small and light and produce images with a high display frame rate during live screening. However, they operate at lower frequencies and therefore sacrifice image resolution.

Four-dimensional imaging has the potential to reduce errors in identifying vessels and prevent overshoot during ultrasound guided central venous cannulation. Further technological advances in this exciting area will see improvements in image quality and miniaturisation of probes.

Acknowledgement

The ultrasound machines were on loan from GE Healthcare, Kretz, Zipf, Austria and Philips Medical Systems, Bothell, WA, USA.

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Supplementary material

The following supplementary material is available for this article:

Video clips available on the website:

- Multiplanar view of needle entering model vessel. Needle seen crossing depth of marker dot in plan view.
- Multiplanar view of internal jugular vein and carotid artery of volunteer.
- Biplane view of needle entering model vessel.
- Biplane view of internal jugular vein overlying carotid artery. Needle enters vessel in-plane in longitudinal view. Transverse view confirms centre of vessel.
- Biplane view of wire passing into vessel.
- Static acquisition (3D) of needle positioned in vessel. Multiplanar and rendered image.

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