

REGIONAL ANAESTHESIA

## Feasibility study of real-time three-/four-dimensional ultrasound for epidural catheter insertion

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### Editor's key points

- A 4D ultrasound-guided in-plane needle insertion technique was evaluated in cadavers.
- Compared with 2D, the 4D technique improved operator orientation of the vertebral column.
- The improvement was at the cost of resolution and needle visibility.
- Further studies are required to assess the 4D technique in a clinical setting.

**Background.** Real-time two-dimensional (2D) ultrasound can be used to facilitate neuraxial anaesthesia. Four-dimensional (4D) ultrasound allows the use of multiple imaging planes and three-dimensional reconstruction of ultrasound data. We assessed how 4D ultrasound could be used to perform epidural catheter insertion in a cadaver model. We then also compared 4D ultrasound and a previously described 2D technique in real-time epidural catheterization.

**Methods.** Epidural catheter insertion was attempted on four embalmed cadavers using a variety of 4D techniques. A feasible, 4D ultrasound-guided in-plane needle insertion technique was then compared qualitatively with the 2D technique in a further six cadavers.

**Results.** A feasible technique of real-time 4D ultrasound-guided epidural insertion used two perpendicular imaging planes to improve the orientation of the operator. It resulted in changes in the needle direction in half of the approaches. Using 4D ultrasound, the Tuohy needle could only be seen reliably in the primary imaging plane. In-plane needle visibility using 4D imaging was inferior to 2D imaging. Successful epidural catheterization was also aided by an acoustic window being present, which allowed visualization of the vertebral body.

**Conclusions.** The study demonstrates that 4D ultrasound can be used for real-time epidural catheter insertion and has both advantages and limitations compared with the 2D technique. Four-dimensional ultrasound has the potential to improve operator orientation on the vertebral column. However, this comes at the price of decreased resolution, frame rate, and needle visibility. Prospective evaluation of the importance of an acoustic window in neuraxial anaesthesia is required.

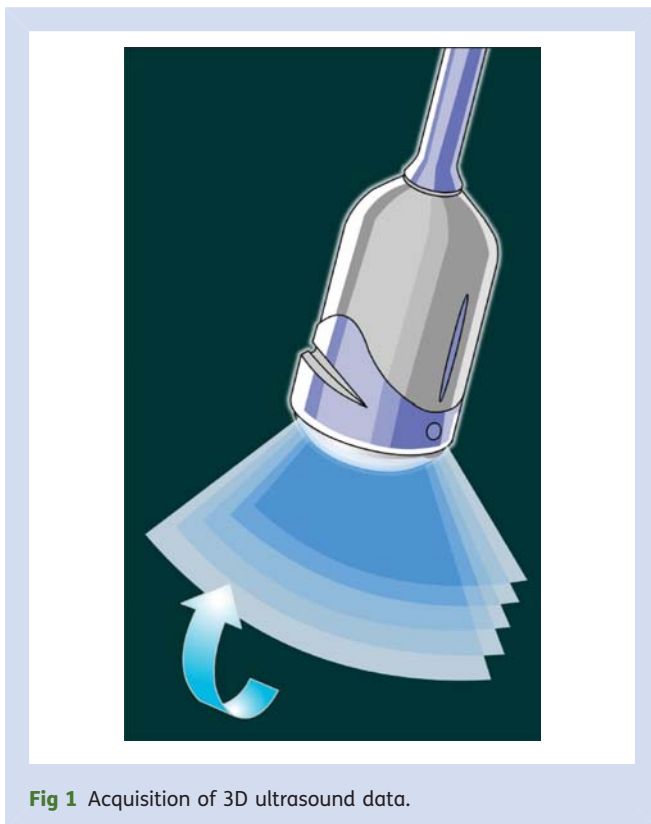
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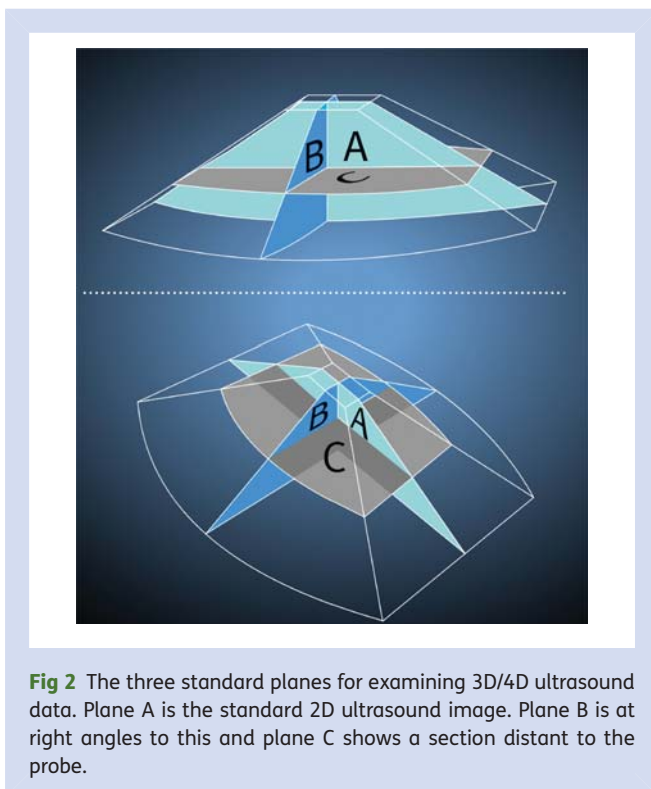
Ultrasound is increasingly being used for neuraxial anaesthesia. A scan before performing the procedure can identify a suitable insertion point and estimate the depth of insertion.<sup>1,2</sup> Ultrasound can also be used real time to guide the needle using an in-plane, paramedian approach.<sup>3</sup> The real-time technique has been used successfully after attempts to use a landmark-guided approach failed.<sup>3,4</sup>

Most reports of neuraxial ultrasound use two-dimensional (2D) curvilinear probes such as those used for abdominal imaging.<sup>1,3,5–7</sup> Three- and four-dimensional (3D and 4D) ultrasound probes similar to those are widely used in obstetric ultrasound imaging. The 3D/4D probe usually contains a 2D curvilinear probe that is moved mechanically in a fan-like manner (Fig. 1). The information collected describes a

pyramid-shaped volume and the data can be digitally manipulated and displayed.<sup>8</sup> An image of any plane can be reconstructed from the volume data. Images of 3D structures, such as baby faces or heart valves, can also be reconstructed from volume data using rendering algorithms. When performing a 3D/4D ultrasound, three orthogonal planes named A, B, and C are commonly displayed (Fig. 2). Plane A is the familiar 2D ultrasound image. Plane B is perpendicular to plane A. If plane A is positioned over the long axis of a structure, plane B would display its short axis. Plane C is perpendicular to the other images and represents echoes from a plane positioned at a distance from the probe. Figures 3 and 4 display the 3D sonogram if the probe is positioned in the paramedian position over the lumbar spine. Plane A displays



**Fig 1** Acquisition of 3D ultrasound data.



**Fig 2** The three standard planes for examining 3D/4D ultrasound data. Plane A is the standard 2D ultrasound image. Plane B is at right angles to this and plane C shows a section distant to the probe.

the sagittal image, plane B displays an axial image, and plane C shows a coronal section. The position of these three planes can be manipulated by the operator to display any plane in the volume examined. Four-dimensional

ultrasound involves acquiring successive 3D volumes of data allowing the display of 3D structures in real time.

In epidural anaesthesia, the use of 3D and 4D ultrasound may facilitate improved anatomical orientation and assessment. There is also a potential to image needle insertion outside the primary imaging plane. For example, the needle could be seen in plane C or rendered in a 3D image.

In this study, we aimed to assess the feasibility of using currently available 3D and 4D ultrasound for real-time ultrasound-guided epidural catheter insertion in a cadaver model.

## Methods

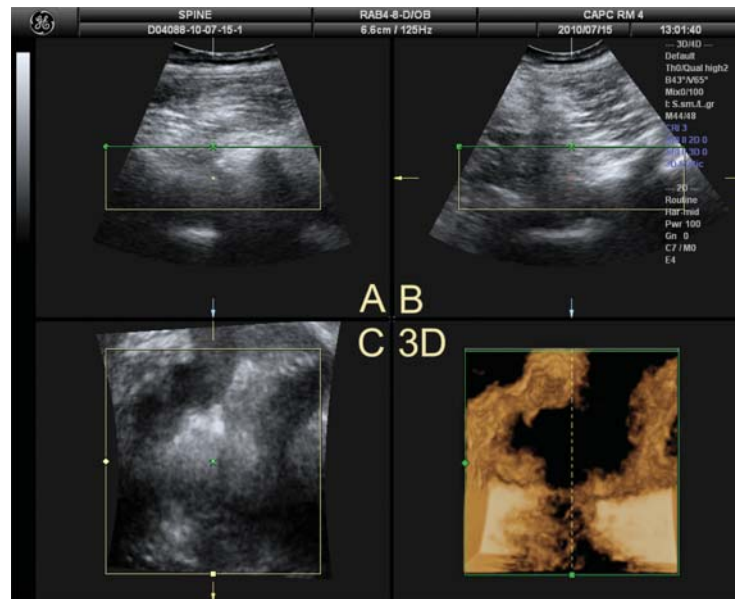
Epidural catheter insertion under real-time 2D and 4D ultrasound guidance was attempted in 10 embalmed human cadavers. All procedures were approved by the Executive of the Gross Anatomy Facility, School of Biomedical Sciences at The University of Queensland, and in accordance with ethical guidelines established by the National Health and Medical Research Council.

## Equipment and technique

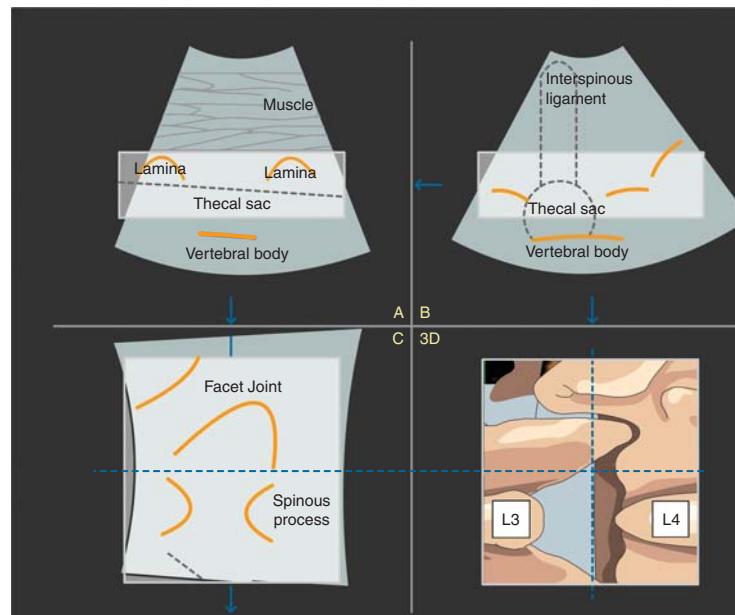
A GE Voluson E8 Expert ultrasound machine with an RAB2-5-D wide-band convex volume transducer, covered in a disposable plastic sheath, was used for all procedures. This 3D/4D probe is a 1–5 MHz convex probe containing 256 piezoelectric elements that swings in a fan-like manner. Ultrasound gel was used inside the sheath and on the cadaver.

An anaesthesiologist experienced in ultrasound-guided procedures, neuraxial ultrasound, and neuraxial anaesthetic techniques performed all needle insertions. The authors had not performed real-time ultrasound-guided epidural needle insertions before this study. The ultrasound machine was operated by qualified sonographers experienced in the use of the machine and in 3D and 4D imaging.

The cadavers were embalmed with Genelyn (Genelyn Pty Ltd, Marden, South Australia, Australia) and phenol 2%. They could not be flexed to optimize the position because of fixation. The cadavers were positioned prone for all procedures. Before needle insertion, the levels for epidural insertion were determined using ultrasound. For lumbar epidurals, the L3/4 interspace was identified by scanning cephalad from the sacrum. For thoracic epidurals, the T9/10 interspace was identified by counting up from the 12th rib. Two-dimensional ultrasound was used to identify the spinous processes, laminae, and facet joints. It was noted whether an acoustic window was present between the laminae, which allowed the identification of the posterior vertebral body. In all epidural attempts, a 110 mm Portex 16 G Tuohy needle was inserted by the first operator. When the needle tip entered between the laminae and resistance of the ligamentum flavum could be felt, the stylet was removed and the second operator advanced the needle while assessing for a loss of resistance to saline. If bone was encountered, the needle was redirected by the first operator and the procedure was repeated. The epidural catheter was then passed. The



**Fig 3** A 3D sonogram of the right paramedian L3/4 vertebral interspace in a live volunteer. Figure 4 shows the relevant anatomy. A is the longitudinal paramedian image, B the axial image, C the coronal image, and 3D the three-dimensional reconstruction.



**Fig 4** A line drawing of the relevant anatomy shown in Figure 3. A shows the longitudinal paramedian image, B the axial image, C the coronal image, and 3D the three-dimensional reconstruction.

catheter was then passed 5 cm beyond the tip of the Tuohy needle. Initial resistance to catheter insertion that was readily overcome was considered successful catheter insertion. A new epidural catheter kit was used on each cadaver.

The study was divided into two stages. In the first stage, we performed epidurals on human cadavers at the lumbar

and thoracic levels ( $n=4$ ). The aims of this initial stage were to gain experience with the 2D technique and determine a feasible 4D technique. In the second stage, the feasible 4D technique was then evaluated against the 2D technique for lumbar and thoracic epidural insertion on a separate set of human cadavers ( $n=6$ ).

### Stage 1: assessment of 4D techniques

In stage 1, the 2D ultrasound technique was similar to that described by Karmakar and colleagues.<sup>3</sup> The transducer was positioned in a paramedian location over the lamina, lateral to the midline. The beam was angled medially aiming to identify an acoustic window between laminae so that either the dura or the posterior vertebral body was visible. The needle was inserted in-plane between the laminae.

We also attempted a variety of approaches using 4D ultrasound to determine a technique that was viable for real-time epidural insertion.

The techniques for 4D ultrasound-guided needle insertion attempted were as follows:

- (1) Needle insertion out of both planes A and B, attempting to identify the needle using 4D volume rendering.
- (2) Needle insertion out of both planes A and B using plane C to identify the needle.
- (3) Needle insertion in-plane A, similar to the 2D approach, while using plane B to orientate the operator relative to the vertebral column and guide the needle into the interlaminar space. This 4D technique was similar to the 2D technique in probe position and needle approach. The Tuohy needle was inserted in plane A. The sonographer adjusted the ultrasound image to position plane B over the interlaminar space so that the position of the probe and needle

relative to the spinous process, lamina, and articular processes could be assessed (Figs 5 and 6). As the needle entered in plane A, it could be seen crossing plane B.

The three techniques were compared for needle visibility during real-time needle insertion.

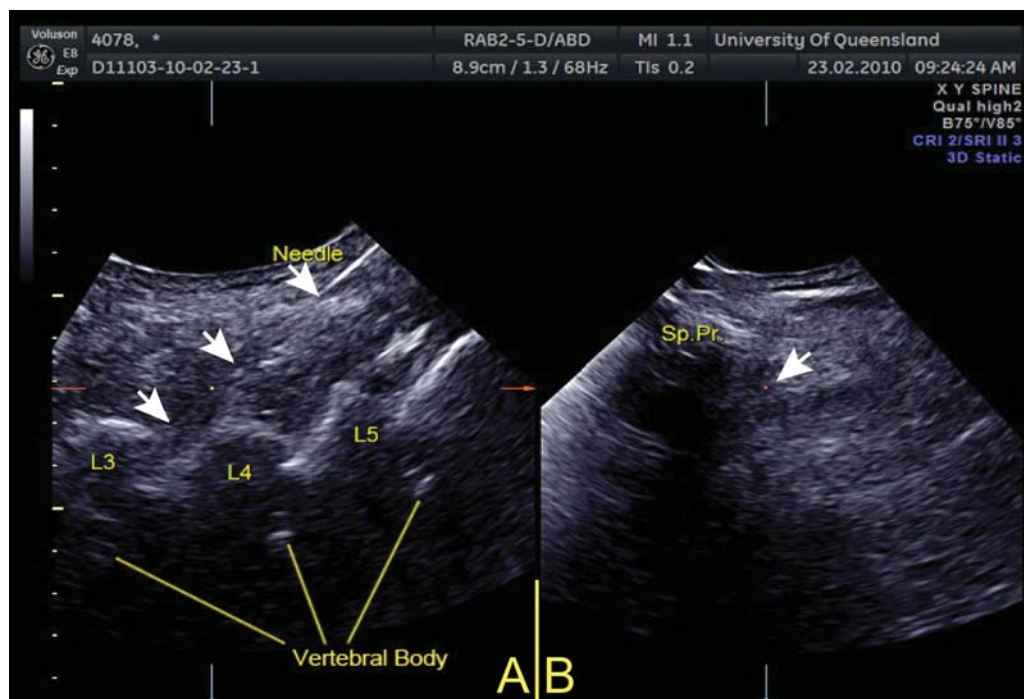
Technique (3) was feasible and was selected as the 4D technique to be compared with the 2D technique in the second stage of the study (see the Results section).

### Stage 2: comparison of 4D and 2D techniques

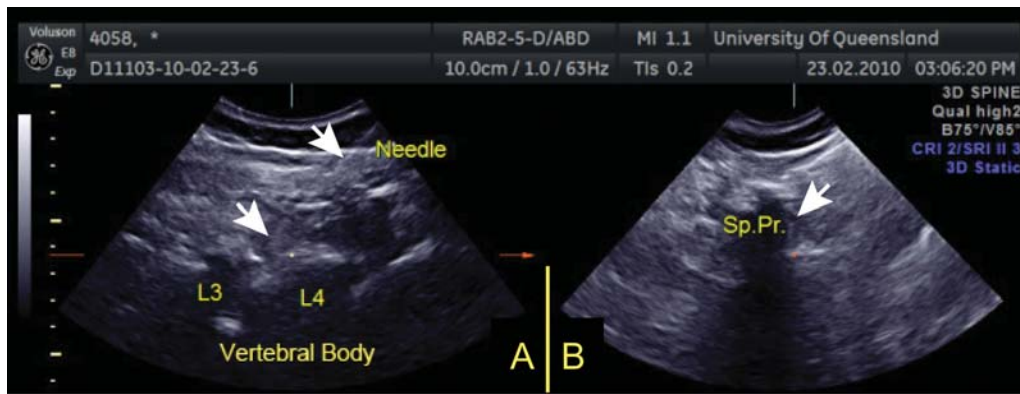
In this second stage, we aimed to compare the 4D and 2D techniques. Both techniques were performed at the lumbar and thoracic levels. The first technique performed at each level (2D or 4D) was alternated between cadavers. At each level, the techniques were attempted on opposite sides to avoid repeated needle passes degrading imaging. Needle visibility was graded as (i) readily visible, (ii) tissue movement only, or (iii) not visible. Any qualitative benefits or drawbacks of the 4D approach were noted. The depth to the epidural space was recorded by measuring off the Tuohy needle.

### Data analysis

The study was not powered for statistical analysis. However, needle visibility was compared between the 2D and 4D techniques using a McNemar exact (binomial) test. The depth to



**Fig 5** A 3D sonogram at the lumbar spine in a cadaver with the needle inserted via a right paramedian approach in the epidural space (arrows). Plane A is positioned in a paramedian location cephalad to the left. Plane B is positioned axially with the right of the image being to the right of the cadaver.



**Fig 6** A 3D sonogram at the lumbar spine in a cadaver with the needle inserted via a right paramedian approach in the epidural space (arrows). Plane A is positioned in a paramedian location cephalad to the left. Plane B is positioned axially with the right of the image being to the right of the cadaver.

the epidural space at the lumbar and thoracic levels measured on the Tuohy needle was compared between the 2D and 4D techniques using a paired, two-tailed Student's *t*-test.

## Results

The mean age at death of the cadavers was 85 yr (sd 11 yr) and two of the 10 were female. In all cadavers, the spinous processes, laminae, facet joints, and transverse processes were readily observed using 2D ultrasound.

### Stage 1

In stage 1, real-time 2D ultrasound-guided epidural catheter insertion was performed successfully.

The three 4D ultrasound-guided techniques listed above were also attempted. The needle could not be recognized at all when using real-time volume rendering of 4D data [technique (1)]. Technique (2), which aimed to identify the needle in plane C, also resulted in poor needle visualization. The needle could only be seen in the subcutaneous fat. The needle could not be recognized as it entered the deeper paraspinal muscles. The needle could only be reliably imaged in the primary imaging plane (plane A). The 4D technique using needle insertion in the primary A plane was judged to be feasible [Technique (3)].

### Stage 2

From this experience, we proceeded with the remaining six cadavers performing 2D and 4D ultrasound-guided techniques at the lumbar and thoracic levels.

Using the 2D technique, epidural catheters were successfully inserted at the planned thoracic and lumbar levels in five of the six cadavers (Table 1). Needle visibility was rated as good in 80% of the approaches.

Using the 4D technique, epidural catheters were also sited at the planned level in five of the six cadavers. Qualitatively, but not statistically, needle visibility was inferior

with 4D imaging compared with the 2D technique (Table 2,  $P=0.12$ ). In half of the 4D catheter insertions, the needle was redirected medially or laterally based on the B plane images. There was no significant difference in depth to the epidural space between the 2D and 4D techniques (Table 3).

Catheter insertion in cadaver 3 was particularly difficult in comparison with the other cadavers. The catheter could not be inserted at the L3/4 using the 2D and 4D techniques, despite the needle passing between the lamina and a loss of resistance to saline being felt. In view of this difficulty, we attempted insertion at L2/3 using the 4D technique. An acoustic window was visible at L2/3, which allowed visualization of the vertebral body. Using 4D imaging, the needle was inserted and encountered bone. The B plane identified the spinous process of L2 as the bony resistance. The needle was redirected using this information, the epidural space was identified, and the catheter inserted successfully. The B plane of the 4D technique provided benefits with this difficult cadaver.

A further difficulty in cadaver 3 was that no acoustic window could be identified using 2D ultrasound at T9/10 or T10/11. The needle was not able to pass between the laminae on either side using the 2D technique. Before attempting the 4D technique, we acquired higher-resolution 3D images at a number of thoracic levels to help find an acoustic window. An acoustic window was present through which the vertebral body could be seen at T8/9 using 3D ultrasound. An epidural catheter was successfully passed at this level using the 4D technique. As a result of this experience, the needle was only inserted in cadavers 4–6 if an acoustic window could be seen at the vertebral level.

No catheter was successfully inserted without the presence of an acoustic window, but the presence of an acoustic window did not guarantee success.

The flow of saline into the epidural space was visible under ultrasound in three of the 2D attempts and in one of the 4D

**Table 1** Record of procedures performed in stage 2. \*Entered space under ultrasound. No resistance to saline flow. †In cadaver 3, a catheter could not be passed at L3/4 using the 2D and 4D techniques. An acoustic window could be seen at L2/3 and the catheter was successfully inserted using the 4D technique. There was no visible acoustic window with 2D ultrasound at T9/10 and T10/11 and the 2D attempts failed. An acoustic window was seen at T8/9 using 3D ultrasound and the 4D approach was successful. ‡No acoustic window was visible at L3/4 on the left side. A solid hyperechoic shadow suggested lumbar spondylosis. The technique was successful at L2/3. §No acoustic window visible at T9/10 on the planned side. Window visible at T10/11. LORS, loss of resistance to saline

Cadaver	2D technique				4D technique			
	Level	Acoustic window	LORS	Catheter passage	Level	Acoustic window	LORS	Catheter passage
1	L3/4	Yes	Yes	Yes	L3/4	Yes	Yes	Yes
1	T9/10	Yes	Yes	Yes	T9/10	Yes	Yes	Yes
2	L3/4	Yes	Yes	Yes	L3/4	Yes	Yes	Yes
2	T9/10	Yes	*	Yes	T9/10	Yes	*	Yes
3	L3/4 <sup>†</sup>	Yes	Yes	No	L3/4 <sup>†</sup>	Yes	Yes	No <sup>†</sup>
3	T9/10, T10/11 <sup>†</sup>	No	No		T8/9 <sup>†</sup>	Yes	Yes	Yes
4	L3/4	Yes	Yes	Yes	L3/4	Yes	Yes	Yes
4	T9/10	Yes	*	Yes	T9/10	Yes	Yes	Yes
5	L3/4	Yes	Yes	Yes	L2/3 <sup>‡</sup>	Yes	Yes	Yes
5	T9/10	Yes	Yes	Yes	T10/11 <sup>§</sup>	Yes	Yes	Yes
6	L3/4	Yes	Yes	Yes	L3/4	Yes	Yes	Yes
6	T9/10	Yes	Yes	Yes	T10/11 <sup>§</sup>	Yes	*	Yes

**Table 2** Contingency table showing the relationship between needle visibility for 2D and 4D ultrasound techniques ( $P=0.125$ ). Movement refers to cases in which the needle was only visible due to the surrounding tissue movement

	Visibility 4D		Total
	Good	Movement	
Visibility 2D			
Good	4	6	10
Movement	1	1	2
Total	5	7	12

**Table 3** Depth to the epidural space measured on the Tuohy needle

	Depth (cm) to epidural space mean (sd)		P-value
	2D	4D	
Lumbar	9.2 (1.6)	9.0 (1.3)	0.8
Thoracic	7.6 (1.1)	8.0 (1.1)	0.5

attempts. The 4D ultrasound cineloop is available as Supplementary Material. On two occasions with each technique, there was no resistance to saline flow when the loss of resistance syringe was attached, suggesting that the epidural space was already entered.

## Discussion

The aim of this feasibility study was to use a cadaver model to assess whether 4D ultrasound can be used to facilitate

epidural catheter insertion. We found that the current 4D ultrasound technology is best used to improve the operator's orientation in three dimensions by displaying the reconstructed B plane [technique (3)]. In this technique, the probe was positioned in a paramedian position and angled such that the A plane was directed between the laminae as in the 2D approach. The needle was then inserted using an in-plane approach in the A plane. In this position, the B plane helped to orientate the probe over the more medial parts of the lamina. As the needle crossed the B plane, the operator could make medial and lateral needle adjustments to optimize the approach relative to the spinous process and facet joints. The advantage of having a B plane was demonstrated by enabling adjustments to needle direction in half of the 4D approaches in stage 2. These adjustments would be more difficult with 2D ultrasound. Confirming the medial to lateral position of the needle using 2D ultrasound would require either a medial to lateral tilt of the probe to identify the spinous processes and facet joints, or a 90° rotation to examine the needle and spine in the short axis.

We found that the needle could not be reliably seen out of the primary imaging plane in 4D techniques (1) and (2). The relatively echogenic surrounding tissues obscured the needle when inserted outside plane A. Other fields that use 3D/4D ultrasound examine relatively echogenic structures (e.g. heart valve or fetus) that are surrounded by fluid (blood or amniotic fluid). The structure of interest can be rendered in 3D from the ultrasound data and can be examined through the relatively echo-free surrounding fluid.

We also found that the presence of an acoustic window was valuable for successful epidural insertion. An acoustic window is present if the dura or vertebral body can be seen between the laminae. In cadaver 3, the 2D technique failed at two thoracic levels. We did, however, succeed with the

4D technique after identifying an acoustic window at T8/9. High-resolution static 3D data sets were obtained at multiple levels and each data set was explored to find an acoustic window. This effort resulted in successful insertion at one vertebral segment above the planned level. Compared with identifying the laminae alone, efforts to find an acoustic window may improve success with epidural catheterization.

Our observation was that needle visibility is inferior with 4D ultrasound when compared with 2D. This observation was not found to be statistically significant, most likely due to the small sample size. The decreased visibility may be due to challenges associated with spinal imaging in this model and limitations of the 4D ultrasound technology used in this study.

There are certain challenges to spinal imaging in cadavers related to embalming and age. As a result of embalming, the cadavers were all prone and could not be positioned in the clinically used flexed positions. Embalming also affects ultrasound imaging by increasing acoustic impedance.<sup>9</sup> In this study, the cadavers were elderly at the time of death, which is associated with a high prevalence of degenerative spine disease. Despite these challenges, epidural catheters were inserted at the intended level in 10 of 12 attempts with the 2D technique and 11 of 12 attempts with the 4D technique.

Previous 2D studies have noted that the needle can be recognized, in some patients, by tissue movement only.<sup>3</sup> This problem is further compounded in 4D imaging due to the lower frame rate and resolution. In this study, the frame rate was as low as 4 Hz. In addition, some image optimization technologies such as spatial compound imaging can only be used in the primary imaging plane.

These technical limitations may be overcome by the newer matrix ultrasound transducer technology, which shows improved 3D imaging.<sup>10</sup> Rather than a single line of piezoelectric crystals, matrix transducers have an array of crystals that are sampled at higher frequencies. Imaging of the needle out of plane A will improve with technological advances and also with echogenic Tuohy needles.

There are limitations in transferring our cadaver experience to the clinical setting. An assistant skilled in operating the advanced ultrasound equipment is required. The technique also introduces increased complexity because the operator is required to concurrently interpret two ultrasound images rather than one. The challenges of a single operator holding the ultrasound probe, directing the needle, and using a reliable loss of resistance to saline technique also remain to be solved. Many anaesthetists favour a midline approach to epidural insertion, particularly at the lumbar levels. This study made no attempt to compare the widely used blind midline techniques with ultrasound-guided techniques, and a midline, ultrasound-guided approach to epidural insertion has not been described. On four passes, the needle was inserted directly into the epidural space using ultrasound guidance alone before attempting loss of resistance to saline. This may have resulted from an embalming effect on the thickness or strength of the ligamentum flavum. However,

this observation suggests a higher potential for inadvertent dural puncture using ultrasound techniques and needs to be assessed in normal tissue. Finally, the endpoint for successful insertion in clinical practice (adequate anaesthesia) is clearly different from the endpoint used in this study (passage of a catheter).

It is promising for the 4D technique that epidural catheters were successfully sited in all cadavers. Further training of operators and using optimal clinical positioning of patients will certainly improve ultrasound-guided epidural insertion. The improved orientation may also be applied to paravertebral catheter insertion and justifies further research.

In conclusion, current commercially available 4D ultrasound technology may offer an incremental advantage in ultrasound-guided epidural catheter insertion by improving the spatial orientation of the operator. This benefit comes with the drawbacks of reduced frame rate and needle visibility, factors that may be resolved by improved technology. We believe that further research into real-time 4D ultrasound-guided epidural catheterization should be conducted *in vivo*. Prospective studies are needed to assess the importance of an acoustic window in real-time epidural catheter insertion.

## Supplementary material

Supplementary material is available at *British Journal of Anaesthesia* online.

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## Conflict of interest

The sonographers and ultrasound equipment were provided by GE Healthcare Australia without charge. GE had no involvement in the design of the study, analysis, or preparation of the manuscript.

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