Ultrasound for Central Neuraxial Blockade

Kyle R. Kirkham · Ki Jinn Chin

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Abstract The evidence base supporting the role of ultrasound to assist the performance of neuraxial anesthesia has become increasingly strong over the last decade. In both the lumbar and thoracic spine, ultrasound has been shown to optimize technical performance, improve patient outcomes, and potentially reduce harm. Specifically, ultrasound aids in identification of intervertebral levels, estimation of depth to epidural and intrathecal spaces, and localization of important landmarks including the midline and interlaminar space. These characteristics can facilitate both planning and performance of neuraxial blockade by reducing the required number of needle insertions and redirections, minimizing the risk of traumatic needle placements, and improving block effectiveness after epidural placement. This report details the evidence supporting each of these outcomes and also discusses the current understanding of both learning and teaching the skill of neuraxial ultrasonography.

Keywords Ultrasound · Epidural anesthesia · Spinal anesthesia

Introduction

The use of ultrasound to facilitate the performance of neuraxial anesthesia was first described in 1980 [1].

Although early studies hinted at potential benefits, it remained under-investigated and infrequently employed until recently. The slow adoption of ultrasound to aid neuraxial anesthesia may be attributed to the perceived ease of surface landmark-guided approaches, a limited understanding of potential benefits, and belief that ultrasound adds an unnecessary layer of complexity. There is, however, growing evidence that ultrasound confers many advantages. Ultrasound permits identification of the target interspace level, evaluation of anatomical variations, and prediction of ease of block performance. Ultrasound can assist with planning needle insertion, trajectory, and depth, thereby improving the number of needle passes required and time taken for successful completion of the procedure. This report outlines the evidence supporting pre-procedural ultrasound imaging of adult patients undergoing both lumbar and thoracic neuraxial block, and the potential for associated improvements in patient outcomes.

Technique of Ultrasound Imaging of the Spine

Detailed descriptions of how to perform ultrasound imaging of the spine have been published [2, 3] and readers are encouraged to review the anatomy and approach outlined in these reports. The two most useful sonographic views of the neuraxis are the paramedian sagittal oblique (PSO) and transverse midline (TM) interlaminar views. They permit evaluation of the soft tissues, bony landmarks, and, most importantly, acoustic windows between the vertebrae that allow penetration of the ultrasound beam into the vertebral canal.

The PSO view is obtained by placing the probe in a longitudinal orientation lateral to the midline and tilting it to direct the beam medially (Fig. 1). The sloping bony

K. R. Kirkham · K. J. Chin (✉)
Department of Anesthesia, Toronto Western Hospital, University
of Toronto, 399 Bathurst St., McL 2-405, Toronto,
ON M5T 2S8, Canada
e-mail: gasgenie@gmail.com

K. R. Kirkham
e-mail: kyle.kirkham@uhn.ca

Fig. 1 The paramedian sagittal oblique (PSO) view of the lumbar spine with corresponding magnetic resonance image. The lumbar laminae appear as sloping hyperechoic lines with acoustic shadowing, and form a “sawtooth-like” pattern. The ligamentum flavum and posterior dura (the posterior complex) are visible between the laminae. The hypoechoic intrathecal space is well below that, and, deeper still, is the hyperechoic anterior complex (composed of anterior dura, posterior longitudinal ligament, and posterior aspect of the vertebral body. Image used with permission from Ultrasound for Regional Anesthesia (USRA) (www.usra.ca)

laminae create a “sawtooth”-like bony pattern, with intervening gaps representing the paramedian interlaminar spaces. In these gaps, two echogenic linear structures can be seen. The more superficial line, representing the ligamentum flavum and posterior dura, is commonly termed the posterior complex. The deeper line, the anterior complex, represents the anterior dura, posterior longitudinal ligament, and vertebral body. The intervening dark space between anterior and posterior complexes corresponds to the intrathecal space. At the most caudad extent of the lumbar spine, the sacrum is visualized as a continuous hyperechoic line. The first cephalad gap thus corresponds to the L5–S1 intervertebral level and subsequent levels may be identified by counting upward from this point. Directing the beam laterally will reveal the vertebral transverse processes and, in the lowermost thoracic region, their articulation with the ribs. The 12th rib can thus provide a second landmark for accurate identification of vertebral level.

The TM view (Fig. 2) is obtained by placing the probe in a transverse orientation across the midline and aligning it with the interspaces identified in the PSO view. Depending on the angle of the spinous processes, a variable degree of cephalad tilting of the probe may be required to optimize the view. In the lumbar spine, the TM view typically shows a dark midline shadow that corresponds to the interspinous ligament. The articular processes are visible as bright echogenic structures on either side of the midline. Similar

to the PSO view, the echogenic posterior and anterior complexes should be visible, separated by the dark intrathecal space. The ability to clearly visualize the structures of the vertebral canal in the PSO and TM views depends largely upon the size of the interlaminar acoustic windows between adjacent vertebrae; a characteristic that has value in predicting ease of epidural or spinal needle entry.

Lumbar Spine

Ultrasound Can Assist Identification of Specific Intervertebral Levels

The identification of lumbar intervertebral levels based on surface anatomical landmarks is notoriously inaccurate. When compared to the gold standard of magnetic resonance imaging (MRI), the correct intervertebral level is identified in as few as 29 % of patients [4]. Similarly, studies have repeatedly shown significant discordance between ultrasound-guided and clinical determinations of lumbar intervertebral level. In a population of 50 patients undergoing total hip arthroplasty, the palpated intercrystal line corresponded to the L3–4 level identified by ultrasound in 72 %, to the L2–3 level in 26 %, and to the L4–5 level in 2 % of patients [5]. In a similar study of 90 parturients, Locks et al. [6] found concordant identification of the L3–4 intervertebral space in only 53 % of non-obese

Fig. 2 The transverse midline (TM) view of the lumbar spine with corresponding magnetic resonance image. The characteristic features here are the hyperechoic posterior and anterior complexes, separated by the hypoechoic intrathecal space. The *midline* is indicated by the dark vertical stripe which represents the interspinous ligament. Note that the transverse processes and articular processes lie in the same transverse plane as the interlaminar space and provide useful cues in difficult scans. Image used with permission from Ultrasound for Regional Anesthesia (USRA) (www.usra.ca)

and 49 % of obese patients. In 93 % of the cases where disagreement occurred, the clinically identified L3–4 level corresponded to a higher (L1–2 or L2–3) level as identified by ultrasound. Two other studies evaluated a cohort of women who received epidural anesthesia for labor analgesia [7, 8]. Both compared the documented epidural insertion level with a post-partum ultrasound assessment of the intervertebral level corresponding to the needle insertion scar. Once again, a high rate of discordance (45–63 %) was observed between the two assessment methods, and the level of insertion determined by ultrasound was more likely to be higher (72–76 %) than that noted in the clinical record.

There is evidence to suggest that ultrasound is more accurate than clinical assessment of intervertebral level. In one study comparing clinical assessment, ultrasound, and the gold standard of lateral spine X-ray examination [9], surface landmarks accurately identified the L2–3 interspace only 30 % of the time, with an additional 7 % of markings placed over the immediately adjacent spinous processes. Ultrasound correctly identified the L2–3 interspace in 60 % of cases with a further 24 % of markings placed over the immediately adjacent spinous processes. It is notable that the margin of error with ultrasound was at most either one space above (9 %) or below (7 %) the intended target. Greater variability was seen during clinical assessments, with margins of error up to two spaces higher (9 %) or lower (18 %). In addition, clinical estimation of intervertebral level was deemed impossible in 4 % of cases compared to none when ultrasound was used.

Facilitating Technical Performance

Ultrasound Can Accurately Measure Depth to Epidural Space

In 1980, Cork et al. [1] evaluated 36 patients using a longitudinal neuraxial scan and, despite relatively primitive ultrasound equipment, were able to identify and measure the depth to the ligamentum flavum in 33 of the 36 patients. They found a high correlation ($r = 0.98$) between measured depth by ultrasound and needle depth to the epidural space. In a subsequent study, Currie [10] also found a high correlation ($r = 0.96$) between ultrasound-measured depth to the lamina in the PSO view and needle insertion depth to the epidural space.

The TM ultrasound view may also be used to measure the depth to the epidural space. A high correlation between the measured depth to the posterior complex and needle insertion depth has been observed in both obese and non-obese parturients undergoing labor epidural analgesia ($r = 0.85$ – 0.88) [11, 12] and has been consistently demonstrated in a large number of trials [13–17, 18•, 19]. The difference between the ultrasound-measured depth and needle insertion depth in most studies is quite small (~ 0.5 cm), with ultrasound usually underestimating the needle depth. This difference is commonly attributed to soft-tissue compression by the ultrasound probe during the scan.

When attempting to predict needle depth for spinal anesthesia, Chin et al. [5] found that greater accuracy and

precision was obtained by measuring the distance to the anterior complex rather than the posterior complex. In the former case, ultrasound tended to overestimate needle depth by only 0.25 cm, whereas, in the latter case, ultrasound underestimated needle depth by, on average, 0.76 cm.

Ultrasound Decreases the Number of Needle Passes Required for Block Success

In an early validation of pre-procedural scanning, Grau et al. [14] randomized 72 parturients with difficult anatomy to surface landmark-guided or ultrasound-assisted epidural placement. Patients had either a history of difficult epidural, kyphoscoliosis, or BMI > 33 kg/m². In this population, needle entry into the epidural space in the surface landmark-guided group required a mean of 2.6 puncture attempts compared to 1.5 in the ultrasound-assisted group ($p < 0.001$). More recently, Chin et al. [20•] studied an older population of 120 orthopedic patients with clinical predictors of difficult neuraxial block, including BMI > 35 kg/m², scoliosis, and prior lumbar surgery. Patients were randomized to either surface landmark-guided or ultrasound-assisted spinal anesthesia. Ultrasound halved the median number of needle insertions from 2 to 1 and significantly reduced the need for additional needle passes (6 vs. 13).

Improved performance of neuraxial blockade after pre-procedural ultrasound imaging is seen even in patients without predictors of technical difficulty. In a randomized controlled trial of epidural analgesia in 300 parturients, the mean number of needle passes was significantly lower with the use of ultrasound compared to surface landmarks alone (1.3 vs. 2.2) [21]. A similar result was reported by Vallejo et al. [18•], who randomized 15 first-year anesthesia trainees to perform 370 labor epidurals with or without the assistance of pre-procedural ultrasound imaging. Fewer insertion attempts were required in the ultrasound-guided group of patients (median of 1 vs. 2).

Ultrasound May Contribute to Block Success and Epidural Efficacy

In addition to reducing the technical difficulty of epidural needle insertion, ultrasound may also increase the efficacy of labor epidural analgesia. In two separate randomized controlled trials by Grau et al. [14, 21], a small but statistically significant decrease in post-block pain scores was noted in the ultrasound-assisted groups compared to the surface landmark-guided groups. This may be partially explained by observed reductions in the incidences of asymmetric and patchy blocks. There was also a significant reduction in the rate of incomplete analgesia (2 vs. 8 %) in

one study [21] and epidural failure (0 vs. 5.6 %) in the other [14]. The use of ultrasound resulted in a similarly impressive reduction in the epidural failure rate in the afore-mentioned study by Vallejo et al. [18•] (1.6 vs. 5.5 %).

A recent systematic review and meta-analysis provided further evidence for an increase in block success with ultrasound. Shaikh et al. [22•] compared ultrasound-guided and non-ultrasound-guided neuraxial procedures, including diagnostic lumbar punctures as well as epidural and spinal anesthetics. They identified 14 publications involving 1,334 patients that met their inclusion criteria. Overall, ultrasound use reduced the risk of procedural failure by 79 %, with the number needed to be treated to avoid one failure being 16. A subgroup analysis of intrathecal [relative risk (RR) = 0.19] and epidural (RR = 0.23) procedures confirmed that this effect is strong for both groups.

Ultrasound Has a Modest Effect on Procedure Time

In their early evaluations of ultrasound-assisted lumbar epidural insertion, Grau et al. [16, 21] found that the ultrasound scan added a maximum of only 60–75 s to the preparation time. In their large randomized controlled trial of labor epidural insertion by trainees, Vallejo et al. [18•] reported that the use of ultrasound increased average total procedure time to a similar extent (60 s). These studies involved a single experienced sonographer and a cohort of healthy obstetric patients. It is possible that more time is required in less-experienced hands or in patients with difficult spinal anatomy. Chin et al. [20•] found that, in patients with scoliosis, prior lumbar surgery, or a BMI > 35 kg/m², pre-procedural scanning took 6.7 min on average to complete compared to 0.6 min for palpation of surface landmarks alone. However, this difference was offset by a decrease in time taken to perform the spinal anesthetic (5.0 vs. 7.3 min).

Ultrasound May Potentially Reduce the Risk of Complications

Ultrasound may reduce adverse effects related to neuraxial anesthesia. Grau et al. [21] observed a significant reduction in the rate of postpartum headache (4.7 vs 18.7 %) and backache (14.7 vs 22.0 %) with ultrasound-assisted epidural insertion. The ability to measure the depth to the epidural space may also reduce the risk of inadvertent dural puncture.

With respect to serious complications, there is no direct evidence demonstrating a reduction in risk with ultrasound, but the decreased technical difficulty associated with ultrasound would suggest a number of theoretical benefits. Hamandi et al. [23] and Reynolds [24] have reported case

series of 5 and 7 patients, respectively, who sustained conus medullaris injuries from spinal needles inserted at a level much higher than intended by the anesthesiologist. Improved accuracy of intervertebral level identification could reduce the risk of this rare but potentially devastating outcome. Spinal hematoma and persistent neurological deficit are similarly rare complications; however, an associated risk factor for both these complications is the technical difficulty in performing the block [25, 26], which can be reduced by ultrasound. The recent meta-analysis by Shaikh et al. [22•] of ultrasound-guided versus non-ultrasound-guided procedures further supports the potential for ultrasound to reduce risk; they found a 73 % reduction in the risk of traumatic procedures with the use of ultrasound.

Ultrasound May Predict Feasibility and Ease of Performance of Neuraxial Blockade

In addition to using ultrasound imaging to directly assist neuraxial blockade, ultrasound may also be used as a predictive tool to guide preoperative decision-making. This has been illustrated in two case reports. The first involved a patient who experienced two previous failed attempts at a spinal anesthetic, having previously undergone L3–5 spinal decompression and fusion with corresponding hardware in situ. Ultrasonography identified a patent acoustic window at the L3–4 level, which permitted a successful spinal anesthetic [27]. The second involved a patient with severe ankylosing spondylitis and a history of failed spinal anesthesia despite persistent efforts. Here, an ultrasound scan in the preanesthetic clinic identified an acoustic window at L4–5, which allowed planning for a spinal anesthetic that was successfully performed at that level on the day of surgery [28•].

The potential of using ultrasound to predict ease of spinal anesthesia has been rigorously evaluated in two cohort studies. Weed et al. [29] performed ultrasound scans using the PSO view in 60 orthopedic patients undergoing spinal anesthesia. Clinicians blinded to the results of the imaging performed the neuraxial anesthetic using a surface landmark-guided approach. There was a remarkable difference in block performance between patients in whom the anterior complex was visible on ultrasound and those in whom it was not. When images were poor, the median number of needle passes required was 10 compared to 4 in patients with good images. Spinal anesthesia was classified as difficult by the operator in 9 % of patients with good images compared to 50 % of patients with poor images of the anterior complex. The positive predictive value of a low-quality image in the PSO view for difficult spinal injection was calculated to be 82.3 %, and the negative predictive value to be 67.4 %.

In a similar study, Chin et al. [30•] studied the utility of both the PSO and TM views for predicting technically difficult spinal anesthesia in a cohort of 100 orthopedic

patients. As in the previous study, the anesthesiologists performing the spinal anesthetic were blinded to the results of the ultrasound scan. If both the posterior and anterior complexes were visible (a good-quality view) in the TM view, the positive predictive value for absence of technical difficulty at that level was 85 %. This discriminative ability was not present, however, with the PSO view. There were a small number of patients in whom spinal anesthesia was challenging despite a good-quality TM view of the vertebral canal. The authors hypothesized that this could have been avoided if the anesthesiologists were not blinded and the pre-procedure ultrasound scan had been used to guide the spinal procedure, as would be the case in the clinical setting.

Thoracic Spine

Unique Challenges in Imaging the Thoracic Spine

Imaging of the thoracic spine presents some challenges compared to the lumbar region. Firstly, level identification is a more complex process as the L5–S1 intervertebral junction is a greater distance away. It may, therefore, be convenient to count up from the articulation of the 12th rib with the T12 transverse process or down from the 1st rib.

Secondly, it is difficult to obtain a good TM view of the vertebral canal in the mid- and upper thoracic regions, due to the caudad angulation and overlapping nature of the spinous processes. The thoracic vertebral canal can be better visualized through the paramedian interlaminar spaces in the PSO view, but this again is more difficult in the upper than lower thoracic spine due to progressive narrowing of these spaces. This was demonstrated by Avramescu et al. [31•] during a study in which they attempted to obtain TM and PSO views of the vertebral canal at all 12 thoracic intervertebral levels in 61 healthy volunteers. They found that the posterior complex was only visible in 37.5 % of all TM views compared to 74.5 % of all PSO views. They also noted that the frequency of good-quality views progressively decreased in a cephalad direction, with the best sonographic visibility between T11–L1 and the worst between T1–T8. Of note, even in the most challenging region of T1–T8, the PSO view afforded a good-quality image of the canal in 63.3 % of subjects.

Ultrasound May Assist in Identification of Thoracic Intervertebral Levels

As in the lumbar spine, surface anatomical landmark-based methods of identifying thoracic intervertebral levels have been shown to be inaccurate when referenced to the gold standard of MRI or X-ray imaging [32–34]. In one study, the

T7 spinous process was accurately identified only 29 % of the time by counting down from the vertebra prominens (C7) and only 10 % of the time when the inferior tip of the scapula was used as the primary landmark [32]. The majority of errors tend to be in the caudad direction [32, 33].

Arzola et al. have demonstrated a similar lack of agreement between ultrasound identification of thoracic intervertebral level (using a counting-up method from the sacrum and 12th rib) and surface anatomical landmarks. As with the earlier studies, the vertebra prominens was a more accurate landmark for C7 (58 % agreement) than the inferior angle of the scapula was for T7 (36 % agreement) [35, 36]. Errors in identifying T7 were most often in a caudad direction (83 % of errors) whereas the errors in identifying C7 were equally distributed in a cephalad and caudad direction. While it is reasonable to expect ultrasound to be more accurate than surface landmarks, it should be noted that, to date, this accuracy has not been verified against a gold standard imaging modality.

Thoracic Epidural

Thoracic Ultrasound Accurately Determines Depth to the Epidural Space

In a small series of 20 patients receiving thoracic epidural analgesia, Rasoulia et al. [36] directly compared ultrasound measurement of the depth to the ligamentum flavum in the PSO view to actual needle insertion depth. There was moderately good correlation ($r^2 = 0.65$) observed between the two measurements, with ultrasound underestimating by a mean absolute difference of 4.68 mm. More importantly, these values were similar to those obtained when CT measurement of the depth to the epidural space was compared to needle insertion depth ($r^2 = 0.69$, mean difference of 4.49 mm). In a separate study of thoracic epidural insertion in 35 patients, Salman et al. [37•] reported similar results. Correlation between ultrasound-measured depth and needle insertion depth was good ($r = 0.75$), and the mean difference was 7.1 mm, with ultrasound tending to underestimate the depth. Taken together, these findings suggest that the reliability and accuracy of ultrasound in estimating depth to the thoracic epidural space is similar to the lumbar spine.

Ultrasound May Assist Technical Performance of Thoracic Epidurals

At present, there is limited evidence supporting the benefit of pre-procedural ultrasound imaging in improving technical performance of thoracic epidurals. Case reports suggest that ultrasound is useful in evaluating the abnormal anatomy and in determining the optimal needle insertion site and trajectory in scoliotic patients [38, 39]. In the study

by Salman et al. [37•], the PSO view on ultrasound was used to determine the optimal needle insertion point for a paramedian approach to mid-to-lower thoracic epidural insertion in 35 healthy adult patients. Successful insertion was achieved with one skin puncture on average, and within two or fewer redirections in 88 % of cases.

The Learning Curve for Ultrasound Imaging of the Spine

The Minimum Number of Procedures for Competency is Unknown

The first published report of trainees learning lumbar ultrasonography was by Watson et al. [40]. In their investigation, 17 lumbar scans were performed to identify specific intervertebral levels by a trainee anesthesiologist who had seen ultrasound images in a volunteer and discussed the technique with a qualified radiologist. This trainee subsequently “cascaded” the knowledge to a second trainee, and the authors claimed that ultrasonographic identification of lumbar intervertebral levels was a relatively simple skill to acquire. However, when their results were compared to MRI, a 24 % error rate in level identification was observed. Halpern et al. [41•] subsequently published results from a pilot study evaluating the learning curve for ultrasonographic identification of lumbar intervertebral levels. Two anesthesiologists without prior experience in neuraxial ultrasonography sought to identify a specific lumbar spinous process, which was then verified using CT imaging. Using the cumulative-sum method, the first subject required 36 procedures to achieve the pre-determined accuracy level of 90 % successful identifications, while the second subject required 22 procedures. Overall accuracy during skill acquisition was 68 %; however, ultrasound was wrong by more than one level in only 2 of the 74 patients studied.

Margarido et al. [42•] also applied a cumulative-sum method to evaluate an instructional program combining didactic teaching with a hands-on workshop. Following completion of the program, participants were evaluated on the performance of three tasks: identification of a specific intervertebral level, marking an optimal needle insertion point, and measuring the depth to the posterior complex. Participants were allowed a maximum of 20 attempts and, within this restriction, only 27 % of candidates achieved competence in determining the correct intervertebral level. In this subset of participants, the median number of attempts required to attain competence in this task was 11 (range 8–18). During this limited series, no candidate achieved competence in determining the optimal insertion point or in estimating the depth to the posterior complex.

These two small studies suggest that elements of the neuraxial ultrasound skill may have different learning curves, that the range in experience to achieve competency at these tasks is broad, and that the optimal number of attempts to reach these goals is undetermined. The learning curve for ultrasonography of the thoracic region and translation of ultrasound skills to improved performance of neuraxial procedures remain unexplored.

The Optimal Teaching Strategy is Unknown

The optimal educational approaches for teaching neuraxial ultrasonography are unclear. Strategies used in the learning curve studies described above include repetitive self-practice [41•] and didactic teaching combined with guided hands-on experience [42•]. Niazi et al. recently described the educational impact of an interactive digital model of ultrasound spine scanning on junior anesthetic trainees. This was combined with a multi-approach learning strategy that included didactic lectures, mentored cadaveric spine dissections, and hands-on scanning of human volunteers [43]. The group exposed to the interactive digital scanning model had higher scores on a task-specific checklist for ultrasonography of the spine compared to the group that was not exposed (mean of 11.5 vs. 8, out of 12). These results suggest that a visual and multi-modal approach to teaching ultrasound of the lumbar spine may generate better performance results. However, the optimal combination of these techniques is unknown. In addition, trainees were only evaluated on a single task performance, so it is unclear if the learning effect is durable over time.

Conclusions

Pre-procedural ultrasound imaging of the spine can clearly reduce the technical difficulty of lumbar neuraxial blockade, particularly in patients with challenging anatomy, and may also improve the clinical efficacy of epidural analgesia. There is less evidence at present for its utility in thoracic epidurals, but ultrasound has been shown to provide reliable estimates of the depth to the epidural space and accurately determine the correct intervertebral level in both the lumbar and thoracic spine. We therefore believe it is a useful skill to acquire. At this time, however, both the optimal educational strategy and the learning curve for competency in ultrasound-assisted neuraxial anesthesia are unclear. Further investigation into these areas is warranted.

Compliance with Ethics Guidelines

Conflict of Interest Kyle R. Kirkham declares that he has no conflict of interest. Ki Jinn Chin is partly supported by a Merit Award from the University of Toronto, Department of Anesthesia.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

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