Pain Medicine, 20(9), 2019, 1750–1755
doi: 10.1093/pm/pnz026
Advance Access Publication Date: 13 March 2019
Preliminary Research Article

OXFORD

NEUROMODULATION & INTERVENTIONAL SECTION

Real-time Ultrasound-Guided Lumbar Epidural with Transverse Interlaminar View: Evaluation of an In-Plane Technique

Hesham Elsharkawy, MD,* Wael Saasouh, MD,[†] Rovnat Babazade, MD,[‡,§] Loran Mounir Soliman, MD,[¶] Jean-Louis Horn, MD,[||] and Sherif Zaky, MD[|||]

*Departments of Anesthesiology and Outcomes Research, Anesthesiology Institute, Cleveland Clinic, CCLCM of Case Western Reserve University, Cleveland, Ohio; [†]Department of Anesthesiology, Detroit Medical Center, Detroit, Michigan; Outcomes Research Consortium, Anesthesiology Institute, Cleveland, Ohio; [‡]Department of Anesthesiology, University of Texas Medical Branch at Galveston, Galveston, Texas; [§]Outcomes Research Consortium, Cleveland, Ohio; [¶]Department of General Anesthesiology, Anesthesiology Institute, Cleveland Clinic, Cleveland, Ohio; [||]Division of Regional Anesthesia, Perioperative and Pain Medicine, Stanford University Medical Center, Stanford, California; [|||]Department of Pain Management, Firelands Regional Medical Center, Sandusky, Ohio, USA

Correspondence to: Hesham Elsharkawy, MD, MBA, MSc, Departments of Anesthesiology and Outcomes Research, Anesthesiology Institute, Cleveland Clinic, CCLCM of Case Western Reserve University, 9500 Euclid Avenue, Mail Code E31, Cleveland OH, 44195, USA. Tel: +1-216-445-3783; Fax: +1-216-444-2294; E-mail: elsharh@ccf.org.

Funding sources: Pajunk Medical Systems (Norcross, GA, USA) provided the epidural needles used in this cohort, as well as a grant of $5,000 USD. None of the investigators were directly compensated or biased in the reported findings. No other external funding is declared.

Disclosure and conflicts of interest: Dr. Elsharkawy has received unrestricted educational funding from Pajunk (Pajunk Medical Systems, Norcross, GA, USA) and consultant fees from Pacira Pharmaceuticals (San Diego, CA, USA). These companies had no input into any aspect of the present project design or manuscript preparation.

Trial registration: This study was registered at clinicaltrials.gov (https://clinicaltrials.gov/ct2/show/NCT01686243, NCT01686243).

Abstract

Objective. The anatomical landmarks method is currently the most widely used technique for epidural needle insertion and is faced with multiple difficulties in certain patient populations. Real-time ultrasound guidance has been recently used to aid in epidural needle insertion, with promising results. Our aim was to test the feasibility, success rate, and satisfaction associated with a novel real-time ultrasound-guided lumbar epidural needle insertion in the transverse interlaminar view. **Design.** Prospective descriptive trial on a novel approach. **Setting.** Operating room and preoperative holding area at a tertiary care hospital. **Subjects.** Adult patients presenting for elective open prostatectomy and planned for surgical epidural anesthesia. **Methods.** Consented adult patients aged 30–80 years scheduled for open prostatectomy under epidural anesthesia were enrolled. Exclusion criteria included allergy to local anesthetics, infection at the needle insertion site, coagulopathy, and patient refusal. A curvilinear low-frequency (2–5 MHz) ultrasound probe and echogenic 17-G Tuohy needles were used by one of three attending anesthesiologists. Feasibility of epidural insertion was defined as a 90% success rate within 10 minutes. **Results.** Twenty-two patients were enrolled into the trial, 14 (63.6%) of whom found the process to be satisfactory or very satisfactory. The median time to perform the block was around 4.5 minutes, with an estimated success rate of 95%. No complications related to the epidural block were observed over the 48 hours after the procedure. **Conclusions.** We demonstrate the feasibility of a novel real-time ultrasound-guided epidural with transverse interlaminar view.

Key Words: Anesthesia; Epidural; Ultrasound Imaging

Introduction

Millions of epidural catheters are placed annually, of which more than 2 million are done before childbirth alone [1]. Overall failure rates of epidural catheter insertions vary by publication and the definition of failure, but they have been reported to be as high as 30–50% [2].

The safety, ease, and reliability of epidural catheter placement are paramount to proper anesthesia practice.

Currently, the most widely used method for locating the epidural space still relies on surface anatomical landmarks. As a result, identification of the epidural space may fail in as many as 40–70% of cases [3–5]. This method may be faced with difficulties and complications in anatomically challenging patients [3], as well as in those with otherwise normal anatomy [4]. This can result in complications such as unintentional dural or vascular puncture, spinal hematoma, discomfort to the patient from multiple attempts, failed block, frustration for the anesthesiologist, poor patient satisfaction, and, rarely, neurological damage [2,3,6].

Real-time ultrasound procedures have been recently gaining attraction as a modality to guide neuraxial needle insertion [7]. Ultrasound has been used for prepuncture scanning [8–11] or to visualize the advancing needle in real time [10] and has been shown to increase the success rate of epidural catheter placement when compared with a traditional anatomical landmark-based technique [5,9,10].

Real-time ultrasound has also been successfully used as a rescue modality after failure of the landmark-guided approach [9,12]. The feasibility of a parasagittal view for ultrasound-guided epidural catheter insertion has been described in the literature [5,13,14]. Although the transverse median, paramedian saggital oblique, and longitudinal median approaches have been described, the use of real-time ultrasound guidance for paramedian epidural catheter insertion in the transverse view has not been well documented [15].

Herein, we aimed to demonstrate the feasibility and success rate of the in-plane transverse interlaminar view technique using a real-time ultrasound-guided paramedian approach to the lumbar epidural space in a prospective trial. Secondarily, we aimed to demonstrate the number of attempts required to successfully place the epidural catheter and to assess operator and patient satisfaction with the procedure.

Methods

Following Cleveland Clinic Institutional Review Board approval, 22 adult patients scheduled for open prostatectomy under epidural anesthesia were enrolled at the Cleveland Clinic Main Campus. All patients gave their written informed consent for participation in the study. The inclusion criteria included age 30–80 years, elective open prostatectomy, and planned surgical epidural anesthesia. Exclusion criteria included allergy to local anesthetics, infection at the needle insertion site, coagulopathy, and patient refusal. A curvilinear low-frequency (2–5 MHz) ultrasound probe was used for the study: SonoSite S nerve (National Ultrasound, Duluth, GA, USA) or Venue 40 low frequency (GE Healthcare, Norcross, GA, USA). Echogenic 17-G Tuohy needles (Pajunk Tuohy Sono; Pajunk Medical Systems LP, Norcross, GA, USA) with 19-G epidural catheters were utilized.

Epidurals were performed with a single-operator technique by one of three attending anesthesiologists (HE, LS, SZ), who are all experienced with real-time ultrasound-guided peripheral nerve blocks (200 blocks per year), have trained on ultrasound-guided/assisted neuraxial blocks, and had performed at least 10 real-time ultrasound-guided epidural insertions before study initiation.

We specified that the feasibility of the procedure would require an observed success rate consistent with 90% or more, along with time to complete the procedure of 10 minutes or less [12,16]. We defined success of an epidural catheter by the ability to complete the surgical procedure under epidural analgesia with or without moderate sedation.

Description of Technique

After establishing intravenous access, routine standard American Society of Anesthesiologists monitoring was applied, including electrocardiogram, noninvasive blood pressure, and pulse oximetry. Intravenous sedation (2 mg of midazolam and 50 μg of fentanyl) was used, per the anesthesiologist's order. In a sitting position (or lateral, if the patient was unable to remain in sitting position), the lower thoracic and lumbar area of the back was prepped and sterilized using povidone iodine. Sterile gloves, mask, hat, and a sterile curvilinear low-frequency (2–5 MHz) ultrasound probe cover were used. A sterile drape was placed in a way to ensure enough room for lateral needle insertion (the window of the drape was moved laterally to the side of needle insertion).

A paramedian sagittal oblique view of the lumbar spine was obtained, and the laminae (L) were visible in cross-section as sloping hyperechoic lines in a "sawtooth" pattern. The L5–S1 junction was identified; then the L1-L2 interspace was traced by counting upwards. Once the L1-L2 level was identified, the probe was rotated 90° into a transverse orientation to obtain the transverse interlaminar view.

The acoustic shadow of the interspinous ligament at midline (less hyperechoic than the spinous process) was surrounded by erector spinae muscles on both sides. Two deeper hyperechoic lines representing the posterior complex (ligamentum flavum/posterior dura) and the anterior complex, separated by the hypoechoic intrathecal space, were identified. Then the transverse processes and articular processes were noted more laterally (Figure 1).

The single operator infiltrated the skin at the puncture site with 1% lidocaine from the right or left side of the probe's footprint. The epidural needle was inserted in plane with the ultrasound probe, keeping the tip of the needle in view in a lateral-to-medial direction. The needle was passed through the erector spinae muscle then passed superficial to the articular process, directed toward the posterior complex. Once the tip of the needle approached the posterior complex, the ultrasound probe was set aside and the needle advanced slowly to the epidural space, confirmed by loss of resistance to saline (Figure 2). The epidural catheter was inserted 4 cm past the needle tip. Once the catheter was positioned, a negative test dose (45 mg of lidocaine and 15 mcg of epinephrine) concluded this portion of the procedure, and the patient was transferred to the operating room. After checking into the operating room and connecting the monitors, 10–15 mL of 1% ropivacaine was injected into the epidural catheter in small increments. An adequate anesthetic dermatomal level around T8 was confirmed before a moderate level of sedation was administered using a propofol infusion. The epidural catheter was connected to a patient-controlled pump in the operating room, which delivered bupivacaine 0.1% with fentanyl 2 mcg/mL at a rate of 5 mL per hour. The continuous rate was used for the length of the procedure; then a patient demand bolus of 3 mL with a lock-out time of 15 minutes between boluses was provided after arrival in the recovery area. The epidural infusion was maintained overnight, and the catheter was removed on postoperative day 1, unless its continuation was deemed necessary for clinical reasons.

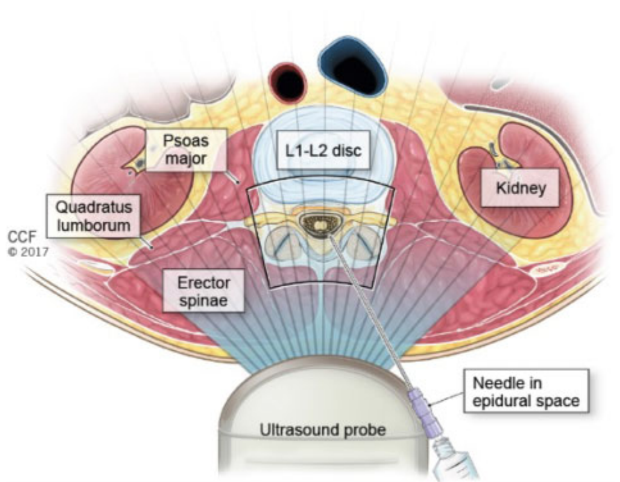

Figure 1. Paramedian approach to the epidural space under real-time ultrasound guidance in transverse interlaminar view. Schematic illustration demonstrating the ultrasound probe position at the L1-L2 space in a transverse orientation. The epidural needle is inserted immediately lateral to the probe and in plane, with the ultrasound directed toward the posterior complex.

Measurements and Statistical Methods

Demographic variables (age, sex) and morphometric measurements (weight, height) were recorded. Block performance time was started at Tuohy needle insertion and ended when the needle was removed. The time for prescanning, local anesthetic administration, and dressing application was not recorded. The number of attempts was recorded and was defined as complete needle removal and reinsertion through a new entry point at the same or an alternate level. Success rate was measured as the rate of cases that had successful insertion of the epidural catheter, and the surgical procedure was performed under epidural anesthesia (without converting to general anesthesia). Cases converted to general anesthesia where adequate dermatomal level was not confirmed were considered unsuccessful.

Other parameters recorded were epidural-related complications (inadvertent dural puncture, postoperative neurological complications), patient satisfaction (measured after the epidural placement and recorded as a numerical score using a five-point Likert-type scale: 1 = very good, 2 = good, 3 = average, 4 = unsatisfactory, 5 = very unsatisfactory), and catheter insertion difficulty (assessed by the anesthesiologist using a 10-point scale, with 0 being the easiest and 10 the most difficult). Quality of the needle tip visualization with ultrasound was recorded and evaluated by the proceduralist as excellent visibility (needle shaft and tip strongly echogenic

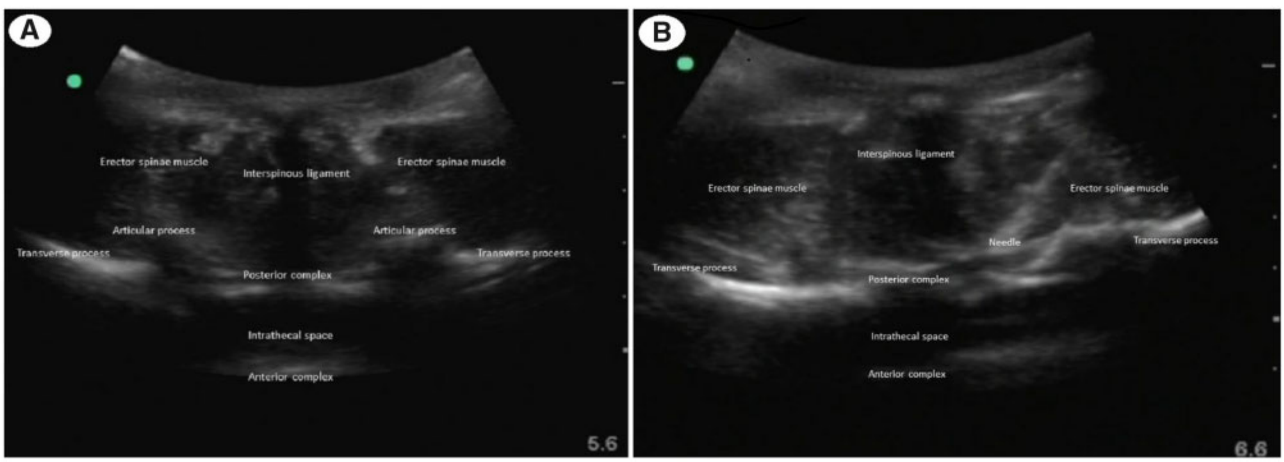

Figure 2. Ultrasound image showing the transverse interlaminar view at L 1–2 without the needle (A) and with the needle (B) positioning for real-time ultrasound-guided paramedian epidural insertion. AC = anterior complex; AP = articular process; ES = erector spinae muscle; IT = intrathecal space; PC = posterior complex; TP = transverse process.

relative to their background and visualized in their entirety), moderate visibility (shaft and tip readily identified as being more echogenic than the background), poor visibility (shaft and tip isoechoic or only slightly more echogenic than the background), or no visibility.

Baseline and intraoperative variables were summarized by standard descriptive statistics (mean ± SD, median [quartiles], or No. (%)). We estimated the success rates of block along with 95% confidence intervals by the exact binomial method. We also estimated the medians and confidence intervals for time of block performance.

Results

Twenty-two patients undergoing open prostatectomy were enrolled into the study. Descriptive statistics of demographic and procedure variables are summarized in Tables 1 and 2.

The median time to perform the block was 268 seconds (4.5 minutes). The epidural space was successfully identified in all 22 (100%) patients. The block success rate was 95%. Fourteen patients (63.6%) found the epidural insertion process to be satisfactory or very satisfactory.

Table 2 summarizes the results and shows that the experience was ranked as relatively "easy" (ranks 1–3) in 10 out of 22 patients (45.5%), whereas it was ranked as relatively "hard" (ranks 8–10) in three patients (13.6%).

Two patients were converted to general anesthesia and counted unsuccessful. One of those patients had a unilateral block, and the other was unable to tolerate the epidural catheter placement after the first trial. We did not observe any complications related to the epidural block, inadvertent dural puncture, or subsequent adverse events during the hospital follow-up over two postoperative days.

Table 1. Descriptive statistics of demographics

Baseline Characteristics	Statistics* (N = 22)
Age, y	61 ± 6
Weight, kg	93 [86–102]
Height, cm	180 ± 7
BMI, kg/m^2	29 [26–33]
ASA physical status	
1	0 (0.0)
2	11 (50.0)
3	10 (45.5)
4	1 (4.5)

ASA = American Society of Anesthesiologists; BMI = body mass index.
*Statistics are mean ± SD, median [quartiles], or No. (%).

Table 2. Descriptive statistics of procedure variables

Procedure Parameters	Statistics* (N = 22)
Time until first analgesic request, min†	67 [48–122]
Patient position during epidural placement	
Sitting	12 (54.5)
Lateral	10 (45.5)
Total No. of needle insertions	
1	16 (72.7)
2	0 (0.0)
3	5 (22.7)
4	0 (0.0)
5	1 (4.5)
Visualization quality of the needle tip	
Excellent visibility	6 (27.3)
Moderate visibility	8 (36.4)
Poor visibility	6 (27.3)
No visibility	2 (9.1)
Operators' assessment of difficulty with needle insertion	
1 (easiest)	1 (4.5)
2	6 (27.3)
3	3 (13.6)
4	2 (9.1)
5 (moderate difficulty)	3 (13.6)
6	2 (9.1)
7	2 (9.1)
8	1 (4.5)
9	1 (4.5)
10 (hardest)	1 (4.5)
Patient satisfaction	
1 (very unsatisfied)	0 (0.0)
2	2 (9.1)
3 (neutral)	4 (18.2)
4	5 (22.7)
5 (very satisfied)	9 (40.9)
Missing	2 (9.1)

Summary of collected and calculated data. A new skin insertion is defined as a separate skin puncture. Visualization quality is based on subjective visibility of the needle tip to the operator.
*Statistics are median [quartiles] or No. (%).
†The time at which a patient requested the first rescue analgesic dose postoperatively.

Discussion

This prospective observational pilot trial demonstrates that a novel in-plane transverse interlaminar view using a real-time ultrasound-guided paramedian approach to the epidural space is feasible, with success achieved in 20 of the 21 patients in whom the block was performed. In these patients, the estimate of median block performance time was 4.5 minutes.

Over the last decade, many techniques for locating and confirming entry into the epidural space have been explored to circumvent the traditional difficulties associated with epidural needle and catheter insertion. The current methods of locating the epidural space rely on surface anatomical landmarks, loss of resistance, and ultrasound-guided needle visualization [17].

Novel and feasible techniques with high success rates can improve clinical practice and patient satisfaction. Real-time ultrasound guidance for epidural catheter insertion has been reported in recent work [18,19] but remains a topic of continued interest. It has been advocated in cases of failed landmark palpation or preprocedural scan of the spine [20], and newer devices are appearing on the market to facilitate real-time visualization of structures while manipulating the epidural needle [21,22].

Tran and colleagues [12] did a pilot study and demonstrated that a real-time ultrasound-guided paramedian epidural approach technique is feasible, with success achieved in 18 of the 19 subjects enrolled. In this study, the authors selected elective cesarean section cases and performed a single sonographer prepuncture ultrasound scan; all the epidural needles were inserted by the same experienced anesthesiologists using a paramedian approach. Karmakar and colleagues [16] enrolled 15 patients and performed real-time ultrasound-guided epidural insertions using a longitudinal paramedian sagittal oblique view with a paramedian needle approach, with a success rate of 93%. Our transverse interlaminar view differs from the previously described paramedian sagittal oblique view in the following aspects: 1) different needle direction, where we have advanced the needle from lateral to medial and directed toward the posterior complex transverse interlaminar (interspinous) process as compared with the caudal to cranial direction in the paramedian sagittal oblique view; 2) different target needle tip position, where we aim toward the midline or as close to it as possible, as compared with the paramedian interlaminal space in the paramedian sagittal oblique view, possibly decreasing the incidence of a unilateral or patchy block; 3) potentially easier identification of target structures and epidural needle insertion in an anatomically difficult spine such as those seen in scoliosis; and 4) potentially easier identification of the anterior complex and thus easier navigation of the epidural needle. Our case series, however, lacks the power to definitively claim advantages of this view, and we recommend a larger, more robust trial to confirm our findings.

We used loss of resistance and real-time ultrasound guidance for epidural needle insertion in our trial. In addition, we judged the success of the epidural catheter by the ability to perform the surgical procedure without reverting to general anesthesia.

The experienced anesthesiologists involved in this study ranked needle insertion as relatively "easy" in 10 out of 22 patients (45.5%) and relatively "difficult" in three patients (13.6%). In addition, visibility of the needle tip was "none" in two patients (9.1%) and "poor" in six patients (27.3%), where the advancement of the needle was dependent on tissue movements. It is worth mentioning that keeping the needle in line with the ultrasound probe requires familiarity with the technique and routine use of ultrasound for nerve blocks.

With the continuous improvement of technology, higher-efficiency devices [23,24] will make their way to routine anesthesia practice and further enhance delivery of safer care.

Patient positioning in the lateral decubitus position may be logistically easier than a sitting position and gives the operator better control of the probe. Tilting the probe to the side opposite the needle insertion before introducing the needle can improve needle visualization. To avoid contact between the needle and the facet joint, several maneuvers can be employed; we recommend identifying the facet joint in the paramedian sagittal articular process view before performing the procedure in the transverse view. The facet joint lies in a more superficial plane than the lamina and the interlaminar space in the coronal plane. The anterior complex and the posterior complex must be visualized before needle insertion.

Our pilot study has limitations. Namely, this was a technique that was not standard practice and was only employed on a limited number of patients included in this study. The three participating anesthesiologists all had good ultrasound experience, but still faced some difficulty in a subset of patients, which limits the generalizability of our results. We were only able to descriptively analyze our numbers; a randomized trial is required to establish conclusive evidence. We did not record the time required to scan the patient before commencing the epidural insertion procedure. The added time of preparation and scanning can lead to patient dissatisfaction, which may easily be managed with some sedation. Scanning time and needle insertion attempts may also be increased in patients with certain changes in their spinal anatomy, such as significant hypertrophy of facet joints or other deposits along the needle track. In addition, we did not correlate the time required to perform the procedure or its overall difficulty with body mass index, which may be a reasonable predictor of anatomical challenges. We also did not account for the number of times the epidural needle was redirected or the periosteum was contacted within the same puncture site, which may correlate with patient discomfort during the procedure. The number of redirections is expected to be inversely proportional to the expertise of the proceduralist, as this technique requires considerable skill to avoid contact with adjacent bony structures. Constant movements of both the ultrasound probe and epidural needle may be required to maintain view of the epidural space.

Considering the aforementioned limitations, the objective of this pilot study was to evaluate the feasibility of performing real-time ultrasound-guided paramedian epidural access, which we have successfully demonstrated. We have considered open prostatectomy surgery successfully performed under epidural anesthesia (with or without sedation) to be the end point for success to eliminate any bias. Our findings require confirmation in a larger, more robust randomized controlled trial, in which procedure times, difficulty, and satisfaction could be better compared.

Conclusions

Real-time ultrasound guidance for epidural needle insertion with a transverse interlaminar view is feasible, and clinical trials would be useful to obtain precise estimates of success rate and time to perform the block in a variety of settings.

Acknowledgments

We thank Xiaohong Li for her assistance with the statistical analysis of the data. We also thank Marwan Abdulsattar for help with the study.

All images were taken with permission from the Cleveland Clinic art photography department.

References

1. Ruppen W, Derry S, McQuay H, Moore RA. Incidence of epidural hematoma, infection, and neurologic injury in obstetric patients with epidural analgesia/anesthesia. Anesthesiology 2006;105(2):394–9.
2. Rawal N. Epidural technique for postoperative pain. Reg Anesth Pain Med 2012;3:310–7.
3. Hood DD, Dewan DM. Anesthetic and obstetric outcome in morbidly obese parturients. Anesthesiology 1993;6:1210–8.
4. Broadbent CR, Maxwell WB, Ferrie R, et al. Ability of anaesthetists to identify a marked lumbar interspace. Anaesthesia 2000;55(11):1122–6.
5. Sahota JS, Carvalho JCA, Balki M, Fanning N, Arzola C. Ultrasound estimates for midline epidural punctures in the obese parturient: Paramedian sagittal oblique is comparable to transverse median plane. Anesth Analg 2013;116:829–35.
6. Srinivasan KK, Lee PJ, Iohom G. Ultrasound for neuraxial blockade. Med Ultrasonogr 2014;16 (4):356–63.
7. Elsharkawy H, Maheshwari A, Babazade R, et al. Real-time ultrasound guided spinal anesthesia in patients with predicted difficult anatomy. Minerva Anestesiol 2017;5:465–73.
8. Kessler J, Moriggl B, Grau T. The use of ultrasound improves the accuracy of epidural needle placement in cadavers. Surg Radiol Anat 2014;36(7):695–703.
9. Grau T, Leipold RW, Conradi R, Martin E, Motsch J. Efficacy of ultrasound imaging in obstetric epidural anesthesia. J Clin Anesth 2002;14(3):169–75.
10. Grau T, Leipold RW, Fatehi S, Martin E, Motsch J. Real-time ultrasonic observation of combined spinal-epidural anesthesia. Eur J Anaesthesiol 2004;21: 25–31.
11. Hasanin AM, Mokhtar AM, Amin SM, Sayed AA. Preprocedural ultrasound examination versus manual palpation for thoracic epidural catheter insertion. Saudi J Anaesth 2017;11:62–6.
12. Tran D, Kamani AA, Al-Attas E, et al. Single-operator real-time ultrasound-guidance to aim and insert a lumbar epidural needle. Canad J Anesth 2010;57 (4):313–21.
13. Salman A, Arzola C, Tharmaratnam U, Balki M. Ultrasound imaging of the thoracic spine in paramedian sagittal oblique plane: The correlation between estimated and actual depth to the epidural space. Reg Anesth Pain Med 2011;36:542–7.
14. Grau T, Leipold R, Horter J, et al. Paramedian access to the epidural space: The optimum window for ultrasound imaging. J Clin Anesth 2001;13(3):213–7.
15. Sahin T, Balaban O. Lumbar ultrasonography for obstetric neuraxial blocks: Sonoanatomy and literature review. Turk J Anaesthesiol Reanim 2018;46: 257–67.
16. Karmakar MK, Li X, Ho AMH, Kwok WH, Chui PT. Real-time ultrasound-guided paramedian epidural access: Evaluation of a novel in-plane technique. Br J Anaesth 2009;102(6):845–54.
17. Arzola C, Davies S, Rofaeel A, Carvalho J. Ultrasound using th transverse approach to the lumbar spine provides reliable landmarks for labor epidurals. Anesth Analg 2007;104(5):1188–92.
18. Soni N, Franco-Sadud R, Schnobrich D, et al. Ultrasound guidance for lumbar puncture. Neurol Clin Pract 2016;6(4):358–68.
19. Pak DJ, Gulati A. Real-time ultrasound-assisted thoracic epidural placement, a feasibility study of a novel technique. Reg Anesth Pain Med 2018;43(6):613–5.
20. Gnaho A, Nau A, Gentil ME. Real-time ultrasound-guided epidural catheter insertion in obese parturients. Can J Anesth/J Can Anesth 2015;62(11): 1226–7.
21. Tiouririne M, Dixon A, Mauldin F, et al. Imaging performance of a handheld ultrasound system with real-time computer-aided detection of lumbar spine anatomy: A feasibility study. Invest Radiol 2017;52(8):447–55.
22. Tiouririne M, Nguyen S, Hossack J, et al. Handheld real-time volumetric imaging of the spine: Technology development. J Med Eng Technol 2014; 38(2):100–3.
23. Beigi P, Malenfant P, Rasoulian A, et al. Three-dimensional ultrasound-guided real-time midline epidural needle placement with epiguide: A prospective feasibility study. Ultrasound Med Biol 2017;43: 375–9.
24. Dong G-C, Chiu L-C, Ting C-K, et al. A coaxial dual-element focused ultrasound probe for guidance of epidural catheterization: An experimental study. Ultrasonic Imaging 2017;39(5):283–94.