Research Article

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Teaching Neuraxial Ultrasonography with a Virtual Reality Simulator of Spine: A Randomized Controlled Study

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ABSTRACT

Objective To evaluate whether adjunctive virtual reality (VR) spine simulation in neuraxial ultrasound training improves performance competency among anesthesia residents compared with traditional didactic teaching alone.

Methods In this single-center, randomized controlled trial, anesthesia residents from the Department of Anesthesiology, Peking Union Medical College Hospital were recruited and randomized (1∶1, computer-generated) to receive either a traditional 30-minute didactic lecture of spine ultrasonography (control group) or an identical teaching session followed by 30-minute VR spine simulation (VR group). After the training, participants were required to perform a preprocedural spine ultrasound scan. The primary outcome was a composite learning score evaluating the theoretical knowledge, practical skills, self-assessed satisfaction, and willingness to apply the technique in future practice. The secondary outcomes included scanning time, score of anatomic structure recognition, and accuracy of depth measurement to the posterior complex.

Results A total of 46 participants (23 per group) were enrolled. Compared to the control group, the VR group achieved significantly higher composite learning scores (0.80±0.05 *vs* 0.74±0.09, $P = 0.01$). The score of anatomic structure recognition (0.85±0.15 *vs* 0.72±0.20, $P = 0.01$) and the accuracy of depth measurement to the posterior complex (73.9% *vs* 43.5%, $P = 0.03$) were also significantly superior in the VR group.

Conclusion Among anesthesia residents, adjunctive VR simulator training improves the technical and cognitive performance in neuraxial ultrasound compared with traditional didactic teaching alone.

Key words: neuraxial ultrasonography; virtual reality; neuraxial anesthesia

INTRODUCTION

Neuraxial anesthesia is an essential regional block technique, with the target puncture interspace traditionally determined by palpating the bony landmarks. However, the anatomic landmarks are difficult to discern by manual palpation in patients with obesity, scoliosis, and existing spinal hardware. This would lead to longer puncture time, repeated insertion attempts, and multiple needle passes, which increase the risks of epidural hematoma, postdural puncture headache (PDPH), and paresthesia.

As a revolutionary technique in regional anesthesia, ultrasound enables the real-time visualization of adjacent anatomical structures, advancement of the needle, and spread of the injectate. It has gained popularity in neuraxial anesthesia since its introduction in the early 2000s[1,2]. A growing body of evidence shows that neuraxial ultrasound could provide precise identification of the desired lumbar interspace and the midline, prediction of the angle of needle puncture, and accurate measurement of the depth to the ligamentum flavum/dura complex[3]. Ultrasound can also be utilized to evaluate the abnormalities in spine anatomy including curvature and rotation as well as spine hardware from previous surgery. Meta-analyses have also proved that ultrasound improves

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the efficacy and safety of neuraxial anesthesia[4-6], as well as patient satisfaction with anesthesia service[7]. Henceforth, neuraxial ultrasound is an indispensable component of the anesthesiologist's armamentarium.

Virtual reality (VR), a cutting-edge technology that combines computer graphics and sensory experiences, has emerged as a promising simulation training method to enhance medical education. It offers a more immersive and engaging experience than traditional teaching methods and is increasingly used in anatomy teaching and procedural training[8-13]. VR appears suitable for neuraxial ultrasonography teaching, helping students relate static anatomy to realistic spatial structures and bridging three-dimensional (3D) anatomic structures with two-dimensional (2D) spinal ultrasonography. Niazi *et al.* [14] developed an interactive VR simulator of spine comprised of three learning modules: spinal anatomy, sonoanatomy, and preprocedural scan simulation of lumbar spine. While proven to enhance students' test scores on spinal anatomy and sonoanatomy, its impact on actual ultrasound scan performance was not assessed. In light of these considerations, we hypothesized that VR simulator may improve the performance of spine ultrasound scanning among trainees. Our current study aims to assess the competency and satisfaction of students training with the VR spine simulator and didactic lecture versus those training with traditional didactic lecture alone.

METHODS

Study design

This randomized controlled trial was conducted at the Department of Anesthesiology, Peking Union Medical College Hospital (PUMCH), from May 2023 to March 2024. This study was registered at Clinicaltrials.gov (NCT05874609), with informed consent obtained from all participants.

Participants

Spine ultrasonography was not compulsory in the routine anesthesia residency program. We recruited anesthesia residents at our department for investigation The exclusion criteria included prior spine ultrasonography training or scanning experience.

The sample size was calculated using our primary outcome with the PASS 11.0 software (Kaysville, UT, USA). We assumed that the mean value of the composite learning score in the control group would be 0.8 (*SD*=0.1), and the intervention in the VR group would enhance the composite learning score to 0.9 with a progression of one *SD*. Based on this assumption, the sample size for each group should be 23 to obtain a significant difference (two-sided $\alpha=0.05$, $1-\beta=0.9$).

Participants were randomized 1: 1 into two groups using permuted blocks of size 4 *via* an Excel-generated list. To ensure concealment, the sequence was stored in password-protected files accessible only to the study coordinator, who was not involved in participant recruitment or assessment. Group assignments were concealed in sequentially numbered, opaque, sealed envelopes, which were opened only after baseline assessments to prevent allocation disclosure.

The first participant enrolled on May 13, 2023. Age, sex, years of working, experience of ultrasound use, and number of neuraxial anesthesia cases of all enrolled participants were collected.

Neuraxial ultrasonography training

The control group received a 30-min traditional didactic teaching session of spine ultrasonography, covering general spine anatomy, sonographic technique and sonoanatomy, five key spine ultrasonographic views (transverse spinous process view, transverse interlaminar view, parasagittal oblique interlaminar view, parasagittal articular process view, and parasagittal transverse process view), and a stepwise preprocedural lumbar spine scan[15]. In the VR group, the participants spent 30 minutes with a VR spine simulator after receiving the didactic teaching session. The VR simulator of spine comprised of three learning modules: spinal anatomy, sonoanatomy, and a simulation of preprocedurary ultrasound scan of lumbar spine (Supplementary **Video 1**). The students reviewed the spine anatomy using the interactive rotatable 3D spine models. The second sonoanatomy module was comprised of ultrasound scanning video of lumbar spine and the corresponding anatomical structures. The simulation ultrasound scan module allowed the students to use a virtual ultrasound transducer to perform a preprocedural ultrasound scan of the lumbar spine. The learning objective with the VR simulator was to review the 3D lumbar spine anatomic model, learn the sonoanatomy presented by a dynamic ultrasound scan of the sagittal and transverse plane, and practice a preprocedural ultrasound scan. The simulation preprocedural scan was the same as the stepwise technique taught in the session (Supplementary **Video 2**): (1) move the transducer caudally to identify sacrum;

(2) slide the transducer cranially from L5/S1 to identify the intervertebral levels with the parasagittal oblique interlaminar view; (3) determine the midline with the transverse spinous view; and (4) locate the L3/L4 intervertebral space and measure the depth to the posterior complex using the transverse interlaminar view. The VR simulator had a feedback system that told the participants whether the determined intervertebral space, midline, and the depth to the posterior complex were correct or not.

Evaluation and study outcomes

After the training, participants were required to perform a preprocedural spine ultrasound scan on healthy volunteers using the stepwise technique taught in the didactic teaching session. The participants were asked to acquire three key ultrasound views during the scan and recognize the anatomic structures in three ultrasound views: parasagittal oblique interlaminar view (posterior complex, anterior complex, lamina, and erector spinae), transverse spinous view (spinous process, lamina, and erector spinae), and transverse interlaminar view (articular process, transverse process, posterior complex, anterior complex, and spinal canal). In the transverse interlaminar view, the participants were also required to perform a measurement of the depth to the posterior complex.

The primary outcome was a composite learning score comprised of investigator-evaluated practical skills (20 points), self-assessed theoretical knowledge (10 points), practical skills (10 points), satisfaction (10 points), and willingness to apply the technique in future practice (10 points). The practical skills were assessed from four aspects (5 points for each aspect) by an investigator unaware of the group allocation: quality of ultrasound imaging, motion and instrument handling, flow of the procedure, and overall performance[16]. Finally, the composite learning score was converted to 100 points for convenience of calculation.

There were three secondary outcomes: (1) scanning time, defined as the interval from transducer-skin contact to the acquisition of three key ultrasound views; (2) score of anatomic structure recognition; and (3) accuracy of depth measurement to the posterior complex. The measurement was deemed correct if the error was less than 0.5 cm.

The evaluator of the scanning process, data collectors, and data analysts were strictly blinded to the allocation. To minimize assessment bias, participants were explicitly instructed not to disclose any details of their training modality to the evaluator during the practical assessment.

Statistical analysis

All data were analyzed using SPSS 26.0 (IBM, NY, USA). Continuous data are expressed as mean±standard deviation (*SD*) or median (interquartile range). Student's *t* test was used for parametric data and the Mann-Whitney test for non-parametric data. Categorical data are described as frequency and analyzed with the chi-square test. The scan time was analyzed as time-to-event data, where the 'event' was defined as the successful completion of the neuraxial ultrasound task. Consequently, the Log-rank test was employed to compare the time to successful scan between the two groups. To adjust for potential imbalanced baseline factor, an analysis of covariance (ANCOVA) was performed for the primary outcome, with the VR group as the fixed factor and sex/prior ultrasound experience as covariates. A *P*-value of <0.05 was defined as significant.

RESULTS

A total of 46 participants (23 per group) were enrolled, and baseline characteristics are shown in **Table 1**.

Compared to the control group, the VR group

Table 1. Baseline characteristics in virtual reality group and control group

Characteristics	VR group (*n*=23)	Control group (*n*=23)
Age (y, mean±SD)	26.8±3.4	25.8±2.1
Sex [*n*(%)]		
Male	9 (39.1)	4 (17.4)
Female	14 (60.9)	19 (82.6)
Years of working (y, mean±SD)	3.5±2.6	3.0±1.8
Experience of ultrasound use [*n*(%)]		
None	1 (4.3)	0 (0)
Novice	8 (34.8)	10 (43.5)
Intermediate	12 (52.2)	10 (43.5)
Advanced	2 (8.7)	3 (13.0)
Number of neuraxial anesthesia cases [*n*(%)]		
<20	8 (34.8)	7 (30.4)
20–40	6 (26.1)	4 (17.4)
>40	9 (39.1)	12 (52.2)

Values are expressed as mean±SD or numbers (%). VR: virtual reality.

achieved significantly higher composite learning score (0.80±0.05 *vs* 0.74±0.09, *P* = 0.01). After adjusting for sex and prior ultrasound experience using the ANCOVA model, we found the difference in the primary outcome remained statistically significant between the VR group and the control group (*P* = 0.04). Both self-assessed (7.00±1.13 *vs* 5.91±2.07, *P* = 0.03) and investigator-assessed practical skills after training (14.74±1.86 vs 13.22±2.37, *P* = 0.02) showed significant differences. Regarding the investigator-assessed practical skills, the VR group scored significantly higher in flow of the procedure (3.43±0.66 *vs* 2.74±0.96, *P* = 0.01) and overall performance (3.87±0.69 *vs* 3.35±0.78, *P* = 0.02). The self-assessed theoretical knowledge after training was not significantly different between the two groups (7.26±1.10 *vs* 6.74±1.63, *P* = 0.20). Both groups were highly satisfied with the training (9.61±0.66 *vs* 9.57±0.79, *P* = 0.84) and were very willing to apply the technique in future (9.35±0.93 *vs* 9.22±1.31, *P* = 0.70). (**Table 2**)

For the secondary outcomes, there was no significant difference in the scanning time (254.0 [221.13, 286.87] *vs* 247.0 [231.35, 262.70], *P* = 0.25). The VR group achieved significantly higher score of anatomic structure recognition (0.85±0.15 *vs* 0.72±0.20, *P* = 0.01). The accuracy of depth measurement to the posterior complex was also better in the VR group comparing to the control group (73.9% *vs* 43.5%, *P* = 0.03). (**Table 2**)

DISCUSSION

Our present study investigated the effectiveness of a VR spine simulator for teaching neuraxial ultrasonography. The result showed that adding VR spine simulator training to traditional didactic teaching significantly improved composite learning scores compared to didactic teaching alone. Both self-assessed and investigator-assessed practical skills were significantly higher in the VR group. In addition, the objectively-evaluated outcomes including score of anatomic structure recognition and depth measurement to the posterior complex also yielded better results after practice with the VR spine simulator.

VR technology is gaining popularity in medical education due to its effectiveness as a training and assessment modality[17]. It has been widely used in areas including surgical skills, emergency medicine training, anatomy education, radiology and ultrasonography, puncture or catheterization training, and soft skills such as communication and clinical management[18]. VR could provide students with an immersive and interactive experience, enhancing their understanding and retention of the presented content. Furthermore, incorporating VR

Table 2. Comparisons of primary and secondary outcomes between VR group and control group

Outcome indexes	VR group (*n*=23)	Control group (*n*=23)	*P* value
Primary outcomes			
Composite learning skill (score, mean±*SD*)	0.80±0.05	0.74±0.09	0.01*
Self-assessed theoretical knowledge after training	7.26±1.10	6.74±1.63	0.20
Self-assessed practical skills after training	7.00±1.13	5.91±2.07	0.03*
Satisfaction	9.61±0.66	9.57±0.79	0.84
Willingness to applicate the technique in future	9.35±0.93	9.22±1.31	0.70
Investigator-assessed practical skills	14.74±1.86	13.22±2.37	0.02*
ultrasound imaging	3.87±0.55	3.65±0.71	0.25
motion and instrument handling	3.57±0.59	3.48±0.51	0.60
flow of the procedure	3.43±0.66	2.74±0.96	0.01*
overall performance	3.87±0.69	3.35±0.78	0.02*
Secondary outcomes			
Time of scan (s, median [IQR])	254.0 (221.13, 286.87)	247.0 (231.35, 262.70)	0.25
Score of anatomic structures recognition (score, mean±*SD*)	0.85±0.15	0.72±0.20	0.01*
Correct rate of depth measurement to the posterior complex [*n*(%)]	17 (73.9)	10(43.5)	0.03*

Composite learning score= (investigator-evaluated practical skills + self-assessed theoretical knowledge + practical skills + satisfaction + willingness to apply the technique in future practice)/60. *P <0.05. VR, virtual reality; *SD*: standard deviation; *CI*: confidence interval; IQR: interquartile range.

into classroom instruction has been associated with improved academic performance, as students are more engaged and motivated to learn when presented with interactive and visually stimulating content. It is also worth noting that VR has been found to help students sustain their attention and focus, as it allows them to actively participate in the learning process, rather than passively receive information.

We used a composite learning score as the primary outcome because relying on a single measure may not be sufficient to assess the educational impact of the VR simulator. Furthermore, Kirkpatrick's framework, a classic four-level model for evaluating medical simulation training[19], supports a multidimensional approach. The design of our composite learning score encompassed the three fundamental levels of Kirkpatrick's framework, thus providing a comprehensive and thorough evaluation of the effectiveness of the VR simulator in teaching neuraxial ultrasonography.

The VR spine simulator used in our study had already been proven by its developer to enhance participants' theoretical knowledge of neuraxial ultrasonography and spine anatomy[14]. Our results showed that the score of anatomic structure recognition improved after training with the VR simulator, which also corroborates that VR simulation training could promote the cognitive performance of participants. Additionally, the accuracy of depth measurement to the posterior complex was also higher in the VR group. This is an important practical skill for the participants to master during the training of neuraxial ultrasonography, as one of the advantages of neuraxial ultrasound is its ability to predict the needle depth of neuraxial anesthesia and facilitate the technical performance of novices[20]. The depth measurement was based on the correct identification of the posterior complex, which is a demanding task for the novices. Among the trainees who missed the posterior complex, most misidentified the anterior complex as the posterior complex because the anterior complex is more hyperechoic in the transverse interlaminar view. The mechanisms underlying this phenomenon could be multifaceted. The posterior complex is the ultrasound image of soft tissues including the ligamentum flavum and posterior dura, while the anterior complex consists of the anterior dura, posterior longitudinal ligament, and posterior vertebral body. Henceforth, the posterior complex is less echogenic than the anterior complex. In addition, the anisotropy of soft tissue amplifies this difference in ultrasound imaging. The posterior complex is not perpendicular to the ultrasound beam in the transverse interlaminar view, resulting in a less hyperechoic ultrasound image[21]. As a result, the novices in neuraxial ultrasound tend to misidentify the more prominent anterior complex as the posterior complex. In the VR group, however, trainees could practice the measurement in the simulated scan. This practice helped them sustain attention and focus, as it allowed them to actively participate in the learning process rather than passively receive information. Furthermore, the simulator provided instant feedback on whether their identification of the posterior complex was accurate in the simulated scan, allowing trainees to reinforce their understanding and impression of the sonoanatomy of the posterior complex.

Our results showed that participants receiving different training methods expressed a similar level of satisfaction and willingness to apply neuraxial ultrasound in future practice. One possible explanation is that participants undergoing traditional didactic teaching were unaware of the use of the VR spine simulator in the other group. Another contributing factor could be that the participants were accustomed and thus more comfortable with the conventional teaching. While didactic instruction builds a knowledge foundation, practical experience is essential for skill mastery. Hands-on practice allows learners to apply theoretical knowledge to real-life situations, learn from mistakes, and thus build competence and confidence. However, performing high-risk procedures like ultrasound-guided neuraxial anesthesia on real patients can be risky, making simulation a safe and effective bridge to clinical practice. Simulated practice enables learners to gain familiarity with equipment, develop muscle memory, and master their technique without risking the patients. Ultimately, combining didactic instruction with practical experience is key to developing competent practitioners.

Limitations

There are several limitations of the current study. First, the evaluation of the performance of students was conducted immediately after training, so we were unable to gauge how effectively the VR training method contributed to students' long-term knowledge retention. Second, the generalizability was limited by the study population, as results may not extend to trainees from other specialties or clinicians with varying experience levels. Third, training time discrepancies and the lack of an active control group (video-based learning or phantom-based practice) prevent ruling out the possibility that the superior performance in the VR group was partially due to the additional practice time rather than the VR technology itself. While not directly compared in this study, VR offers distinct advantages over traditional hands-on workshops. Unlike resource-intensive workshops requiring instructors and equipment, VR enables independent, repetitive practice. It also facilitates unique 3D spatial visualization impossible with live models and simulates complex pathologies (e. g., obesity, scoliosis). Future research should employ an active control design to isolate the VR simulator's educational efficacy.

Conclusions

This study demonstrated the practicability and effectiveness of a VR stimulator in neuraxial ultrasonography training. Combined with traditional didactic lecture, VR simulator training improved learners' technical skills and cognitive performance of neuraxial ultrasound. Further studies should explore the long-term knowledge retention after VR training and the transfer of VR training to clinical practice.

ARTICLE INFORMATION

Supplementary materials

Available online at http://dx.doi.org/10.24920/004567.

Conflicts of interest

The authors declare no conflicts of interest.

Authors' contributions

Yuan Q: Methodology, funding acquisition, writing–original draft; Cui XL: Conceptualization, investigation; Li X: Investigation; Tan G: Data curation, formal analysis; Yi J: Writing–review & editing; Huang YG: Supervision. All authors read and approved the final version of the manuscript to be published.

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Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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