Current Science
CS 5 (3), 2601-2608 (2025)
Received 24 Feb 2025 | **Revised 22 March** 2025 | **Accepted 28 April**. 2025 | **Online Available 26 May** 2025
https://doi.org/ 10.52845/CS/2025-5-3-43

Current Science

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OPEN ACCESS

ISSN (O) 2795-8639

Original Article

Validation of Optical Augmented Reality Display Technology in Ultrasound-Guided Paravertebral Model Puncture

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Abstract:

Objective: Validation of the Feasibility of an Optical Augmented Reality Display System in Ultrasound-Guided Paravertebral Model Puncture

Methods: A highly realistic 3D-printed paravertebral gel model was created. Two junior anesthesiologists (beginners in ultrasound-guided puncture) and two senior anesthesiologists (with more than five years of experience in ultrasound-guided puncture) were randomly assigned using a random number table to perform paravertebral puncture under either conventional ultrasound guidance or an optical augmented reality display system. A total of 84 punctures were performed and categorized into four groups (n=21): senior augmented reality-guided puncture group (AR-S), junior augmented reality-guided puncture group (AR-B), senior conventional ultrasound-guided puncture group (C-S), and junior conventional ultrasound-guided puncture group (C-B).For each puncture, the procedure time, the number of needle adjustments, and the operator's satisfaction score with the procedure were recorded. A single observer verified whether the needle tip reached the target location and whether the pleura or dura was punctured.

Results: Compared with the C-B group, the puncture time in the AR-B group was reduced ($P < 0.05$). There was no statistically significant difference in puncture time between the AR-S and C-S groups ($P > 0.05$).Compared with the C-B group, the number of needle adjustments in the AR-B group was lower ($P < 0.05$). There was no statistically significant difference in the number of needle adjustments between the AR-S and C-S groups ($P > 0.05$).Compared with the C-B group, the satisfaction score in the AR-B group was higher ($P < 0.05$). There was no statistically significant difference in satisfaction scores between the AR-S and C-S groups ($P > 0.05$).Compared with the C-S group, the number of head movement shifts in the C-B group was higher ($P < 0.05$). No head movement shifts were observed in the AR-B and AR-S groups.All needle tips successfully reached the target area, and no dural punctures occurred. In the C-B group, three cases of pleural puncture were observed, with an incidence rate of 14.3%.

Conclusion: Optical augmented reality display technology in ultrasound-guided paravertebral model puncture can eliminate the operator's need for head movement shifts during ultrasound-guided procedures. For junior anesthesiologists, it significantly reduces puncture time, decreases the number of needle adjustments, improves operator satisfaction, and lowers the incidence of related complications. However, senior anesthesiologists do not show significant benefits in these aspects.

Keywords: Augmented Reality, Ultrasound Imaging, Thoracic Spine, Nerve Block

Introduction

Ultrasound-guided puncture procedures are becoming increasingly common in clinical anesthesia and pain management and are an essential component of precision medicine. However, due to the high demands on anatomical

knowledge, ultrasound proficiency, and hand-eye coordination, the learning curve for these procedures is relatively long.In recent years, augmented reality (AR) technology has advanced significantly and has been gradually applied in preoperative simulation assessments [1] and medical education [2]. However, due to previous limitations in equipment and technology, its application in real-time ultrasound-guided puncture procedures has been relatively rare. The emergence of high-resolution, lightweight optical AR display devices has now made real-time ultrasound-guided AR applications feasible.This study aims to validate the use of an optical AR display system for ultrasound-guided paravertebral model puncture. The details are reported as follows.

Materials and Methods：

1. Fabrication of the Puncture Model

The original two-dimensional grayscale DICOM image data from a thin-slice (1.25 mm) CT scan of the thorax (sourced from the open-source PaddleHub platform) was imported into 3D reconstruction software (3D Slicer). The thoracic vertebrae and ribs were segmented and extracted, with the segmented thoracic vertebrae and ribs having a width of 190 mm and a height of 200 mm to meet the size requirements of the 3D printer. The model was then exported as an STL file for 3D printing.

The STL file was imported into a high-precision (0.02 mm) NOVA3D Whale2 photopolymer resin printer (Nova Company, China). After 20 hours of printing (Figure 1), the model was removed, cleaned, dried, and subjected to surface photopolymerization, resulting in a highly realistic thoracic vertebra model with ribs (Figure 2).

Figure 1 Photopolymerized 3D-Printed Thoracic Vertebra Model

Figure 2 Completed 3D-Printed Thoracic Vertebra Model

A 0.05 mm flexible polyethylene (PE) membrane was fixed to the anterior side of the thoracic vertebrae and ribs of the model to simulate the pleural structure. A latex water sac was placed inside the spinal canal to simulate the dura mater and cerebrospinal fluid. The model was then placed in a suitable transparent fixation slot to facilitate observation of the pleura on the thoracic cavity side of the model.

A gel solution was prepared by mixing 200 g of pea starch, 2 g of gellan gum, 2 g of potassium sorbate, and 0.6 g of sodium chloride into 1000 mL of purified water at room temperature. While stirring, the mixture was heated to 100°C to ensure complete dissolution, resulting in a gel solution. The solution was then cooled while maintaining a temperature above 90°C.The heated solution was poured into the thoracic vertebra fixation slot in multiple layers. Before pouring, the solution was vigorously stirred at high speed to introduce a large number of microbubbles. The gel was poured layer by layer, allowing each layer to cool and solidify before adding the next. This process accurately mimicked the layered structure of biological tissues, ultimately producing a highly realistic ultrasound-guided paravertebral puncture model.Ultrasound structural comparison: Real human anatomy (Figure 3), model (Figure 4).

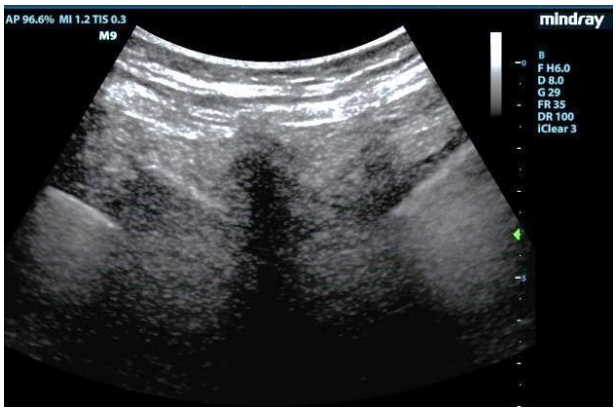

Figure 3 Ultrasound Image of the Real Human Thoracic Spine

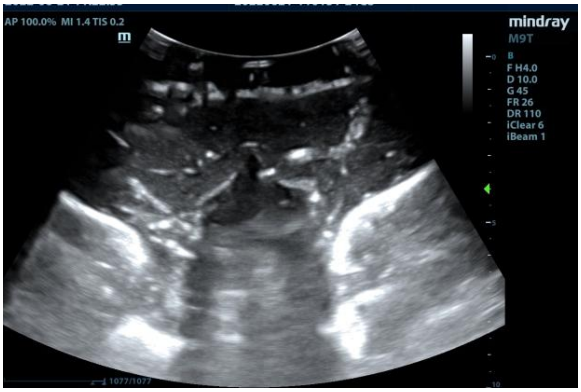

Figure 4 Ultrasound Image of the Paravertebral Model

2. Optical AR Display System:

In this study, the Mindray M9 ultrasound (Mindray, China) output a 720p HDMI signal, which was sent to an image processor (Zhinxen, Hong Kong). The ultrasound image was then converted into a signal that the AR glasses could recognize and transmitted via a dedicated cable to the MAD Gaze Glow Plus AR glasses (Zhinxen, Hong Kong), after removing the light-blocking filter. Using the birdbath optical visual overlay technology (Figure 5), which features high brightness, high contrast, and high resolution, the operator could simultaneously view the operational field and real-time high-definition ultrasound images through the optical lenses (Figure 6).Compared to traditional ultrasound-guided puncture, there was no need for field switching (Figure 7).

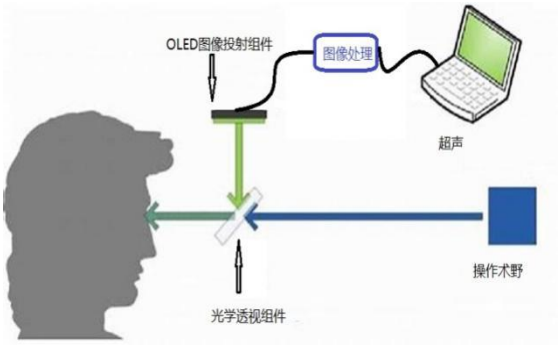

Figure 5 Optical Augmented Reality Display Principle (Birdbath)

Figure 6 Optical Augmented Reality Display Guiding Puncture

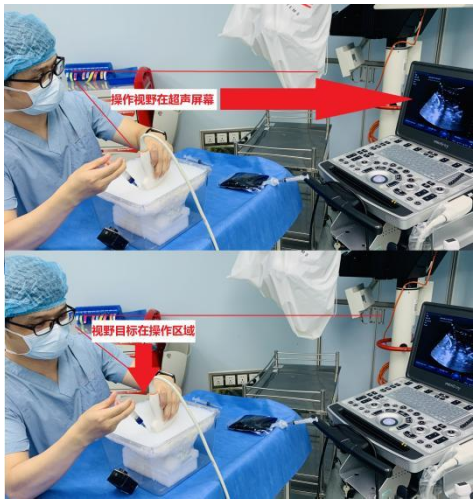

Figure 7 Conventional Ultrasound-Guided Field Switching Method

3. Experimental Process:

The experiment was divided into two operation modes: AR mode, where the optical AR display system was used to guide the puncture, and C mode, where the conventional method was used for ultrasound-guided puncture of the paravertebral model. Both modes used the C5-1S low-frequency phased array probe (Mindray, China) for guiding the puncture, targeting the paravertebral triangle region. The procedure was considered a failure if the needle tip did not reach the target region, exceeded the region, or punctured the dura or pleura.

The following parameters were recorded for each operation: puncture time (from when the ultrasound probe made contact with the model to when the procedure was confirmed as complete), the number of needle adjustments (if the needle failed to be fully visualized, requiring adjustments to the ultrasound probe or needle), and the operator's self-assessment of the procedure satisfaction (5-point scale, with 1 being the worst satisfaction indicating failure, 2 indicating poor satisfaction and difficulty in completing the procedure, 3 indicating acceptable satisfaction with multiple adjustments of the probe or needle, 4 indicating good satisfaction with a smooth

procedure, and 5 indicating the best satisfaction with a successful puncture on the first attempt).The same person recorded the data and confirmed whether the needle tip reached the target area and whether the dura or pleura was punctured.

The operators consisted of two senior anesthesiologists with more than five years of experience in ultrasound-guided procedures and two junior anesthesiologists who were beginners in ultrasound-guided clinical operations. To increase the realism of the model puncture procedure, each operator randomly used one of the two modes for each operation, with an interval of more than one day between each procedure. A computer randomization software (https://www.randomizer.org) was used to generate operation mode codes, which were sealed in opaque envelopes numbered sequentially. Before each operation, the mode was drawn randomly and opened by the recorder, resulting in four groups: senior AR system puncture group (AR-S), junior AR system puncture group (AR-B), senior ultrasound-guided puncture group (C-S), and junior ultrasound-guided puncture group (C-B). Prior to the project, all participants received standardized training and simulation exercises.

Statistical analysis was performed using SPSS 23.0 software. Normally distributed continuous data were presented as mean ± standard deviation (SD), and intergroup comparisons were performed using independent samples t-tests. Skewed distribution data were described as median (interquartile range) [M(IQR)], and intergroup comparisons were performed using the rank sum test. Chi-square tests were used for categorical data comparisons. A P value of < 0.05 was considered statistically significant.

Results： From August 5, 2024, to December 9, 2025, the four operators completed a total of 84 model puncture procedures, with no invalid operations. The 84 procedures were randomly divided into the AR-B group (n=21), AR-S group (n=21), C-B group (n=21), and C-S group (n=21). Throughout the study, no violations of the study protocol were reported, and there were no missing data regarding the primary and secondary outcomes.

The tables and figures are as follows:

Table 1 Comparison of Operation Conditions among Various Groups（n=21)

group	Operating number	Operating time	Needle Adjustment Frequency	Satisfaction with the Procedure	Head Move-ment Shifts	Failure Rate
	（次）	*[s，M(IQR)]*	*[次，M(IQR)]*	*[分，M(IQR)]*	*[次，M(IQR)]*	*（%)*
AR-B	21	74(14)*	0(1)*	4(1)*	0	0
C-B	21	91(17)*	3(1)*	3(1)*	14(5)*	14.30%
AR-S	21	56(19)**	0(1)**	4(1)**	0	0
C-S	21	58(12)**	0(0)**	4(1)**	9(3)*	0
Z value	/	4.06*,0**	4.92*,1.64**	4.93*,0.27**	4.63*	/
P value	/	<0.001*,1**	<0.001*,0.101**	<0.001*,0.787**	<0.001*	/

Note: Same labeling*，**Compare between groups

Operation Time: Compared with the C-B group, the puncture time in the AR-B group was reduced ($P < 0.05$); compared with the C-S group, there was no statistically significant difference in puncture time between the AR-S group and the C-S group ($P > 0.05$).

Needle Adjustment Frequency: Compared with the C-B group, the number of needle adjustments in the AR-B group was reduced ($P < 0.05$); compared with the C-S group, there was no statistically significant difference in the number of needle adjustments between the AR-S group and the C-S group ($P > 0.05$).

Satisfaction with the Procedure: Compared with the C-B group, the satisfaction score in the AR-B group was higher ($P < 0.05$); compared with the C-S group, there was no statistically significant difference in the satisfaction score between the AR-S group and the C-S group ($P > 0.05$).

Head Movement Shifts: Compared with the C-S group, the C-B group had more head movement shifts ($P < 0.05$); there were no head movement shifts in the AR-B and AR-S groups.

All needle tips reached the target area; no dural puncture occurred. The C-B group had three cases of pleural puncture, with an incidence rate of 14.3%.

Discussion：

To demonstrate the applicability of the system, a low-frequency ultrasound-guided thoracic paravertebral puncture was selected as the validation model. This procedure is an advanced ultrasound-guided puncture operation, as the target puncture site is deep, making ultrasound visualization of the paravertebral structures challenging. Due to the large needle insertion angle, needle visualization is difficult. The paravertebral region is obstructed by the costovertebral joints and ribs, and important surrounding structures such as the pleura and dura mater are present. Puncture-related complications such as pneumothorax, spinal anesthesia, incorrect needle placement, and poor drug diffusion may occur [3]. Therefore, this procedure requires a high level of skill from the operator and has a long learning curve.

Ultrasound is a two-dimensional plane, and for the procedure to be effective, the target area, important adjacent structures (such as the pleura, blood vessels, etc.), the ultrasound beam, and the puncture needle must all be in the same plane. The operator must continuously adjust the probe and needle through hand-eye coordination to obtain an ideal image. During this process, the operator needs to switch back and forth between the screen and the operational field of view. In this study, it was shown that the senior group required 9(3) field switches to complete a model puncture, while the junior group required 14(5) field switches. During these field switches, maintaining the needle tip under continuous imaging supervision is challenging, especially for beginners. This often leads to prolonged operation times and may even cause injury to important surrounding organs. In this study, the puncture time for the junior group using conventional ultrasound guidance (91[17]s) was significantly longer than the senior group's time (58[12]s), and there were 3 cases of pleural puncture in the junior group, while no pleural punctures occurred in the senior group using conventional ultrasound guidance.

To overcome the limitations of ultrasound-guided puncture, scholars have continuously attempted new methods, such as ultrasound puncture guidance frames [4], ultrasound magnetic navigation [5], and ultrasound puncture needle enhancement display technology [6]. While these can improve the success rate, they have limited popularity, high costs, and constraints in terms of compatible probes, puncture needles, and puncture range. Some scholars have also tried to improve puncture outcomes using virtual reality (VR) technology [7], but it has drawbacks such as high software development costs, significant delays, heavy VR headsets causing dizziness, and other issues. Since VR technology isolates the user from the real environment, it is difficult to apply in clinical settings. The emergence of augmented reality (AR) technology has provided new ideas for various real-time operational scenarios. Lee S and others utilized AR technology to project ultrasound-acquired vascular information onto the patient's body surface to guide vascular puncture [8]. Additionally, with the miniaturization and lightweight development of optical AR glasses, practical usage in real operations has become possible. Rene Przkora and others explored the potential applications of AR in ultrasound guidance [9], and Research shows that AR devices using optical see-through technology are more suitable for real-time guided operations [10]. Young-Eun Jang from Korea reported that using this type of AR device for pediatric radial artery puncture improved the first-attempt success rate [11].

The new AR device used in this validation experiment has a high resolution (1080P), high contrast (greater than 2000:1), a wide field of view (53°, equivalent to a 112-inch screen at 3 meters), and is lightweight (92g). It provides high-definition signals with no delay, and the ultrasound images are displayed clearly. Through optical perspective technology, the surgical field and ultrasound images are overlaid, eliminating the need for field switching. This study showed that under AR guidance, novice practitioners reduced the number of needle adjustments, significantly shortened puncture time, decreased

the puncture failure rate, and improved satisfaction with the procedure. This allowed novice practitioners to perform at a level closer to that of experienced practitioners, thus reducing the learning curve. During AR-assisted ultrasound-guided puncture, the AR glasses reduced repetitive head, neck, and eye movements between the ultrasound screen and the surgical field, enhancing both operational efficiency and comfort.

This study found that for experienced practitioners, AR technology did not provide a significant advantage, either in terms of operation time or satisfaction. This may be because for experienced physicians who are already accustomed to switching fields of view and have good hand-eye coordination, eliminating the need for field switching did not result in a noticeable improvement in their technical performance.

The AR glasses also have some technical issues. First, the AR glasses used in this study weigh 92g, which is heavier than regular glasses (25 to 50g). Prolonged use of AR glasses may cause discomfort in the nose and ears. Additionally, for individuals who already wear glasses, wearing AR glasses is an added burden. Secondly, in this study, the AR glasses and video processing module required a wired connection, which created inconvenience during operation and increased setup time. Although wireless connections are possible, they come with noticeable visual delays and cannot be used for real-time operations. As technology advances in the future, these issues may be gradually resolved.

In conclusion, the optical augmented reality display system in ultrasound-guided paravertebral model puncture can eliminate the need for field switching during ultrasound-guided puncture. For novice anesthesiologists with less experience, it can significantly reduce puncture time, decrease the number of needle adjustments, improve operator satisfaction, and reduce the occurrence of related complications.

Author Contributions:

Jinyu Li: Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Jianzhi Shi, Jurong Xia:** Validation, Resources, Methodology, Investigation, Data curation. **Bo Wang, Jie Zhou:** Software, Resources, Methodology, Investigation, Formal analysis. **Yingqian wang, Zhiwei Yang:** Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition, Conceptualization.

Funding: Information None.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The raw data supporting the conclusions of this article will be madeavailable by the authors on request.

Acknowledgements: Not applicable.

Declaration of competing interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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