BMC Medical Education

RESEARCH

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Outcome-based simulation training for ultrasound-guided central venous catheter placement: clinical impact on preventing mechanical complications

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Abstract

Background Central venous catheter placement has been associated with mechanical complications, some of which can be life-threatening. Recent studies have shown that simulation-based education on ultrasound-guided central venous catheter placement improves puncture success rates; however, its effect on reducing mechanical complications remains unclear. This observational study examined how outcome-based simulation training for ultrasound-guided central venous catheter placement affects the incidence of mechanical complications in a clinical setting.

Methods The Safe Central Venous Catheter Placement and Management Committee established a reporting system to monitor central venous catheter placement. In 2016, a skill assessment of ultrasound-guided central venous catheter placement was conducted. Outcome-based simulation training was introduced in 2017. Skills were evaluated using the skill assessment tool developed by the Japanese Society for Medical Simulation.

Results After implementing skill assessment and outcome-based simulation training, the mechanical complication rate decreased from 2.2% in 2015 to 1.2% in 2023.

Conclusions A recent meta-analysis reported a 2.3% mechanical complication rate during ultrasound-guided central venous catheter placement. In comparison, the 1.2% complication rate at our institution is notably lower. This study suggests that outcome-based simulation training for ultrasound-guided central venous catheter placement may help reduce the incidence of mechanical complications in clinical settings.

Keywords Outcome-based simulation training, Ultrasound-guided, Central venous catheter placement, Central venous catheterization, Mechanical complications

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Background

Central venous catheters are widely used in various fields of medicine [1]. Despite their usefulness, life-threatening mechanical complications, including accidental arterial puncture, massive hematoma, pneumothorax, and hemothorax, have been reported during central venous catheter placement [1, 2]. Simulation training for surgical procedures has become an essential component of medical education, facilitating skill acquisition and reducing surgical complications [3]. Specifically, simulation training for central venous catheter placement is necessary to minimize the risk of fatal mechanical complications. A meta-analysis showed that simulation-based education on vascular access improves overall success rates compared to traditional education [4]; however, whether this approach reduces the incidence of mechanical complications remains unclear [4].

This observational study examined the impact of outcome-based simulation training for ultrasound-guided central venous catheter placement on reducing the incidence of mechanical complications in a clinical setting.

Methods

Establishing a reporting system for central venous catheter placement

In 2007, our hospital established a Safe Central Venous Catheter Placement and Management Committee (Safe CVC Committee). The committee defined the role of central venous catheters in clinical situations and developed safety measures. The Committee initiated a reporting system for every central venous catheter placement, which was integrated into nursing practice by the Nursing Division.

Tunneled catheters and central venous ports, which involve surgery under local or general anesthesia, remained under the jurisdiction of the institution's Patient Safety Department rather than the Safe CVC Committee.

This study was approved by the local ethics committee (approval no. H29-114).

Reporting system

During each central venous catheter placement, a nurse recorded the procedure details in the reporting system while the physician performed the puncture. Mechanical complications were defined as arterial puncture, pneumothorax, or hematoma, whereas fatal complications, such as arterial catheter misplacement, hemopneumothorax, airway obstruction due to hematoma, pseudoaneurysm, and arteriovenous fistula, were supplemented with incident reports. The number of punctures was also recorded, and all documentations were retained in medical records, referred to as the CVC Excel Chart. This chart includes not only the mechanical complications, but also details such as the type of catheter, length of catheter placement, surgeon, surgeon's CVC certification, date of the procedure, and patient's risk factors for mechanical complications (such as bleeding predisposition, general condition, and contraindicated puncture sites). The Department of Patient Safety Management compiled and accumulated the data in the Excel Chart monthly. The CVC Committee meets every two months to monitor these data and devise measures.

After several years of investigation, the Safe CVC Committee expressed concerns regarding multiple punctures, which may induce serious complications [5–7]. To reduce multiple punctures, the committee recommended ultrasound-guided central venous catheter placement. Since 2015, practitioners who performed more than five puncture attempts, regardless of the presence or absence of mechanical complications, were required to report a significant event analysis (SEA) [8]. The SEA is a clinical audit methodology and tool used for reflective learning, managing medical risks, and improving patient safety [8].

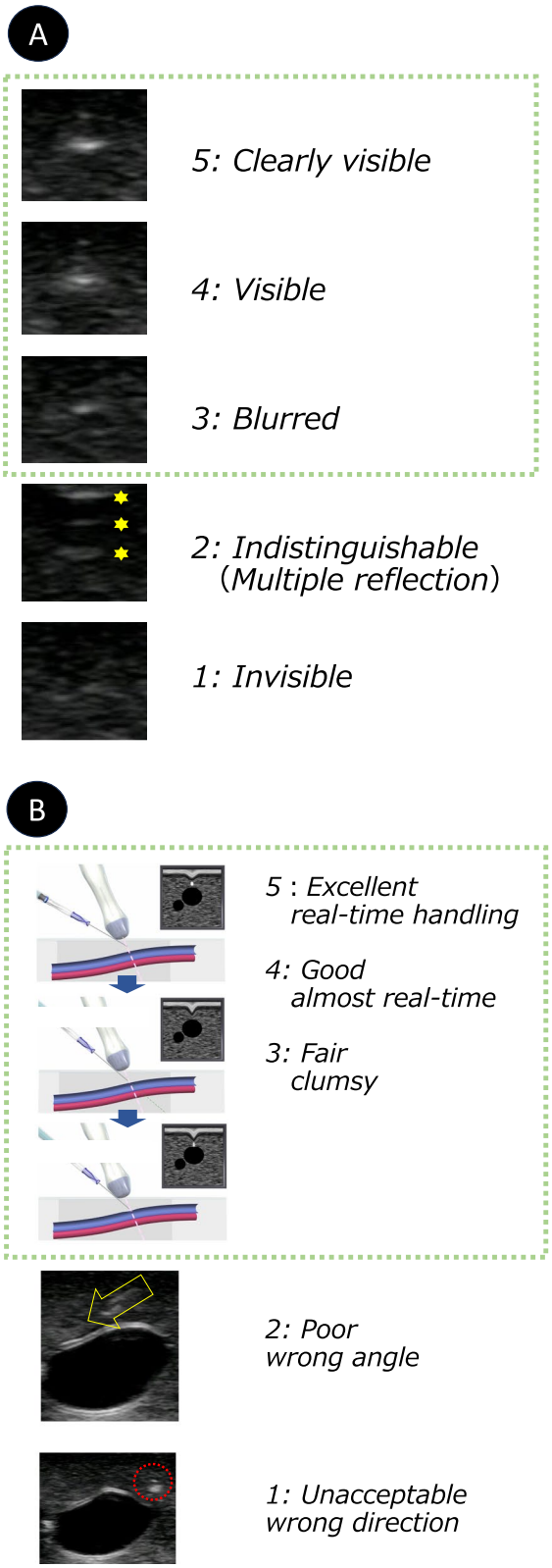
Technical certification for ultrasound-guided central venous catheter placement

In 2016, a technical certification program for ultrasound-guided central venous catheter placement was launched. The committee mandated this certification exam (skill test) for junior residents and newly hired senior residents before they could perform central venous catheter placements in a clinical setting. Previously, preclinical testing focused only on procedural flow, not technical certification.

As part of their training, junior residents first watched a video created by the committee, demonstrating ultrasound-guided internal jugular venipuncture in a clinical setting. They then trained independently in the Clinical Simulation Lab using a simulator, an ultrasound machine, and a central venous catheter set for testing.

Skill assessment for ultrasound-guided central venous catheter placement

The skill assessment was based on the guidelines of the Japanese Association for Medical Simulation's Instructors' Guide Ver. 5: Skill assessment of simulation training for ultrasound-guided central venous catheterization [9]. The test evaluated needle tip visualization (Fig. 1a), hand–eye coordination (Fig. 1b) [9, 10], and the avoidance of posterior wall penetration of the vein (Fig. 2) [10, 11]. The skill test was evaluated on three criteria: needle visibility, proper coordination between the needle and the ultrasound probe (Fig. 1), and avoidance of posterior wall penetration of the target vein (Fig. 2). In the case of failure, the examiner (JT) explained which specific



◀ **Fig. 1** Needle tip visualization and hand–eye coordination. Panel **A** Needle tip visualization. When the ultrasound beam captures the needle tip, it appears as a bright white spot on the ultrasound image, receiving scores of 5 and 4. If the tip is displaced, the brightness diminishes, resulting in a blurry white spot (score 3). Even when the ultrasound beam captures the needle tip, its precise location might be unclear because of multiple reflections (score 2). If the ultrasound beam does not capture the needle tip, it is not visible (score 1). A minimum score of 3 is required to pass the test. The multiple reflections in score 2 could be a natural phenomenon and not necessarily indicative of the test-taker's skill. Therefore, since the test-taker oneself may be able to improve the needle tip visibility (score 5–3) by moving the needle using another basic skill, hand–eye coordination (described below), the score 2 is reserved for judgment. Panel **B** Hand–eye coordination. To advance the needle tip and accurately determine its position, the ultrasound beam needs to be positioned ahead of the needle's anticipated arrival point, ensuring that the tip is tracked as it approaches. Once the needle tip and ultrasound probe (beam) are synchronized smoothly, the needle tip remains clearly visible throughout the movement (score 5). Smooth hand–eye coordination allows for real-time puncture. If this coordination is poor or the brightness of the needle tip is clumsy, the score is adjusted accordingly (score 4 or 3). If the needle tip trajectory deviates from the target vein (score 2) or misses the target vein from onset (score 1), this indicates insufficient skill. A minimum score of 3 is required to pass the test

aspects of the test needed improvement. The trainees were allowed to retake the test until they successfully passed.

Outcome-based simulation training for ultrasound-guided central venous catheter placement

Many residents struggled to pass the technical examinations with only independent training. Therefore, outcome-based simulation training for ultrasound-guided central venous catheter placement was initiated in 2017.

Newly hired junior and senior residents were required to attend this training course within six months of employment. The Safe CVC Committee encouraged senior residents who reported experiencing multiple punctures or were involved in incidents during central venous catheter placement to participate. The CVC Committee coordinated the dates of the simulation training courses with the availability of the participants and instructors.

The training followed a competency-based approach [12, 13], focusing on essential skills, such as needle and probe manipulation. It integrated these skills to teach proper probe adjustment as the needle advanced. The seminar included a 20-min lecture on the internal jugular vein's anatomy [10] and common pitfalls of the short-axis out-of-plane technique (Fig. 2) [10, 11], followed by a demonstration by an ultrasound-guided vascular access expert (JT) (Fig. 3). Trainees then engaged in 60 min of hands-on practice. Each seminar accommodated one to four trainees, each assigned to an equipped booth. The

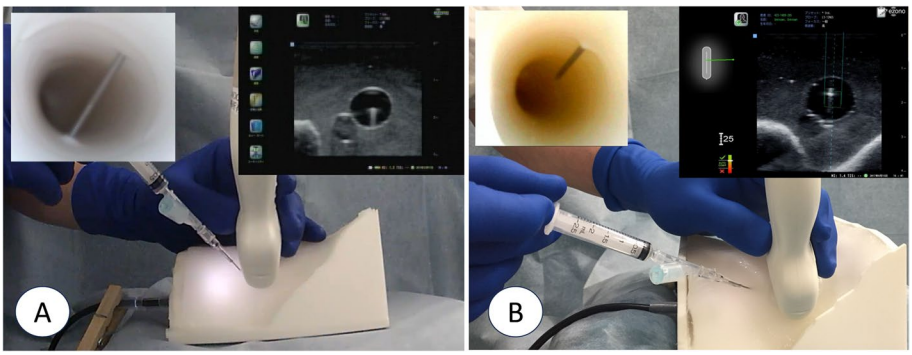


Fig. 2 Posterior vein wall penetration. The out-of-plane method has a pitfall that makes it difficult to distinguish the needle tip from the needle axis when the needle crosses the ultrasound beam on the ultrasound image (Figs. 1 and 2 of Reference 11, reprinted with the permission of the copyright holder). Panel **A** In the ultrasound image, the needle tip appears in the vein; however, in reality, the needle tip completely penetrates the vessel in the simulator. Panel **B** The needle tip enters the vein correctly

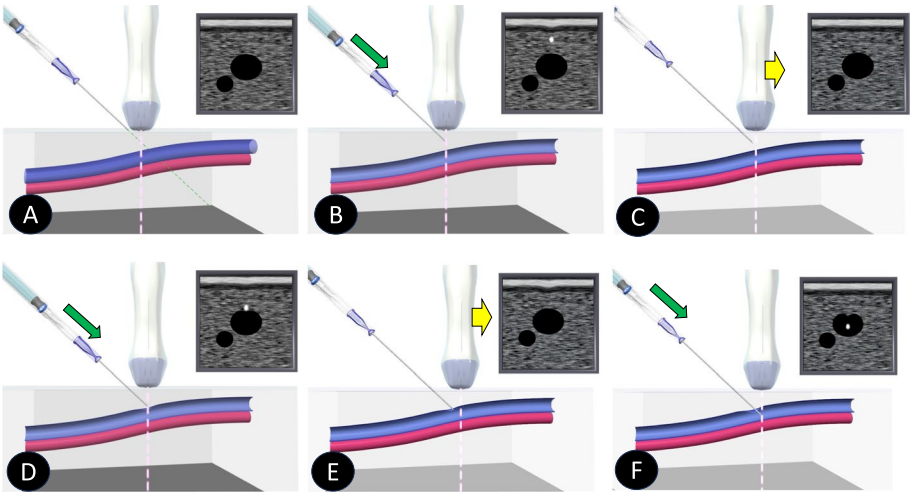


Fig. 3 Ultrasound-guided central venous catheter placement. Panel **A** Ultrasound-guided catheter placement. Ultrasonography shows only the target internal jugular vein and the adjacent common carotid artery. Panel **B** The operator advances the needle toward the vein (green arrow). When the needle tip intersects the ultrasound beam, it appears as a bright white dot on the ultrasound image, indicating the needle tip's location. Panel **C** Rather than advancing the needle further, the operator moves the ultrasound probe (ultrasound beam) slightly forward (yellow arrow). The ultrasound image shows no bright white dots at this stage. Panel **D** The operator resumes needle advancement as shown in Panel B. The ultrasound image now shows the needle tip positioned just above the target vein. Panel **E** The operator adjusts the ultrasound beam, as done in panel C. Panel **F** The needle tip reaches the target vein

booths were equipped with a central venous catheter simulator (CVC Insertion Simulator II®, Kyoto Kagaku Co., Kyoto, Japan), an ultrasound machine (SonoSite MicroMaxx®, SonoSite Inc., Bothell, WA, USA) with a linear array probe (13–6 MHz), and a central venous catheterization kit (Argyle™ Fukuroi SMAC™ Plus Micro Needle Type, Cardinal Health Japan Co., Tokyo, Japan).

Study exclusions

Peripherally inserted central venous catheters (PICCs) are rarely associated with fatal mechanical complications; therefore, there is little significance in investigating their puncture status to ensure patient safety. However, the Safety CVC Committee still monitors PICC puncture data with the hope that increased PICC usage will reduce the total number of central venous catheter placements and consequently decrease mechanical complications that compromise patient safety. However, in this study, PICCs were excluded to avoid a statistical bias that might falsely suggest that increased PICC use correlates with fewer mechanical complications.

Results

We analyzed data on central venous catheter placements at our institution from October 2008 to March 2024. A total of 24,915 placements were performed, including 14,918 internal jugular venous catheters, 1,287 subclavian venous catheters, 7,668 femoral venous catheters, and 1,024 PICCs (Fig. 4). The rate of multiple punctures dropped from 3.9% in 2008 to 1.5% in 2015. Following the introduction of skill assessment and outcome-based simulation training, the rate decreased to 0.6% in 2023 (Fig. 5, Statistically calculated excluding PICC). Similarly, the incidence of mechanical complications decreased from 3.9% in 2008 to 2.2% in 2015, and after implementing the training program, the mechanical complication rate dropped to 1.2% in 2023 (Fig. 6, Statistically calculated excluding PICC). The total number of seminar participants increased from 55 in 2017 to 135 in 2018 and has remained between 130 and 170 annually.

Discussion

In 2003, McGee et al. reported in a review article that mechanical complications during central venous catheter placement ranged between 5 and 19% [1]. In comparison, the Safe CVC Committee identified the mechanical

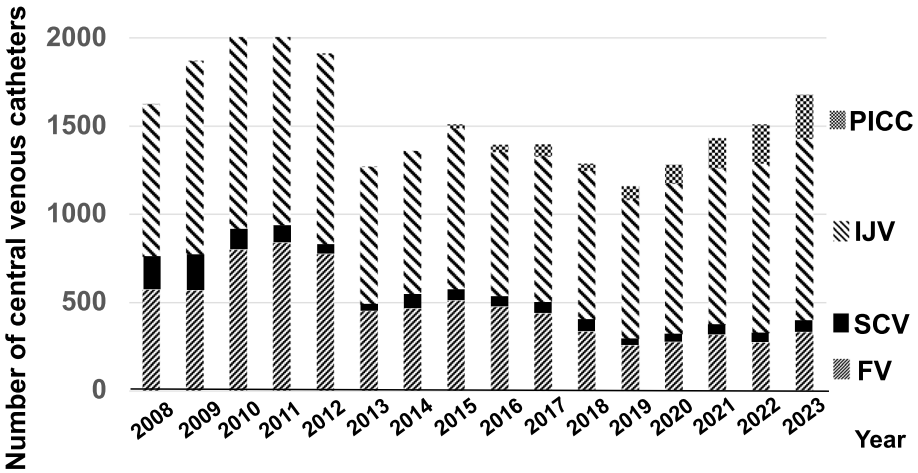


Fig. 4 Number and puncture site of central venous catheters from 2008 to 2013. PICC, peripherally inserted central catheter; IJV, internal jugular vein; SCV, subclavian vein; FV, femoral vein; Year: Academic year in Japan from April 1 to March 31

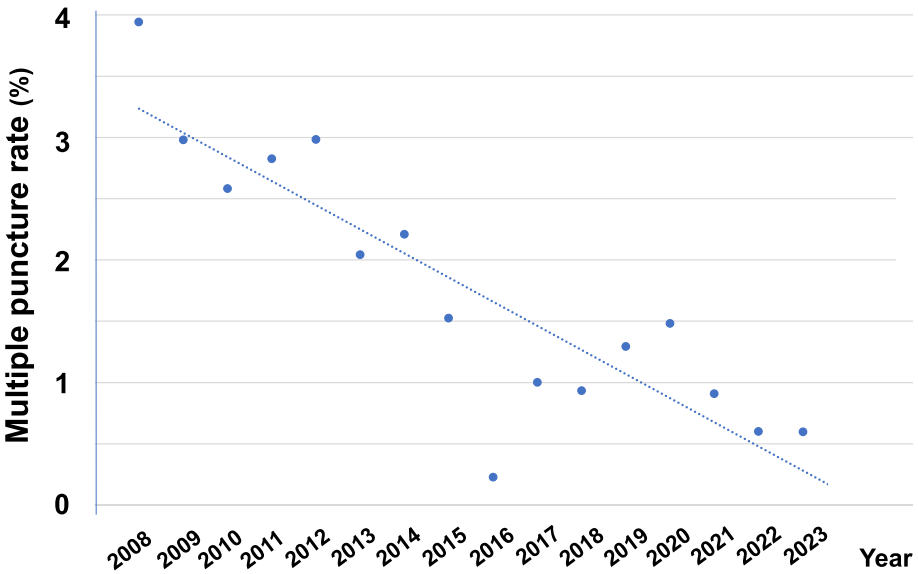


Fig. 5 Multiple puncture rate from 2008 to 2023. The dashed blue line indicates the regression line. Year: Academic year in Japan from April 1 to March 31

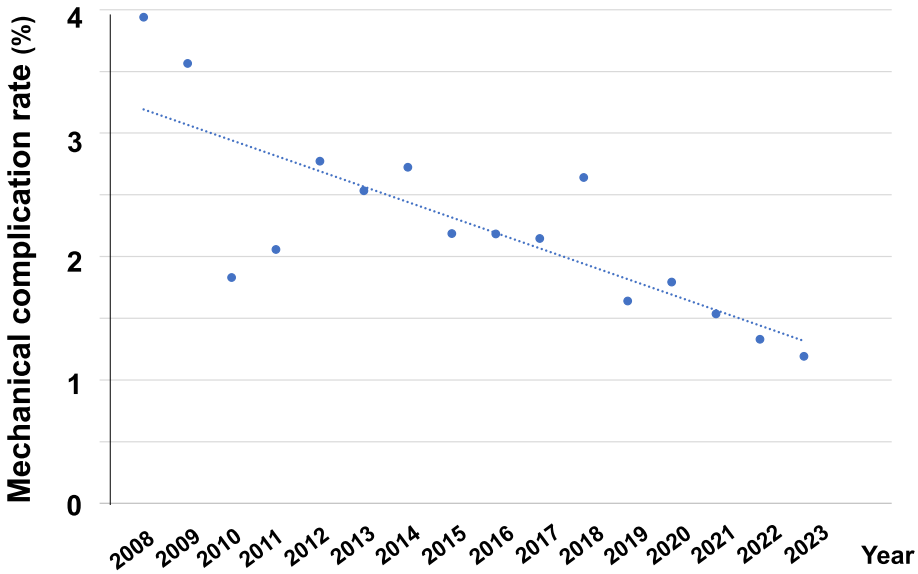


Fig. 6 Mechanical complication rate from 2008 to 2023. The dashed blue line indicates the regression line. Year: Academic year in Japan from April 1 to March 31

complication rate at our institution as 3.9% in 2008. This suggests that mechanical complication rates may have decreased over the prior five years due to increased awareness of these risks. From 2008 to 2015, the Safe CVC Committee focused on monitoring central venous catheter placement and developing a safety management system, successfully reducing mechanical complications by approximately 2%. To achieve further improvements, simulation-based education for ultrasound-guided central venous catheter placement was initiated, along with an outcome-based training system. A meta-analysis by Teja et al. reported a 2.3% incidence of mechanical complications during ultrasound-guided central venous catheter placement [14], based on randomized controlled trials published between 2015 and 2023, reflecting the current situation. In this context, the mechanical complication rate at our institution is exceptionally low, even by global standards.

The optimal educational approach for ultrasound-guided central venipuncture remains uncertain. In 2014, Schmidt et al. proposed a curriculum integrating both technical skills and cognitive elements to address this question [15]. They emphasized the importance of video-based learning for procedural flow and ultrasound-based skills such as hand–eye coordination and needle tip visualization [15]. In addition, they highlighted the need for supervision by experienced clinicians who can provide feedback for improvement during the insertion process in clinical settings [15]. Although we did not investigate how junior residents were instructed during ultrasound-guided central venous catheter placement in clinical practice, those who participated in outcome-based simulation training in 2017 have since progressed to roles as senior residents, fellows, attending physicians, or mentors. From this perspective, our institution has gradually fulfilled the requirements proposed by Schmidt et al. since implementing outcome-based simulation training.

We hypothesized that multiple punctures during central venous catheter placement contributed to the occurrence of mechanical complications. Previous studies have suggested that multiple punctures may increase the risk of such complications [5, 6], and limiting the number of punctures could potentially reduce this risk [7]. Although difficult punctures sometimes necessitate multiple attempts, these are not always due to practitioners' lack of skill. Therefore, it may not be correct to immediately associate multiple punctures with poor technique. However, the present observational study clearly indicates a correlation between the reduction in mechanical complications and the decrease in multiple punctures.

Why is outcome assessment (skill test) necessary for acquiring ultrasound-guided vascular access skills? In a previous study, we investigated whether self-learning through a web-based learning system could replace seminars for ultrasound-guided vessel-securing techniques [13]. While the results showed that self-training could help acquire the necessary skills, objective evaluation through skill testing proved crucial, as self-assessment was not sufficient.

Study limitations

The central venous catheter placement reporting system ensures that nurses can objectively record the number of punctures and any associated complications, promoting accurate documentation. However, since its inception in 2008, the submission rate of these records has only been 70–80%, which has posed a challenge for the committee in reviewing the data. Consequently, some data were missing before 2019 (though the submission rate has been 100% in recent years).

For ultrasound-guided puncture techniques, education initially focused on the "tilting technique" [10] when the skills test was introduced in 2016. However, in the past two to three years, training has shifted to the "sliding technique" (Fig. 3) to accommodate PICC insertion. While the skills test criteria (Fig. 1) [9] remained unchanged, the change in training methods represents a limitation of this long-term study.

Additionally, we defined multiple punctures as five or more attempts, although no standardized definition exists. Studies suggest that limiting the number of attempts to three may reduce complications.

Prospects for the future study

Our research focused on task-based technical training. However, CVC placement encompasses various issues that cannot be resolved by puncture technique alone. In contrast, recent studies have made great strides in developing comprehensive curricula for CVC training [16, 17]. These studies highlight the importance of designing a curriculum that integrates strategies for preventing complications alongside technical skills training to further reduce the incidence of complications.

Conclusions

This study showed that outcome-based simulation training for ultrasound-guided central venous catheter placement may lower the incidence of mechanical complications in clinical settings.

Abbreviations

CVC Central venous catheter
PICC Peripherally inserted central venous catheter
SEA Significant event analysis

Acknowledgements

The authors thank Dr. Yoshiaki Shiokawa (Emeritus Professor, Kyorin University), Mr. Hiroshi Nishina (Administrative Staff, Kyorin University), Ms. Anna Saeki (Administrative Staff, Kyorin University), and Mr. Takahito Suzuki (Administrative Staff, Kyorin University) for their assistance.

Authors' contributions

JT and TY contributed to the drafting and editing. TS contributed to data acquisition. KM and TY contributed to the critical evaluation of the manuscript. JT, CO, and TS assisted in organizing seminars and hands-on training of instructors. TY contributed to the data validation and supervision of this study. All the authors have read and reviewed the final version of the manuscript.

Funding

No funding was received.

Data availability

The data are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

Faculty of Medicine Research Ethics Committee, Kyorin University (approval no. H29-114) approved this study and waived the need for informed patient consent for participation. The authors confirm that this study was conducted in accordance with the Helsinki Declaration.

Consent for publication

Not applicable.

Competing interests

JT is a technical adviser of Cardinal Health Japan Co. who is an instructor of an ultrasound-guided technical training course. The other authors declare no competing interests.

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Received: 12 October 2024 Accepted: 21 January 2025
Published online: 28 January 2025

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