Simulation-based mastery learning reduces complications during central venous catheter insertion in a medical intensive care unit*

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Objective: To determine the effect of a simulation-based mastery learning model on central venous catheter insertion skill and the prevalence of procedure-related complications in a medical intensive care unit over a 1-yr period.

Design: Observational cohort study of an educational intervention.

Setting: Tertiary-care urban teaching hospital.

Subjects: One hundred three internal medicine and emergency medicine residents.

Interventions: Twenty-seven residents were traditionally trained and did not receive simulation-based education. These residents were surveyed regarding complications and procedural self-confidence on actual central venous catheters they inserted in the medical intensive care unit. Subsequently, 76 residents completed simulation-based training in internal jugular and subclavian central venous catheter insertions. Simulator-trained residents were expected to meet or exceed a minimum passing score set by an expert panel and measured by performance on a skills checklist (given both before and after the educational intervention), using a central venous catheter simulator. Simulator-trained residents also took a written pre- and posttest. Simulator-trained residents were surveyed regarding complications and procedural self-confidence on actual central venous catheters they inserted in the medical intensive care unit.

Measurements and Main Results: Simulator-trained residents reported fewer needle passes (p < .0005), arterial punctures (p < .0005), catheter adjustments (p = .002), and higher success rates (p = .005) for actual central venous catheters inserted in the medical intensive care unit than traditionally trained residents. At clinical skills examination pretest, 12 (16%) of 76 simulator-trained residents met the minimum passing score for internal jugular central venous catheter insertion and 11 (14%) of 76 residents met the minimum passing score for subclavian central venous catheter insertion: mean (internal jugular) = 50.6%, SD = 23.4%; mean (subclavian) = 48.4%, SD = 26.8%. After simulation training, all residents met or exceeded the minimum passing score at posttest: mean (internal jugular) = 93.9%, SD = 10.2; mean (subclavian) = 91.5%, SD = 17.1 (p < .0005). Written examination performance improved from mean = 70.3%, SD = 7.7%, to 84.8%, SD = 4.8% (p < .0005).

Conclusions: A simulation-based mastery learning program increased residents’ skills in simulated central venous catheter insertion and decreased complications related to central venous catheter insertions in actual patient care. (Crit Care Med 2009; 37:2697–2701)

Key Words: central venous catheterization; medical education; anatomic model; complications; clinical competence; quality of health care

Postgraduate trainees including internal medicine (IM) and emergency medicine (EM) residents commonly perform central venous catheter (CVC) insertions in critical care settings and are required to demonstrate knowledge about indications, contraindications, complications, and sterile technique for CVC insertions (1, 2). Traditional education in CVC insertion usually involves learning at the bedside, using real patients without standardized opportunities for prior deliberate practice and skills assessment (3). Proficiency in this procedure is important because CVC insertion is associated with potentially life-threatening adverse events, such as arterial puncture and pneumothorax (4). Recent reimbursement decisions by the Centers for Medicare and Medicaid Services (5) have also made reducing preventable complications a high priority for hospitals throughout the United States.

Simulation-based education has been used to provide opportunities for safe and deliberate practice, shape the acquisition of clinical skills (6–17), and improve patient care (9, 15, 16). Recently, the American Board of Internal Medicine recommended that IM residents receive simulation training before performing invasive procedures on patients (1). In an earlier study, we used a simulation-based mastery learning model to train residents in CVC insertion and found that residents who received simulation training required fewer needle passes to insert actual CVCs in the medical intensive care unit (ICU) than residents who had not received simulator training (9). This is clinically relevant because increased needle passes correlate with higher rates of mechanical complications after CVC insertion (4, 18–21).

The current study has two aims. The first aim is to confirm that a simulation-based mastery learning model improves CVC procedural skills in residents from two disciplines (IM and EM). The second aim is to assess the effect of simulation training on several quality indicators related to CVC insertion (number of needle passes, arterial puncture, need for CVC adjustment after chest radiograph, suc-
cessful CVC insertion, and pneumotho-
rax).

MATERIALS AND METHODS

Study Design

This was an observational cohort study of an educational intervention with historical controls (22) of CVC insertions by 103 2\textsuperscript{nd} and 3\textsuperscript{rd} year IM and EM residents rotating in the medical ICU of a university-affiliated teaching hospital from March 2007 to March 2008. The Northwestern University Institutional Review Board approved the study and subjects provided their informed consent before participation.

Procedures

The medical ICU is staffed by IM and EM residents who perform daily patient care and routine bedside procedures including CVC insertions. In the medical ICU, residents insert almost all CVCs, and may do so independently after inserting five CVCs under direct supervision. There was no formal method of CVC insertion competency assessment before the simulation-based intervention.

Twenty-seven residents rotated through the medical ICU during a 4-mo preintervention phase and were surveyed daily about CVC insertions. These residents were the traditionally trained group and did not receive simulation training. Subsequently, 76 residents received simulation-based training in CVC insertion and they comprised the simulator-trained group (Fig. 1). These residents were also surveyed daily about medical ICU CVC insertions. A historical control rather than a simultaneous control was selected because this approach offered a more stringent test of the impact of the intervention by clearly separating the two groups.

Demographic data were obtained from participants including age, gender, ethnicity, year of training, medical school, and scores on the United States Medical Licensing Exam (USMLE) Steps 1 and 2.

Simulator-trained residents underwent baseline skill testing (pretest), using a 27-item checklist (9) in internal jugular (IJ) and subclavian (SC) CVC insertion, using Simulab’s CentrallineMan and the Sonosite 180 Plus ultrasound device. Simulator-trained residents also took a written pretest examination on CVC insertion.

Residents in the simulator-trained group received two 2-hr education sessions. One hour contained a videotaped lecture on the indications, technique, contraindications, and complications of CVC insertion. The remaining 3 hrs featured ultrasound training and the opportunity for deliberate practice with individualized feedback (23). Use of full barrier precautions and proper sterile technique were emphasized. Residents were required to use ultrasound for IJ CVC insertions; ultrasound use was optional for SC CVC insertions (4).

After training, residents were retested, using the 27-item skill assessment checklist (posttest) with the requirement to meet or exceed a minimum passing score (MPS) set previously by a multidisciplinary expert panel (9, 24). Residents who did not achieve the MPS in IJ or SC CVC insertion had more deliberate practice and were retested until the MPS was reached, a key feature of mastery learning (9, 23, 25). Simulator-trained residents also took a written posttest examination on CVC insertion. The simulator-trained residents completed the intervention 1 to 2 mos before their medical ICU rotation.

Outcome Measures

Pre- and posttest checklist and written examination scores of simulator-trained residents were compared to measure the impact of training sessions.

Medical ICU residents were surveyed daily about quality indicators related to actual CVC insertions. These residents were the traditionally trained group and did not receive simulation-based training, and they comprised the simulator-trained group (Fig. 1). These residents were also surveyed daily about medical ICU CVC insertions. A historical control rather than a simultaneous control was selected because this approach offered a more stringent test of the impact of the intervention by clearly separating the two groups.

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Measurement

Checklists were developed by one author (J.H.B.), using a step-by-step process (26), and reviewed by two others with expertise in CVC insertion and checklist development (K.J.O., D.B.W.). All pre- and posttests were graded on the checklist by a single unblinded instructor (J.H.B.) and were videotaped. If the artery was punctured, or >2 needle passes were made before cannulating the vein, the test was stopped and the remaining steps were marked wrong.

A 50% random sample of pre- and posttest sessions were rescored by a second rater (D.B.W.) to assess interrater reliability. The second rater was blind to the results of the first checklist recording and to pre- or posttest status of the examinee.

The multiple choice written examination was developed, using examination development guidelines (27) and appropriate reference articles (4, 18–21), and was piloted by 23 2\textsuperscript{nd} and 3\textsuperscript{rd} year nonstudy-participant residents. Results allowed creation of two different 40 question multiple-choice examinations (pretest and posttest) that were equivalent in content and difficulty.

Data on actual CVC insertions were collected by contacting daily all medical ICU residents. This allowed for CVC insertions to be identified within 24 hrs. All survey data were anonymous and collected by a single investigator, who was not involved in medical education. The primary inserter of each CVC was questioned about quality indicators and procedural self-confidence. Femoral catheters and CVCs primarily inserted by nonstudy participants (first-year residents or subspecialty fellows) were excluded.

Outcome Measures

Pre- and posttest checklist and written examination scores of simulator-trained residents were compared to measure the impact of training sessions.

Medical ICU residents were surveyed daily about quality indicators related to actual CVC insertions.
CVC quality indicators were compared between traditionally trained and simulator-trained groups, using the Mann-Whitney U test for number of needle passes, whereas the chi-square statistic was used for the other quality indicators.

Self-confidence differences were assessed using Student’s t tests whereas demographic differences were assessed with the Student’s t test and the chi-square statistic. Spearman’s rank-correlation coefficient was used to assess relationships between USMLE Steps 1 and 2 scores and pre- and posttest checklist and written examination performance, and between self-confidence and CVC insertion quality indicators.

RESULTS

One hundred three 2nd and 3rd year IM and EM residents rotated in the medical ICU during the study period. All eligible residents participated in the study and completed the entire protocol. As shown in Table 1, there were no significant demographic differences between the traditionally trained and simulator-trained groups.

A total of 407 CVCs were inserted in the medical ICU by interns and residents during the study period. As shown in Table 2, 164 (40%) CVCs were primarily inserted by traditionally trained and simulator-trained residents, for a mean of 1.6 CVC insertions per study resident. Simulator-trained residents reported significantly fewer needle passes (p < .0005), arterial punctures (p < .0005), CVC adjustments (p = .002), and higher CVC insertion success rates (p = .005) in the medical ICU compared with performance of traditionally trained residents. The groups did not differ in pneumothorax rates.

In the simulator-trained group, 100% (114 of 114) of IJ CVC insertions used ultrasound compared with 94% (29 of 31) in the traditionally trained group. One resident in each group used the ultrasound for SC CVC insertion.

A graphic portrait of the simulator-trained residents’ skill test and written examination performance is shown in Figure 2. Interrater reliability measured by the mean κ coefficient was very high (κ = 0.91) across the 27 IJ and SC checklist items. At baseline skills testing (pretest), 12 (16%) of 76 residents met the MPS (79.1%) for IJ CVC insertion and 11 (14%) of 76 residents met the MPS (79.1%) for SC CVC insertion. All simulator-trained residents met or exceeded the MPS after simulation training. Seventy-three (96%) of 76 residents achieved IJ skill mastery and 67 (88%) of 76 residents achieved SC skill mastery within the standard 4-hr curriculum. The remain-

### Table 1. Comparison of demographic data between traditionally trained and simulator-trained residents

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Traditionally Trained Residents</th>
<th>Simulator-Trained Residents</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean age (sd)</td>
<td>28.37 (2.20)</td>
<td>28.21 (2.02)</td>
</tr>
<tr>
<td>Male</td>
<td>13 (48.1%)</td>
<td>37 (48.7%)</td>
</tr>
<tr>
<td>Female</td>
<td>14 (51.9%)</td>
<td>39 (51.3%)</td>
</tr>
<tr>
<td>African-American</td>
<td>1 (3.7%)</td>
<td>3 (3.9%)</td>
</tr>
<tr>
<td>Caucasian</td>
<td>15 (55.6%)</td>
<td>42 (55.3%)</td>
</tr>
<tr>
<td>Asian</td>
<td>10 (37.0%)</td>
<td>26 (34.2%)</td>
</tr>
<tr>
<td>Hispanic</td>
<td>0 (0%)</td>
<td>1 (1.3%)</td>
</tr>
<tr>
<td>Other</td>
<td>1 (3.7%)</td>
<td>4 (5.3%)</td>
</tr>
<tr>
<td>Mean USMLE Step 1 (sd)</td>
<td>231.52 (13.57)</td>
<td>233.70 (14.75)</td>
</tr>
<tr>
<td>Mean USMLE Step 2 (sd)</td>
<td>233.70 (14.75)</td>
<td>240.08 (15.39)</td>
</tr>
<tr>
<td>PGY2</td>
<td>18 (66.7%)</td>
<td>37 (48.7%)</td>
</tr>
<tr>
<td>PGY3</td>
<td>9 (33.3%)</td>
<td>39 (51.3%)</td>
</tr>
<tr>
<td>Emergency medicine</td>
<td>5 (18.5%)</td>
<td>12 (15.8%)</td>
</tr>
<tr>
<td>Internal medicine</td>
<td>22 (81.5%)</td>
<td>64 (84.2%)</td>
</tr>
<tr>
<td>U.S. medical school</td>
<td>27 (100%)</td>
<td>76 (100%)</td>
</tr>
</tbody>
</table>

USMLE, United States Medical Licensing Exam; PGY, postgraduate year.

No differences were statistically significant.

### Table 2. Comparison of traditionally trained and simulator-trained residents during actual central venous catheter insertions in the medical intensive care unit

<table>
<thead>
<tr>
<th>Subclavian CVCs, n = 19</th>
<th>Internal Jugular CVCs, n = 145</th>
<th>Total CVCs, n = 164</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Traditionally Trained Residents</td>
<td>Simulator-Trained Residents</td>
</tr>
<tr>
<td># of CVCs</td>
<td>11</td>
<td>8</td>
</tr>
<tr>
<td>Mean (sd) # of CVC needle passes</td>
<td>.97</td>
<td>.79</td>
</tr>
<tr>
<td>Arterial puncture (%)</td>
<td>1/11 (9%)</td>
<td>0/8 (0%)</td>
</tr>
<tr>
<td>CVC adjustment (%)</td>
<td>1/7 (14%)</td>
<td>1/5 (20%)</td>
</tr>
<tr>
<td>Success rate (%)</td>
<td>5/8 (63%)</td>
<td>5/8 (63%)</td>
</tr>
<tr>
<td>Pneumothorax (%)</td>
<td>0/11 (0%)</td>
<td>1/8 (13%)</td>
</tr>
</tbody>
</table>

CVCs, central venous catheters.

CVC adjustment could not be measured if the insertion was not successful.
ing residents subsequently reached the MPS with <1 hr of additional practice time.

Cohort posttest skill test and written examination scores improved significantly from pretest ($p < .0005$).

There was no difference in mean self-confidence regarding CVC procedural skills in the traditionally trained group (83%) compared with the simulator-trained group (87%). Spearman’s rank-correlation coefficient showed no significant correlation between USMLE Steps 1 and 2 scores and clinical skills examination performance. In addition, there was no significant correlation between resident self-confidence and CVC insertion quality indicators.

**DISCUSSION**

This study demonstrates the use of a mastery learning model to develop CVC insertion skills to a high achievement level among IM and EM residents. Our data confirm that procedural skills that are poor at baseline can be increased significantly, using simulation-based training (6, 8–17, 25), and support American Board of Internal Medicine recommendations regarding use of simulation (1). Based on these findings, all residents in our program are now required to demonstrate skill mastery in a simulated environment before independently performing CVC insertions in the medical ICU.

We previously reported that simulation-based education reduced the number of needle passes used in CVC insertions in the medical ICU (9). That study was the first to link simulation training in CVC insertion to improved patient care as an increased number of needle passes has been linked to increased rates of procedure-related complications (4, 18–21). Our current results advance what is known about the impact of simulation training as residents also reported fewer arterial punctures, catheter adjustments, and a higher rate of successful CVC insertion. A dramatic reduction in arterial puncture rates to 1%, which is lower than the 3.1% to 9.4% described in other published reports (4, 18), is a particularly encouraging finding. Our sample size and number of CVCs inserted was likely too small to show a reduction in less frequent complications, such as pneumothorax.

Our results also show that resident self-confidence about actual CVC insertions was not affected by simulation training. There was also no correlation between self-confidence and performance on quality indicators related to actual CVC insertions. This reminds us that differentiating improved self-confidence from improved clinical outcomes is important because self-assessment does not always correlate with performance ability (30). The lack of correlation between USMLE Steps 1 and 2 scores and clinical skills examination performance reinforces the difference between academic achievement and acquisition of technical abilities.

Further study is needed to assess the impact of simulation-based training on CVC insertion. Simulator-trained residents in this study preferentially selected the IJ site, possibly due to improved competence or confidence using ultrasound. More education in SC CVC insertion may be needed because the number of SC catheter insertions in this study was too small to fully evaluate the effect of simulation-based training. Additionally, the impact of simulation-based education on catheter-associated bloodstream infections and the duration of skill retention require further investigation. These studies are ongoing at our institution.

This study has several limitations. First, it was performed at a single institution and reflects a small number of CVCs due to the strict exclusion criteria employed. Second, the primary evaluator was not blind to pre- or posttest status during the clinical skills examination. This was accounted for by using a second rater, who was blind to pre- or posttest status of examinees. Third, outcome data were measured via resident questionnaires, which relied on resident recall about CVC insertion rather than observer ratings. This method was selected because observer ratings could not be standardized due to the large number of clinical supervisors in the medical ICU over a
1-yr period. Direct observation of CVC quality indicators by study personnel was not possible because residents could not be allowed to err on actual patients without intervention. Information about needle passes and arterial puncture are also not documented in procedural notes and would not be available by chart review. Residents were surveyed daily to reduce recall bias and surveys were collected anonymously by an investigator not involved in medical education to promote unbiased self-reports. Finally, residents’ clinical experience in CVC insertion was not studied. However, groups did not differ in year of training or clinical rotations, and there is evidence to suggest that clinical experience is not a proxy for healthcare quality (31).

CONCLUSIONS

This study demonstrates that a mastery learning program featuring simulation-based education and deliberate practice improved performance of both simulated and actual CVC insertions and reduced the mechanical complication of arterial puncture. In teaching hospitals, there are important concerns regarding the quality of care provided to patients and a desire to eliminate preventable complications of invasive procedures. Simulation-based training has been shown to improve quality of care provided by IM residents in Advanced Cardiac Life Support (16) and CVC insertion (9). We believe that medical simulation is a powerful adjunct to standard clinical education for physicians-in-training.

ACKNOWLEDGMENTS

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