Original Article

Simulation-based Ultrasound Curriculum for Novice Clinicians to Assess Neonatal Endotracheal Tube Position

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Abstract

Background: To evaluate the efficacy of a simulation-based mastery curriculum to train clinicians with limited-to-no sonography experience how to use ultrasound (US) to assess neonatal endotracheal tube (ETT) positioning. **Methods:** In a single-centered, prospective, educational study, 29 neonatology clinicians participated in a simulation-based mastery curriculum composed of a didactic lecture, followed by a one-on-one simulation session using a newly designed, three-dimensional (3D) printed US phantom model of the neonatal trachea and aorta. After mastery training, clinicians were evaluated with a performance checklist on their skills obtaining US images and assessing ETT positioning in the US phantom model. They also completed pre- and postcurriculum knowledge assessment tests and self-assessment surveys. The data were analyzed using Wilcoxon signed rank tests and repeated measures analysis of variance. **Results:** The mean checklist score improved significantly during three attempts (mean difference: 2.6552; 95% confidence interval [CI]: 2.2578–3.0525; $P < 0.0001$). The mean time to perform US decreased significantly from the first to third attempt (mean difference: −1.8276 min; 95% CI: −3.3391 to − 0.3161; $P = 0.0196$). In addition, there was a significant improvement in median knowledge assessment scores (50% vs. 80%; $P < 0.0001$) and survey ratings on knowledge and self-efficacy ($P < 0.0001$). **Conclusion:** Clinicians with limited-to-no sonography experience demonstrated improved knowledge and skill acquisition in using US to assess ETT positioning through simulation-based mastery training. The use of 3D modeling enhances simulation experiences and optimizes the quality of training during limited opportunities to achieve procedural competency in a controlled environment before further application into the clinical setting.

Keywords: Neonatal intubation, simulation, ultrasound

Introduction

Critically ill neonates who require mechanical ventilation due to respiratory failure present unique challenges due to their small size. Endotracheal tube (ETT) positioning within the trachea is dynamic and fluctuates with minor movements of the head, neck, and shoulders, causing the ETT to become malpositioned with an incidence of 35%–50%.[1] In situations of clinical decompensation, clinical teams must quickly assess for ETT malposition, which could result in an unplanned extubation, right main bronchial intubation, or carinal intubation. Clinical assessment with direct laryngoscopy, lung auscultation, and carbon dioxide colorimetry can help determine if patients remain intubated, but chest radiography (CXR) is ultimately required to determine the ETT's position.[2] Point-of-care ultrasound (POCUS) is an alternative clinical tool that can provide valuable, rapid, real-time information.

Previous studies have demonstrated the feasibility of utilizing ultrasound (US) to visualize the ETT tip.[3,4] When compared to CXR, US is comparable for determining ETT positioning within the trachea using the aortic arch[4-9] or right pulmonary artery[10-12] as an anatomical surrogate for the level of the carina. In addition, US may be faster than CXR,[5,11,13] with a reported range of <1 min to 19 min.[5,8,10,11,13] Of note, the majority of these

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Received: 29-06-2021 **Revised:** 04-04-2022 **Accepted:** 26-04-2022 **Available Online:** 16-08-2022

Access this article online	
Quick Response Code:	**Website:** www.jmuonline.org
	DOI: 10.4103/jmu.jmu_143_21

How to cite this article: Huang D, Watkins LA, Weinschreider J, Ghazi A, Wang H, Dadiz R. Simulation-based ultrasound curriculum for novice clinicians to assess neonatal endotracheal tube position. J Med Ultrasound 2023;31:40-7.

studies utilized experienced sonographers (e.g. radiologists, US technicians, and trained neonatologist).[5,8,10,11,13]

It is unclear whether clinical providers with little-to-any US experience could learn to use US to successfully visualize and assess ETT positioning. We developed and piloted a novel US curriculum that included a didactic lecture on basic US principles and a simulation-based mastery training session utilizing a *de novo* US phantom model of the neonatal trachea and aortic arch. We aimed to assess the efficacy of this curriculum on learner self-efficacy, knowledge acquisition, and skill acquisition. We hypothesized that after participating in the curriculum, learners would demonstrate improved performance of the necessary steps to obtain US images of the ETT tip and assess its position within the trachea in an US phantom model, as measured by a performance assessment checklist.

Materials and Methods

Study participants and setting

This single-centered, prospective observational study took place from February 2020 to June 2021 at a high-acuity level IV neonatal intensive care unit (NICU) located at an academic medical center in the United States after obtaining exemption approval from the institutional review board (study id: STUDY00004444). Eligible participants were enrolled on a rolling basis until the target sample size was achieved. Clinical providers who provide airway management of infants in the NICU were eligible to participate. These included neonatologists, neonatology fellows, pediatric residents, advanced practice providers, and transport team members. Clinical providers who care for infants outside of the NICU and who are certified through a formal training program to perform sonography independently (e.g., sonographers, emergency physicians, and radiologists) were excluded from the study. Written consent was waived by the IRB, because the study was deemed to pose minimal risk to participants.

Overview of study design

This study evaluated the efficacy of a pilot US curriculum that included two components: asynchronous review of an online, video-recorded didactic lecture, followed by an in-person, one-on-one simulation-based mastery training session, during which learners practiced the US technique on a custom-designed US phantom model until skill acquisition was achieved. Before participating in the curriculum, learners completed an online survey and knowledge assessment. Learners then reviewed the online didactic lecture on fundamental US concepts and completed a knowledge assessment that was identical to the precurriculum knowledge assessment within 1 month of the online didactic lecture. Learners subsequently participated in a one-on-one simulation session with a course instructor (DH) 1 to 3 months after completing the didactic session. After observing a demonstration and practicing the US technique on a gelatin model, the learner measured the distance between the ETT tip to the aortic arch to assess the ETT position in three consecutive, timed attempts. The instructor observed and scored the learners' technique using the performance checklist. After completing the simulation session, learners completed a postcurriculum survey.

Curriculum development

The didactic lecture was a prerecorded online, narrated slide-based presentation that consisted of essential US concepts for novice learners, as well as a review of the scientific evidence, relevant anatomy, and rationale for assessing ETT positioning by US. It included photos and videos that demonstrated US images and technique. The course instructor appraised available POCUS course materials, lectures, and POCUS textbooks to develop the lecture, and faculty with expertise in education and performing POCUS reviewed the content and quality of the presentation. The instructor iteratively revised the content, piloted the presentation with a group of NICU providers, and finalized and recorded the presentation.

For the simulation portion of the course, an US phantom model was designed, constructed, and iteratively tested by a team that included a neonatologist, a pediatric radiologist, a POCUS-trained critical care physician, a mechanical engineer and materials science expert, and a laboratory research group that specializes in the development of anatomical US models using three-dimensional (3D) printing. The team imported DICOM images of the chest computed tomography of a neonate with normal airway anatomy into a segmentation software (Mimics 21.0, Materialise, Belgium). Segmentation was completed for each component of the patient's neonatal airway and aorta and imported into 3-matic 13.0 (Materialise, Belgium) to render a virtual 3D model of the patient's anatomy, including the trachea, carina, main bronchi, aortic arch, major aortic branches, and the descending aorta [Figure 1a]. Using Netfabb 2020 and Fusion 360 software (Autodesk, San Rafael, CA), the 3D model was further adapted for 3D printing. Specifically, the object was thickened to create a sturdy tracheal wall and scaled to accommodate a 3.5-mm uncuffed ETT. The trachea was also artificially lengthened to ensheath and secure the entire length

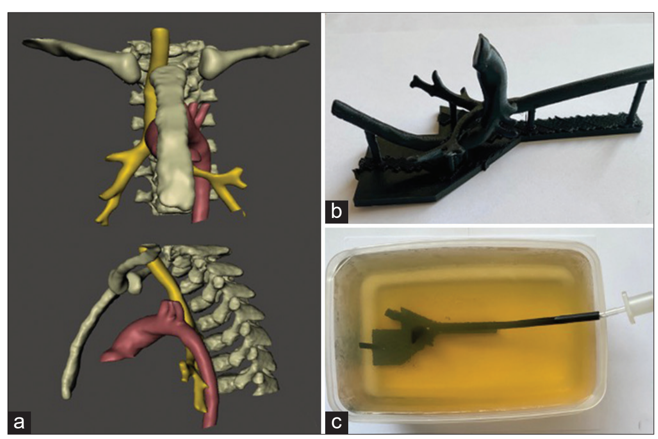

Figure 1: US phantom model design. (a) Anterior-posterior and sagittal views of 3D images derived from a computed tomography of a neonatal chest; (b) 3D-printed model of the neonatal trachea, bronchi, and aorta; (c) 3D-printed model cast in gelatin to form final US phantom model. US: Ultrasound, 3D: Three-dimensional

of the ETT, and scaffolding was added to properly orient the entire structure relative to the bottom of the container used for casting. The final 3D object was then printed with a Prusa i3 MK3 3D printer (Prusa Research, Prague, Czech Republic) using polylactic acid filament [Figure 1b]. The 3D printed structure was ultimately cast in gelatin to create the final US phantom model [Figure 1c], which simulated the anatomic relationship between the neonatal trachea aortic arch and exhibited dimensions and sonographic properties such that the ETT tip and aortic arch could be simultaneously viewed, captured, and measured on US imaging [Figure 2].

Assessment tools development

Participant surveys

Learners completed pre- and postcurriculum surveys, which were developed, reviewed, piloted, and iteratively revised. The precurriculum survey asked for demographic information that included prior education and experiences performing and interpreting US studies. The postcurriculum survey asked for feedback about the training program. Both surveys asked learners to rate their knowledge and confidence in obtaining and interpreting US images in the form of six five-point Likert scale questions, where a Likert rating of 1 represented a novice learner with no knowledge or comfort and a rating of 5 represented an expert with enough knowledge and comfort to teach someone else. Survey data were collected and managed using REDCap electronic data capture tools hosted at the university.[14,15]

Knowledge assessments

Learners completed two identical knowledge assessments before and after reviewing the online didactic presentation, which consisted of twenty multiple-choice questions that assessed their knowledge of US physics, machine operation, image orientation and optimization, recognition of image artifacts, and specific anatomy relevant to visualizing and assessing the ETT position on US. The content and quality of these questions and answers were developed, reviewed, and iteratively revised by faculty educators and POCUS experts. These knowledge assessments were administered online via REDCap.

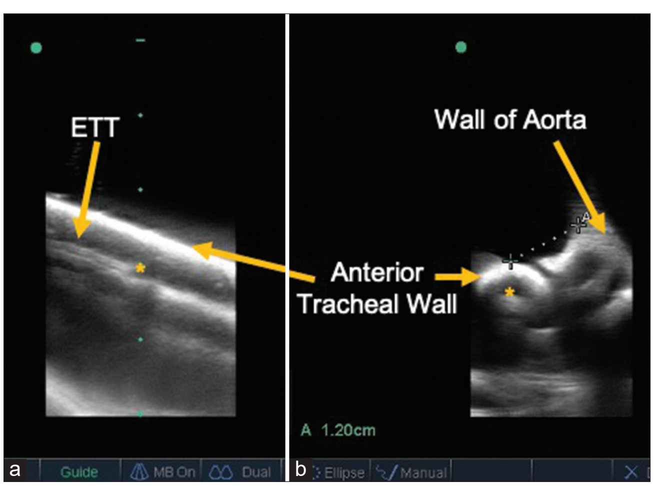

Figure 2: US images of phantom model. (a) Midsagittal view of the ETT and its tip (*) within the trachea; (b) Oblique view measuring the distance between the aortic arch and ETT tip within the lumen of the trachea, noted by the comet tail artifact. US: Ultrasound, ETT: Endotracheal tube

Performance assessment checklist

A performance skill checklist was developed to assess learners' US technique on a phantom model during their simulation session. The checklist consisted of fifteen items that corresponded to the essential steps of operating the US machine, obtaining US images, and assessing ETT positioning within the trachea [Appendix 1]. The instructor used the checklist to score and time learners, who assessed and measured different positions of the ETT within the phantom gel model during three consecutive attempts. The instructor awarded one point for each step that learners achieved independently without prompting. Furthermore, learners were only given credit for measurements that were ±0.25 cm from the actual measurement. The measurement of time started when learners touched the US machine and stopped when they measured and verbalized an assessment of the ETT's position. Of note, the timer continued despite learners' interruptions soliciting guidance from the course instructor. The instructor recorded checklist scores and times into REDCap.

Outcome measures, sample size, and data analyses

The primary hypothesis was to compare learners' mean performance checklist scores over the three attempts of assessing ETT positioning in the US phantom. Secondary outcomes included learners' mean duration of time to assess ETT positioning (duration per attempt), their knowledge assessment scores, and their survey responses. Assuming a moderate effect size of 0.5–0.6, we estimated a sample size of 24–34 subjects to achieve a power of 80% with an alpha of 0.05 to reject the null hypothesis that the performance checklist scores would remain similar.[16] Repeated measures analysis of variance (ANOVA) was used to compare the checklist scores and duration of each US attempt, with within-subject correlations adjusted and an unstructured covariance matrix specified. Wilcoxon signed rank tests were used to compare pre- and postcurriculum survey Likert scale ratings and knowledge assessments. Descriptive statistics were used to summarize demographic data. All tests were two-sided, and $P < 0.05$ was considered statistically significant. All data were analyzed using SAS version 9.4 (SAS Institute, Inc., Cary, North Carolina).

Results

Study population

A total of 42 subjects were enrolled, of whom 29 learners participated in the simulation-based training session [Figure 3]. Since the primary outcome was performance checklist scores, descriptive statistics and data analyses of all outcomes were limited to only the 29 learners who completed the simulation-based training session. For paired comparison measures such as knowledge assessment scores and Likert scale survey responses, only patients with complete paired observations were included for analyses.

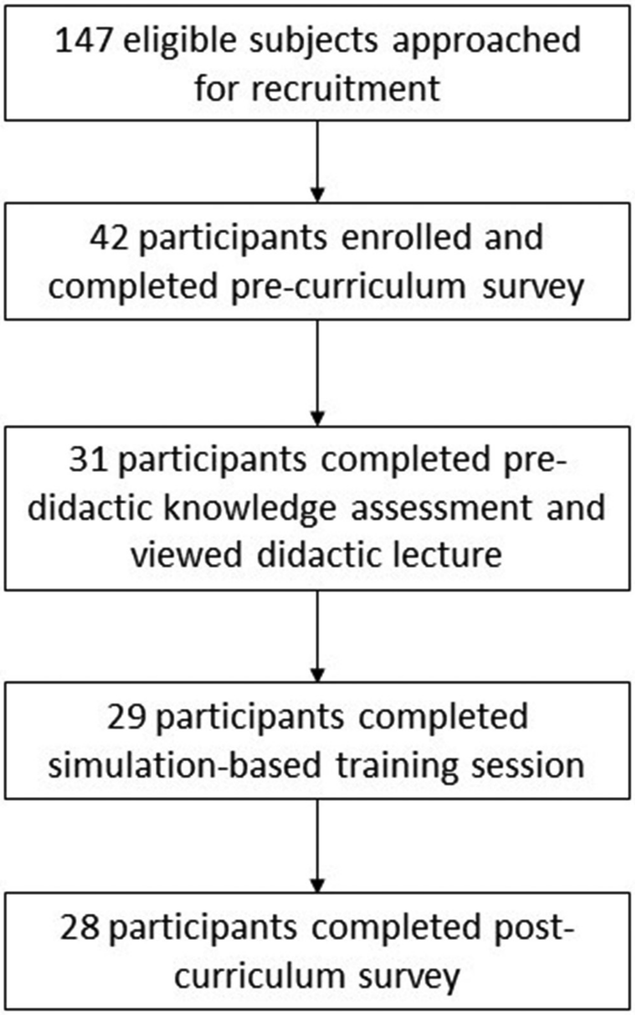

Figure 3: Participant enrollment. Flow diagram summarizing participant enrollment and completion of the curriculum and study measures

Table 1 summarizes the demographic characteristics of the 29 learners who completed simulation mastery training. Of note, the majority of learners never had any formal training in interpreting (69%) or performing US studies (62%). Of the minority of learners who had prior training, most reported <1 month of training on how to interpret (67%) and perform (82%) US.

Knowledge and skill acquisition

Learners demonstrated knowledge acquisition after reviewing the didactic lecture, with a significant improvement in the median test scores from 50% to 80% [$P < 0.0001$, Figure 4]. In addition, learners demonstrated skill acquisition after participating in simulation-based mastery training, with significant improvements in their mean performance checklist scores [Figure 5]. Repeated measures ANOVA showed a significant within-subject effect over time ($P < 0.0001$). In particular, the mean checklist score improved significantly from the first to third attempts (mean difference: 2.6552; 95% confidence interval [CI]: 2.2578–3.0525; $P < 0.0001$). *Post hoc* comparisons also showed a significant improvement from both the first to second (mean difference: 1.2414; 95% CI: 0.7575–1.7253; $P < 0.0001$) and from the second to third attempts (mean difference: 1.41 38; 95% CI: 1.04–1.7876; $P < 0.0001$). Repeated measures ANOVA did not demonstrate a significant within-subject effect over time on the mean duration per attempt ($P = 0.0624$). However, *post hoc* comparisons showed a significant decrease in time from both the first to second (mean difference: −1.4828 min; 95% CI: −2.9046 to −0.06089; $P = 0.0416$) and from the first to third attempts [mean difference: −1.8276 min; 95% CI: −3.3391 to −0.3161; $P = 0.0416$, Figure 6]. Subgroup analyses did not

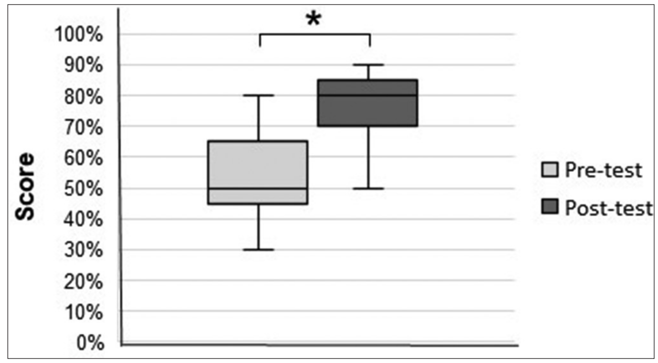

Figure 4: Knowledge assessment scores. Learners demonstrated a significant improvement in median knowledge assessment scores after participating in the didactic portion of the curriculum (*$P < 0.0001$, Wilcoxon signed rank test)

Table 1: Participant demographics

Total participants (*n*=29)	*n* (%)
Participant role	
Advanced practice provider (NP/PA)	13 (45)
Resident	7 (24)
Fellow	3 (10)
Attending physician	4 (14)
Other*	2 (7)
Prior training in interpreting US images	
None	20 (69)
<1 month	6 (21)
1 month-<1 year	0
1-3 years	2 (7)
>3 years	1 (3)
Prior training in performing US studies	
None	18 (62)
<1 month	9 (31)
1 month-<1 year	0
1-3 years	2 (7)
>3 years	0
Number of US exams performed within the last year	
None	18 (62)
1-2	6 (21)
3-5	2 (7)
6-10	2 (7)
>10	1 (3)

*Hospitalist and respiratory therapist. US: Ultrasound, NP: Nurse practitioner, PA: Physician assistant show significant differences in the pre- and postcurriculum change in test scores, performance checklist scores, or time to perform US between different professional groups and between clinicians of varying experience in interpreting US images and performing US studies [Table 2].

Survey responses

After participating in the curriculum, learners reported significant improvements in their general knowledge in interpreting US images, performing US, and using US to assess the ETT's position. The median Likert scale ratings ranged from 1 to 2 precurriculum and increased to a median range of 2–3 postcurriculum [all $P < 0.0001$, Table 3]. Learners also reported significant improvements in their confidence, with median Likert ratings of 1 precurriculum to a median range of 2–3 postcurriculum [all $P < 0.0001$, Table 3]. All survey respondents agreed that participating in a training curriculum on how to use POCUS to visualize and assess ETT position in infants would enhance their ability to provide patient care.

Discussion

In this pilot study of a novel US training curriculum, learners demonstrated significant improvements in their knowledge, skills, and self-efficacy in applying US to perform and assess ETT positioning in an US gel phantom model. In contrast to previous studies that included expert sonographers such as radiologists and US technicians,[4,6-9] this was the first study that incorporated many clinicians with limited-to-no sonography experience to learn the application of US skills in the assessment of ETT positioning.

This study provides an effective framework that combined technological advances in 3D modeling and printing with simulation-based mastery training to introduce US skills to novice clinicians. Creating an US phantom task trainer that models the realistic anatomic relationships between the neonatal trachea and aorta enabled clinicians to learn and practice their US skills for a specific procedural skill. In addition, clinicians may be taught in a concise, graduated manner by first optimizing their skills and confidence in a controlled, non-clinical learning environment with an educator who individualizes their training before applying their skills in the clinical setting. The successful use of simulation-based mastery training has been described for other procedural skills, such as central line placement.[17] Such an approach has been shown to improve clinical procedural success and patient outcomes in clinicians with novice skills.[17-19]

There has been increasing interest and drive to incorporate POCUS into the field of neonatology.[20] The use of POCUS has been well established in other pediatric and adult critical care specialties that have demonstrated how it may improve clinical decision-making[21] and clinical outcomes,[22] such as the management of septic shock. Our study demonstrated the feasibility of training NICU clinicians in US effectively and safely in a simulation-based training environment. Future simulation-based curricular design may also incorporate other POCUS applications to critically-ill infants, such as US-guided peripherally inserted central catheter insertion,[23] central catheter tip localization,[24] and suprapubic bladder aspiration.[25] Continued efforts to develop a high-quality POCUS curriculum that utilizes a standardized approach to training would entail ongoing multidisciplinary collaboration that includes individuals with expertise in 3D printing, clinical education, and the use of POCUS in clinical environments.

Further investigation is needed to assess the true utility and feasibility of using US in clinical situations where clinicians with limited US experience need to identify ETT positioning in a timely manner. Research could investigate (1) the time to assess ETT positioning, when compared with the time to obtain

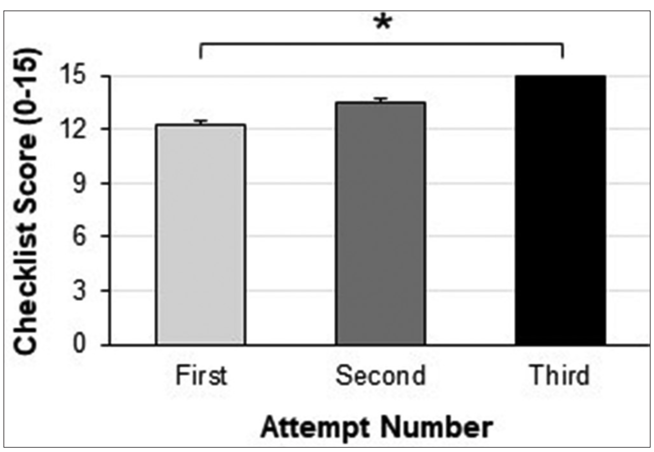

Figure 5: Mean performance checklist scores of assessing endotracheal tube position by ultrasound. Bar graph comparing the mean performance checklist score for each consecutive, observed attempt of assessing the endotracheal tube position by ultrasound. Learners demonstrated a significant increase in scores (*$P < 0.0001$, repeat measures ANOVA). ANOVA: Analysis of variance

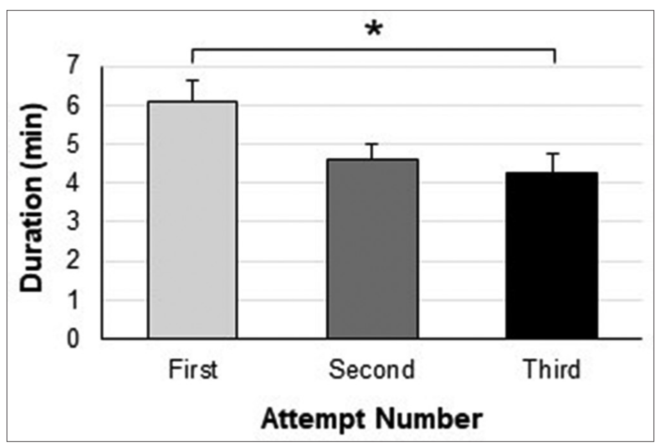

Figure 6: Mean duration of assessing endotracheal tube position by ultrasound. Bar graph comparing the mean duration of time for each consecutive, observed attempt of assessing the endotracheal tube position by ultrasound. Learners demonstrated a significant decrease in time when comparing the first and third attempts (*$P < 0.020$, repeat measures ANOVA). ANOVA: Analysis of variance

Table 2: Subgroup analyses of the change in knowledge and performance outcome measures pre-and postcurriculum

Subgroup	Test score, median (minimum-maximum)		Mean±SD			
			Checklist score		Duration	
	Change	*P*	Change	*P*	Change	*P*
Professional group						
Physician (*n*=16)	0.2 (0.1-0.4)	0.4	2.4±1.0	0.2	−1.6±3.1	0.3
Other clinician (*n*=13)[a]	0.3 (−0.1-0.4)		3.0±1.1		−2.5±4.9	
Experience interpreting US images						
None (*n*=20)	0.3 (−0.1-0.4)	0.5	2.7±1.2	0.9	−2.0±4.3	0.9
At least some (*n*=9)[b]	0.2 (0.1-0.4)		2.7±0.7		−1.4±3.5	
Experience performing US studies						
None (*n*=18)	0.3 (0.1-0.4)	0.2	2.7±1.2	1.0	−1.4±4.9	0.6
At least some (*n*=11)[b]	0.1 (−0.1-0.4)		2.6±0.8		−2.5±1.6	

[a]Other clinician includes advanced practice providers, hospitalist and respiratory therapist, [b]At least some includes clinicians who have noted at least <1 month of experience in Table 1. US: Ultrasound, SD: Standard deviation

Table 3: Participant self-assessment of knowledge and efficacy pre-and postcurriculum

Survey item	Mean±SD		*P*
	Precurriculum (*n*=28)	Postcurriculum (*n*=28)	
Knowledge			
Interpreting general US images	1.6±0.5	2.5±0.8	<0.001
Performing general US studies	1.4±0.6	2.6±0.8	<0.001
Using US to assess ETT position	1.1±0.3	2.6±0.6	<0.001
Self-efficacy			
Interpreting US images	1.4±0.5	2.4±0.7	<0.001
Performing US studies	1.3±0.5	2.5±0.7	<0.001
Using US to assess ETT position	1.1±0.3	2.5±0.6	<0.001

Likert Scale definitions: 1=Novice: No knowledge/comfort; cannot achieve any steps, 2=Beginner: Can achieve for some basic steps, 3=Competent: Can achieve all basic steps, but needs help with complex cases, 4=Advanced: Can achieve all basic steps and trouble most complex cases, 5=Expert: Can teach knowledge/skills. ETT: Endotracheal tube, US: Ultrasound, SD: Standard deviation

chest radiographs, (2) clinical outcomes such as the reduction of unilateral endotracheal surfactant administration in the delivery room, and (3) the potential reduction in chest radiographs and radiation exposure in intubated infants, especially for those patients who require regular surveillance of ETT positioning.

Limitations

Developed as a pilot training course, study limitations were primarily methodological, which may have introduced sources of bias. While using a translucent model was a deliberate decision made by the team to enhance learners' 3D visual-spatial understanding of the anatomy during training, learners may have been able to estimate the relative depth of the ETT within the model's trachea by noting the relative length of the ETT outside of the model. In addition, learners could align the probe with the tracheal section and localize the aortic arch, but they still needed to learn how to visually identify the ETT tip by its ultrasonographic artifact. In future training, instructors may encase the anatomical model in opaque gelatin, so that internal anatomical structures are no longer visible. In addition, they may cover the external depth of the ETT from the learner's view.

We developed the performance skill checklist as a tool to assess learners' skills. However, the instructor who taught the learners also evaluated the learners using the checklist, which may have introduced a source of observer bias. In future studies, checklist scores may be verified by including additional reviewers who observe and score learner performance to assess interobserver reliability.

Conclusion

NICU clinicians with limited-to-no sonography experience can be taught to use US to assess ETT position using simulation-based mastery training. Further study is needed to validate this POCUS application in the clinical setting. There is growing evidence that neonatal clinicians want to incorporate POCUS into their practice and widespread adoption and training should be encouraged.

Acknowledgment

We would like to thank Dr. Alison Kent and the Scholarly Oversight Committee for their mentorship during the project.

Financial support and sponsorship

Nil.

Conflicts of interest

There are no conflicts of interest.

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Appendix 1: Performance assessment checklist

Attempt Number: __________

Performance Start Time: __________

Performance End Time: __________

Attempt Duration (minutes): ____

Steps:

1. Turns on ultrasound (US) machine, places machine in B-mode
2. Selects high frequency linear probe, applies US gel to probe
3. Places probe parallel to trachea to obtain sagittal view, indicator is facing up
4. Correctly orients self by verbally identifying the anterior/posterior (top/bottom) and superior/inferior (left/right) directions on US screen
5. Adjusts depth appropriately
6. Adjusts gain on machine to optimize view
7. Rotates probe (indicator facing left) to obtain and optimizes transverse view of the endotracheal tube (ETT)
8. Scans through transverse sections of the ETT
9. Correctly identifies the tip of the ETT by verifying that it is the most distal portion of the ETT from the appearance of the comet artifact
10. *Captures a video of scanning the ETT to identify ETT tip
11. Shifts view of ETT tip to left of screen
12. Rotates probe around the point of ETT tip until aortic arch comes into view
13. Obtains and captures still image of aortic arch and ETT tip in same view, if possible
14. †Uses calipers to measure distance from ETT tip to aortic arch, if possible
15. Makes an assessment on ETT position based on this information

Total Score: ____/15

*Point awarded if learner visually demonstrated appearance/disappearance of comet tail artifact while scanning above and below level of ETT tip.

†Point awarded if measurement obtained was within ±0.25cm of the actual distance.