Developing and evaluating an abbreviated extracorporeal membrane oxygenation (ECMO) course for physicians and nurses

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Abstract

Background: Extracorporeal Membrane Oxygenation (ECMO) is a modification of cardiopulmonary bypass that allows prolonged support of patients with severe respiratory or cardiac failure. ECMO indications are rapidly evolving and there is growing interest in its use for cardiac arrest and cardiogenic shock. However, current ECMO training programs are limited. Training of emergency medicine and critical care clinicians could expand the use of this lifesaving intervention. We aimed to develop and evaluate an abbreviated ECMO course that can be taught to emergency and critical care physicians and nurses.

Methods: We developed a training model using Yorkshire swine (*Sus scrofa*), a procedure instruction checklist, a confidence assessment, and a knowledge assessment. Participants were assigned into teams of one emergency medicine or critical care physician and one nurse and completed an abbreviated eight-hour ECMO course. An ECMO specialist trained them on preparation of the ECMO circuit and oversaw vascular access and ECMO initiation. We used the instruction checklist to evaluate performance. Participants completed confidence and knowledge assessments before and after the course.

Results: Seventeen teams (34 clinicians) completed the abbreviated ECMO course. None had previously completed an ECMO certification course. Immediately following the course, all teams successfully primed and prepared the ECMO circuit. Fifteen teams (88%, 95% CI 64% to 99%) successfully initiated ECMO. Participants improved their knowledge (difference 21.2, 95% CI 16.5 to 25.8) and confidence (difference 40.3, 95% CI 35.6 to 45.0) scores after completing the course.

Conclusions: We developed an accelerated one-day ECMO course. Clinicians' confidence and knowledge assessments improved and 88% of teams could successfully initiate venoarterial ECMO after the course.

Introduction

Extracorporeal Membrane Oxygenation (ECMO) is a modification of cardiopulmonary bypass that allows prolonged support of patients with severe respiratory or cardiac failure. There is some variation in ECMO circuits, but the essential components are the same: large bore vascular cannulas, blood pump with control module, membrane oxygenator, and oxygen source. Venovenous (VV) ECMO replaces lung function in patients with respiratory failure by removing deoxygenated blood, oxygenating the blood via the membrane oxygenator, and returning the blood to a patient's central vein. Venoarterial (VA) ECMO replaces heart function in patients with heart failure by removing blood from a central vein and pumping it into a central artery. Veno-arterial-venous (V-AV) ECMO supports both lung and heart function by removing blood from a vein, oxygenating the blood, and pumping the blood back into both a central artery and vein.

A randomized controlled trial published in 2009 demonstrated that referral to an ECMO capable center was an efficacious and cost-effective strategy for patients with severe acute respiratory distress syndrome (ARDS).(1) In that same year there was unprecedented use of ECMO for adults with respiratory failure secondary to H1N1 Influenza.(2) These two factors have spurred a rapid increase in ECMO utilization and established it as a valuable therapy for severe ARDS.(3) Additionally, ECMO indications are rapidly evolving and there is now growing interest in its use for cardiac arrest, cardiotoxic xenobiotic overdose, and cardiogenic shock.(4,5) ECMO has been used in the prehospital environment for cardiac arrest; however, the efficacy and appropriate patient selection procedures remain unclear.(6,7,8) The United States (US) military has placed combat casualties on ECMO prior to evacuation from the combat theater with a high survival rate.(9,10)

Despite the expansion of ECMO use, the number of hospitals with ECMO capability and ECMO trained personnel is still limited.(11,12) Even fewer medical systems have the ability to provide immediate ECMO to prehospital, emergency department, and intensive care unit cardiac arrest patients. Expansion of ECMO training may increase the use of this life-saving intervention; however, current ECMO training programs are limited, frequently require travel, typically three to five days in duration, and may be cost prohibitive.(13,14) Within the US military, some casualties have died while awaiting the arrival of the military ECMO team.(10) Expansion of this skill via an abbreviated ECMO training course may provide this life-saving intervention to a greater number of patients in need of immediate therapy due to active or impending cardiac arrest. The objective of this study was to develop and evaluate an abbreviated (less than 8 hour) ECMO course that can be taught to emergency and critical care physicians and nurses.

Methods

Study Design

We conducted a prospective controlled study evaluating the efficacy of an abbreviated ECMO training course to provide emergency and critical care nurses and physicians the skills necessary to initiate and maintain ECMO therapy as well as troubleshoot common ECMO complications using swine as a live animal model. The 59th Medical Wing (59th MDW)

Institutional Review Board reviewed the human study protocol and approved the study as exempt. The study was also approved by the WHASC Clinical Investigations and Research Support (CIRS) Institutional Animal Care and Use Committee (IACUC).

Study Setting and Population

We solicited volunteer students from Brooke Army Medical Center (BAMC), the Department of Defense's only level 1 trauma center, via email, word of mouth, and presentations at department grand rounds. Personnel eligible for inclusion as students included attending emergency medicine physicians, third year emergency medicine residents (from a single three-year emergency medicine residency), critical care attending physicians, critical care fellowship physicians, emergency medicine nurses, and critical care nurses who had no previous formal ECMO training.

The study was conducted in accordance with the regulations and guidelines of the Animal Welfare Act, the National Institutes of Health Guide for the Care and Use of Laboratory Animals, and the American Association for the Accreditation of Laboratory Animal Care. The animals were housed at the 59th Medical Wing/CIRS vivarium, where the study was conducted. The study was funded by the Congressionally Directed Medical Research Program (CDMRP) Joint Program Committee 6 (JPC-6)/Combat Casualty Care Research Program.

Materials

The CARDIOHELP ECMO pump (Maquet Getinge Group CARDIOHELP-I REF 70104-8012) and circuit (Maquet HLS Set Advanced 7.0, HLS 7050 USA, 701052794) was used. Cannulation was performed using the Maquet Arterial and Venous Cannulas (PAL 1523, PVS 1938 and PVL 2155).

Course Materials

The course was set up in a teach, train, test model in which the students first reviewed educational materials (1.5 hours), next received step by step instructor training on a live swine model (2-3 hours) and finally were tested by on their ability to prime and prepare the circuit and place the live animal on ECMO utilizing the provided checklist (2 hours).

Educational materials were developed from the current 3-day BAMC ECMO course. Visual slides used for didactic lectures from the BAMC ECMO course were condensed to the knowledge material necessary for participants to identify appropriate ECMO patient candidates, initiate ECMO therapy, maintain ECMO therapy, and troubleshoot common ECMO complications. Since the purpose of the course was to provide physicians and nurses with the ability to initiate ECMO therapy until the hospital ECMO team assumed care, knowledge materials that focused on the weaning of ECMO therapy and decannulation were not included. The lectures developed covered the following topics: ECMO indications and contraindications, ECMO physiology, ECMO patient management, ECMO cannulation strategies and cannula selection, and ECMO circuit management (routine and emergencies). Following the development

of condensed slides, the primary investigator recorded videos of the narrated lectures with visual slides and posted these videos on a secure network, accessible only to the research team.

Step-by-step instruction checklists were also developed from the current 3-day BAMC ECMO course. These checklists were developed to provide a stepwise guide to assist students in initiating ECMO and troubleshooting ECMO complications. ECMO instruction checklists were developed for the following tasks: set-up and priming of the ECMO circuit, patient cannulation, and management of ECMO complications.

We performed three model development sessions prior to student enrollment to assist in ensuring lecture and checklist accuracy as well as improve instructor performance.

Student Lecture-based Training

At the beginning of each abbreviated ECMO course one physician and one nurse arrived at the training lab and completed a survey to obtain baseline demographic information and their ECMO comfort level as well as a written assessment to determine their ECMO knowledge (Table 1). Upon completion of the survey and pretest, each student was provided a laptop on which they watched each of the aforementioned recorded audiovisual lectures.

Animal Preparation

We sought to provide training and validation using a live animal model given the inability to evaluate mortality and physiology using a mannequin model. Practicing ECMO procedures on human volunteers is impractical and unethical, therefore due to the similarities between human and swine cardiopulmonary anatomy, we elected to use Yorkshire swine (Sus scrofa) weighing between 70-90 kilograms. These swine were fasted overnight except for water ad lib. Prior to induction of anesthesia, all animals were sedated with ketamine at an intramuscular dose of 10 mg/kg, and endotracheal intubation was performed. Mechanical ventilation was commenced and adjusted to maintain the arterial partial pressure of carbon dioxide (PCO_2) between 38 and 42 mm Hg using a volume-limited, time-cycled ventilator (Drager-Siemens, Fabius GS anesthesia machine, New York City, NY). During the placement of catheters, isoflurane was administered in a range between 1% and 3.5%. Anesthesia was maintained by a qualified surgical technician using isoflurane titrated in air oxygen to maintain sedation and a stable blood pressure.

An arterial line was placed in the carotid artery via micropuncture to monitor blood pressure (Drager Inifinty HemoMed Pod) and an intravenous line was started in the ear for the administration of maintenance fluids (normal saline). Once all lines were placed, isoflurane was maintained between 1-2% to mitigate isoflurane-induced hypotension and apnea. Electrocardiogram (ECG) electrodes were placed for continuous monitoring of heart rate and rhythm. A Foley catheter was placed in the bladder of females, and a suprapubic catheter for males, for urine collection. Animal temperature was maintained between 37.5 and 40 degrees using heating adjuncts as needed (warmed induction and operating room and warming blanket).

At this point, animals were allowed to acclimate and the blood pressure to stabilize (at least 10

minutes). The fraction of inspired oxygen (FiO_2) was maintained at 0.40. Following animal stabilization, a baseline arterial blood gas was collected. Baseline biochemical measurements included oxygen saturation, PaO_2, $PaCO_2$, hemoglobin (Hb), pH, bicarbonate, base excess, and lactate (ABL 800 Flex blood gas analyzer, Radiometer America, Westlake, OH).

Student Hands-on Training

Subjects were taken to the ECMO lab where the research team, consisting of an ECMO trained physician, an ECMO trained nurse, and nurse assistants provided verbal and hands-on instruction to the students as they assembled and primed the ECMO circuit and cannulated the femoral veins and one of the femoral arteries. The ECMO students were reminded to use the previously developed written instructions in a stepwise fashion throughout this process. For the initial training and testing team we started the swine on VV ECMO and then transition to V-VA ECMO; however, following the initial swine we determined that the high propensity of swine to develop cardiac dysrhythmias made initiation of VA ECMO followed by transition to V-AV ECMO more advantageous and was performed for the following sixteen animals.

Cannulation was accomplished using percutaneous Seldinger technique aided by ultrasound. Placement of the guidewire was verified by the cannulating physician via fluoroscopy before placing the appropriate cannula. Following appropriate wire placement confirmation, heparin was administered intravenously. Serial dilations of one of the femoral veins was performed using both the Maquet percutaneous insertion kit (12Fr.-18Fr.) [PIK 150-USA] and the Avalon Elite Vascular Access Kit (20Fr.) [#12210]. A 21-French venous cannula [Maquet Venous HLS Cannulae/PVL 2155 21Fr was placed in one of the femoral veins. Serial dilations of a femoral artery were performed up to 14 French, using the Maquet percutaneous insertion kit. A 15-French arterial cannula [Maquet Arterial HLS Cannulae/PAL 1523 15Fr.] was placed in the femoral artery. Cannulas were de-aired and attached to the ECMO circuit. The cannulas were sutured into place for stabilization.

Following confirmation of successful VA ECMO initiation and swine stabilization, cannulation of the second femoral vein was accomplished using percutaneous Seldinger technique aided by ultrasound. Following placement of the guide wire, verification of cannulation of the appropriate vessel was verified by the cannulating physician via fluoroscopy. Serial dilations of the second femoral vein was performed using the Maquet percutaneous insertion kit up to 18-French. A 19-French arterial cannula [Maquet Arterial HLS Cannulae/PAS 1923 19Fr.] was placed in the second femoral vein. The cannula was then de-aired and a clamp was placed to ensure there was no entrainment of air or leaking of blood from the cannula. In order to initiate veno-arterial-venous ECMO (V-AV ECMO), the arterial line flowing out of the ECMO circuit was clamped and cut. A Y-connector [NovoSci, 3/8” x 3/8” x 3/8”/C330S] was placed allowing the oxygenated blood from the ECMO circuit to be diverted into the 15-French arterial cannula and the 19-French venous cannula. Flow regulator clamps were placed on the tubing of the 19-French femoral vein cannula, allowing the ECMO participants to regulate the blood flow from the Cardiohelp between the arterial and venous system to ensure adequate blood pressure and oxygenation.

Following confirmation of successful V-AV ECMO initiation and swine stabilization, the students were provided with hands-on training on how to identify and correct the following common ECMO complications: loss of electrical power, access insufficiency (often referred to as "chatter"), air in the ECMO circuit, and loss of circuit integrity (i.e. a hole in the tubing).

Training validation and testing

Upon completion of the hands-on training, the students were provided with all of the supplies necessary to prime and prepare the circuit, access and cannulate the required blood vessels, initiate and maintain ECMO therapy, and troubleshoot the common complications.

Two research assistants independently observed the students to evaluate and document performance and time to completion of each of the major tasks taught during the hands-on training. Any difference in documented information between the research assistants were clarified via consensus. If the two research assistants could not reach a consensus, the primary investigator made the ultimate determination.

In the event, that the students were unsuccessful in initiating ECMO therapy, an ECMO specialist would intervene and initiate ECMO. Failed ECMO initiation was documented and the students then proceeded to the following phase of study.

After initiation of ECMO, the students were asked to leave the room. While the students were out of the room, the research team induced a common complication. The students were then called back into the room and instructed to assess the patient and the Cardiohelp System, state what complication they encountered, and perform the necessary steps to correct the problem. This scenario was repeated for each of the following complications: loss of electrical power, excessive blood flow turbulence (often referred to as "chatter"), diagnosis and removal of air from the venous side of the circuit, diagnosis and removal of air from the arterial side of the circuit, and loss of circuit integrity. Two research assistants independently observed the students to evaluate and document their performance and a lab timer kept track of how long it took to resolve each issue and resume ECMO therapy.

Following the troubleshooting phase, all questions and concerns were addressed with the students, prior to completing the post training knowledge and comfort level assessment. After completion of the troubleshooting phase of both the training and testing portions of the study, the swine were euthanized (IV Pentobarbital, 100mg/kg) by a qualified veterinary technologist under veterinary guidance in accordance with the American Veterinary Medical Association Panel on Euthanasia guidelines.

Measurements

The central premise of this study was to evaluate an abbreviated ECMO training course, evaluating competency following course completion. The success of each team in completing the tasks of initiating ECMO and troubleshooting the aforementioned ECMO complications were compared.

In addition, the students' comfort and knowledge were assessed with a survey and an assessment immediately before and after the ECMO training course. Descriptive summaries of participant demographics and backgrounds were conducted. The confidence assessment consisted of 10 items that described necessary steps to initiate and maintain ECMO. Students were asked to rate their confidence and experience level for each item on a scale from 0 ("no experience") to 5 ("expert"). The knowledge assessment consisted of 20 questions (multiple choice and true/false) about ECMO procedures, indications, complications, and troubleshooting.

Arterial blood gases to include electrolytes were collected at each blood draw (baseline, immediately post ECMO initiation, and at study completion) with blood obtained from the carotid artery and/or the ECMO circuit.

Data Analysis

We reported categorical variables as frequencies and percentages and continuous variables as means with standard deviations. The primary endpoint was a binary outcome (successful ECMO initiation, yes vs. no). Other variables of interest include successful priming and preparation of the ECMO circuit (yes vs. no), preparation time (from start of lab to completion of circuit preparation), procedure time (from start of lab to completion of cannulation procedure), and lab time (from start of lab to completion of lab).

Swine characteristics and physiology were reported but not analyzed for comparisons. We evaluated inter-rater agreement on the procedure instruction checklist using percent agreement over all items and teams (calculated as number of items in agreement across all teams divided by the total number of items across all teams) and Cronbach's alpha as a measure of internal consistency for the 10-item confidence assessment. Scores from each item on the confidence assessment were summed and a percentage score was calculated out of the 50 possible points. We also calculated the proportion of students who rated themselves as "competent" (a score of 3) or better on each item. For the knowledge assessment, we calculated the percent of correct answers (out of 20 items). Analysis of these secondary outcomes included paired t-tests (for continuous variables) and McNemar tests (for nominal variables) comparing pre-training scores to post-training scores to assess improvements on the confidence and knowledge assessments.

Power Analysis

A precision analysis was performed *a priori* and determined that a sample size of 17 teams (2 clinicians per animal) could produce a 95% confidence interval of 90% to 100% with the assumption of 99.9% success rate in ECMO initiation. Analyses were performed using SAS v9.4 (SAS Institute, Inc. Cary, North Carolina). Statistical tests are two-sided with a significance level of 5%.

Results

Characteristics of Study Subjects

A total of 34 clinicians (17 teams) completed the ECMO course including 11 attending emergency medicine physicians, 5 third-year emergency medicine residents, and 1 pulmonary critical care fellow. The majority of physicians (88%) had been in their current position for five years or fewer. Most students had no experience caring for a patient on ECMO and none had ever completed formal ECMO training prior to this course (Table 1).

Primary Outcome

All 17 teams successfully primed and prepared the ECMO circuit (Table 2). One team did not use a lab timer; the remaining 16 teams prepared the circuit with a mean time of 31±6 minutes (95% CI 28 to 35 minutes). Fifteen of the 17 teams (88%; 95% CI 64% to 99%) could complete the cannulation procedure (mean time from start of the lab 59±25 minutes (95% CI 45 to 74 minutes). Two teams were unable to initiate ECMO due to the students causing an arterial laceration during the cannulation process. One team successfully initiated VA ECMO but lacerated the second femoral vein and was unable to transition to V-AV ECMO. The mean total lab time (from start to finish) was 145±23 minutes (95% CI 121 to 163 minutes).

Secondary Outcomes

The procedure validation checklist had 92% inter-rater agreement across all items and teams and the confidence assessment showed good reliability (Cronbach's alpha = 0.90). All students showed an increase in confidence in completing ECMO tasks after the course. On average, their overall confidence scores improved from pre-test (17.3±10.8) to post-test (57.6±18.1; mean difference 40.3, 95% CI 35.6 to 45.0). The proportion of students rating themselves as "competent" or better significantly improved for each item on the confidence assessment after the accelerated course (Table 3); these post-course competency rates ranged from 47% (initiation of ECMO in a critical patient in a deployed setting) to 85% (initiation of IV anticoagulation). Nearly all students (33/34, 97%) improved their knowledge assessment scores after completing the course. Their overall knowledge assessment scores improved from pre-test (64.7±11.1) to post-test (85.9±8.7; mean difference 21.2, 95% CI 16.5 to 25.8).

All 15 teams who successfully initiated ECMO could troubleshoot ECMO complications (Table 4). These complications included loss of circuit integrity, loss of power, venous air, arterial air, and access insufficiency. In those 15 animals successfully placed on ECMO, ABG values and vital signs remained stable (Table 5).

Discussion

We found that following a brief one-day lecture and live-tissue hands-on ECMO training course, most emergency medicine and critical care physicians and nurses successfully initiated ECMO on a swine model. All student teams were successful at setting up and priming the ECMO circuit and troubleshooting common ECMO complications. To the best of our

knowledge, our study is the first to evaluate the capability of a brief (less than one day) ECMO course to training emergency medicine and critical care physicians and nurses in the basics of initiating ECMO and troubleshooting ECMO complications. The expansion of similar training to emergency department and intensive care unit staff may allow for the initiation of life-saving ECMO therapy for those patients with potentially reversible causes of cardiogenic shock and pulmonary failure, with the eventual transfer of care to an advanced ECMO team.

Our study also demonstrates a significant improvement in students' confidence of comfort level. However, the level of confidence was below 80% in nine of the ten categories measured (Table 3). In addition, two of the student teams were unable to initiate VA ECMO and one team was unable to transition from VA to V-AV ECMO. While more confidence and a higher success rate is ideal for most procedures, ECMO is a therapy reserved for those patients who are unlikely to survive without it. In a case series of eight cardiopulmonary collapse patients placed on ECMO by emergency physicians and admitted to the hospital, five survived to hospital discharge neurologically intact.(4) Given the neurologically intact survival rate in cardiac arrest patients failing ACLS is near zero percent, an 80% ECMO initiation success rate may result in clinically significant outcomes.

All 3 critical failures occurred due to laceration of a central vessel. In each of these cases, the physician created a false tract using the dilator or when placing the catheter. In each of these cases this was due to advancing the wire and the dilator or catheter simultaneously. When this occurs, the wire fails to guide the dilator/catheter and instead the dilator/catheter can advance the wire to and undesired location damaging the central vessel. This is a known complication of large bore central vessel catheterization. When this occurs in a clinical setting, vessel repair may be performed by a vascular surgeon; however, fatalities have occurred. While wire control and avoiding the simultaneous advancement of the wire and dilator was emphasized during the hands-on training, three of the seventeen teams still made this error. While ECMO cannulation is commonly performed by vascular surgeons and other surgical specialties, Conrad et al demonstrated than non-surgeons treating in ECMO and with sufficient ECMO experience have similar success rates compared to surgeons.(15) Further training and practicing of the skill may improve skill performance and this will be emphasized and tested in our subsequent study.

A significant proportion of the US population lacks geographic access to ECMO facilities and the majority of cardiac arrests are treated at facilities without ECMO.(16) While ECMO transport teams exist and the number of ECMO centers has increased significantly, some patients may benefit from the initiation of ECMO by emergency and critical care clinicians before transfer to advanced ECMO teams. Within US military operations the ability to deploy an ECMO team throughout global theater of operations exists. However, activating and transporting this team of highly trained individuals to the patient can take thirty or more hours. Those critically ill patients requiring ECMO are at high risk for clinically decompensating or dying during this critical time.(9,10) Therefore, ECMO training protocols similar to ours, in addition to skills maintenance and practice, may allow for the ability of physicians and nurses who do not currently perform ECMO to initiate this viable treatment modality in patients that may not otherwise survive.

Our plan is to train clinicians using ECMO simulation mannequins and then test them using a live swine model. Our expectation is that this lecture and mannequin based course could be utilized in military and civilian hospitals throughout the country. Preparing emergency room clinicians to recognize the time-sensitive need to for ECMO therapy and to initiate and maintain therapy until the ECMO specialty team arrives and assumes care could have potential lifesaving outcomes.

Our follow-on study will evaluate the use of the same audiovisual lectures and checklists in combination with mannequin-based hands-on training instead of a live-tissue training model. The mannequin will also permit the students to practice cannulation multiple times (something the live-tissue model did not provide). We hypothesize that in increased practice will increase cannulation wire control, decrease damage to the central arteries and veins, and improve student confidence in performing this challenging procedure.

Limitations

Our study has several limitations. First, given the logistical and ethical issues of performing training and testing on humans, we used an animal model as a substitute; however, there are significant similarities in swine and human anatomy. While the femoral vessels in swine are more tortuous, this likely makes performing cannulation on swine more challenging than on humans. Extrapolation of our findings to other institutions may be limited given most institutions do not have live-tissue training labs. Our follow-on study will use lecture and mannequin-based training with testing on live swine, to determine if a mannequin-based course is sufficient. Additionally, the testing of the students occurred immediately following the hands-on training. It is unclear how long following the training the students would remain proficient and what skills maintenance training is required. However, the audiovisual lectures were intentionally developed with the plan to post them online for viewing by interested physicians and nurses as necessary. The hands-on portion of the training took less than two hours and could be incorporated into graduate medical education or faculty education programs. Finally, our training was focused on training individuals to initiate ECMO and was not designed to prepare students to maintain and wean ECMO therapy since those are tasks that would likely be transitioned to an inpatient ECMO team at an advanced care hospital.

Conclusions

We developed an abbreviated one-day ECMO course that resulted in an improvement of emergency and critical care physicians' and nurses' confidence and knowledge assessments. Following the training, 88% of teams successfully initiated VA ECMO therapy and 82% successfully initiated V-AV ECMO.

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Table 1. Student characteristics

Variable	Total sample (n=34)	Physicians only (n=17)	Nurses only (n=17)
Time in position			
<1 year	5 (15%)	5 (29%)	0 (0%)
1-5 years	15 (44%)	10 (59%)	5 (29%)
6-10 years	10 (29%)	1 (6%)	9 (53%)
>10 years	4 (12%)	1 (6%)	3 (18%)
Department			
ED	20 (59%)	16 (94%)	4 (24%)
ICU	14 (41%)	1 (6%)	13 (76%)
Time in department			
<1 year	4 (12%)	2 (12%)	2 (12%)
1-5 years	22 (65%)	12 (71%)	10 (59%)
6-10 years	6 (18%)	2 (12%)	4 (24%)
>10 years	2 (6%)	1 (6%)	1 (6%)
Work experience caring for ECMO patient(s)			
None	20 (59%)	8 (47%)	12 (71%)
1-10 hours	7 (21%)	5 (29%)	2 (12%)
11-35 hours	4 (12%)	3 (18%)	1 (6%)
>36 hours	3 (9%)	1 (6%)	2 (12%)
Formal ECMO training experience			
None	34 (100%)	17 (100%)	17 (100%)
Other training			
Advanced trauma life support (mannequin lab)	18 (53%)	15 (88%)	3 (18%)
Advanced trauma life support (animal lab)	10 (29%)	9 (53%)	1 (6%)
Pediatric advanced life support	28 (82%)	16 (94%)	12 (71%)
Neonatal resuscitation program	19 (56%)	15 (88%)	4 (24%)
Emergency war surgery course	5 (15%)	2 (12%)	3 (18%)
Swine procedure lab or research	5 (15%)	5 (29%)	0 (0%)
Other emergency medicine procedure lab	5 (15%)	5 (29%)	0 (0%)

Values given are count (column percentages).

Table 2. Team characteristics and results of ECMO simulation

Team ID	Time in position, years		Department		Time in department, years		Work experience with ECMO patients, hours		Successfully primed ECMO circuit?	Time to prime circuit, minutes	Successfully initiated VA ECMO?	Successfully transitioned to VAV ECMO?	Time to ECMO initiation, minutes	Total lab time, minutes	Notes
	PHYS	RN	PHYS	RN	PHYS	RN	PHYS	RN							
1	<1 (A)	8	ED	ICU	3	8	0	1-10	Yes	-	Yes (VV)	Yes	-	-	Did not use timer
2	3 (R)	9	ED	ICU	3	5	11-35	0	Yes	27	Yes	Yes	64	147	
3	<1 (A)	3	ED	ICU	3.3	11	1-10	0	Yes	43	Yes	Yes	86	163	
4	2 (A)	5	ED	ICU	5	4	0	≥36	Yes	35	No	-	-	-	Fatal arterial laceration
5	5 (A)	4	ED	ED	8	<1	0	0	Yes	37	Yes	Yes	125	185	
6	11 (A)	8	ED	ICU	14	5	0	0	Yes	30	Yes	Yes	72	167	
7	<1 (A)	5	ED	ICU	<1	4	1-10	0	Yes	43	No	-	-	-	Fatal arterial laceration
8	3 (R)	6	ED	ICU	3	3	1-10	0	Yes	26	Yes	Yes	37	117	
9	2 (A)	1	ED	ICU	6	<1	0	0	Yes	29	Yes	Yes	61	147	
10	2 (A)	12	ED	ICU	5	6	0	≥36	Yes	32	Yes	Yes	37	121	
11	2.5 (R)	10	ED	ICU	2.5	5	1-10	0	Yes	28	Yes	Yes	51	135	
12	1 (A)	9	ED	ED	4	9	0	0	Yes	33	Yes	Yes	54	157	
13	<1 (F)	13	ICU	ICU	<1	10	≥36	0	Yes	35	Yes	Yes	49	158	
14	3 (R)	9	ED	ICU	3	4	0	0	Yes	24	Yes	Yes	39	119	
15	<1 (A)	6	ED	ICU	4	3	11-35	11-35	Yes	31	Yes	Yes	81	172	
16	7 (A)	4	ED	ED	1	4	1-10	1-10	Yes	25	Yes	No	40	141	Lacerated femoral vein in transition
17	3 (R)	6	ED	ED	3	2	11-35	0	Yes	24	Yes	Yes	33	107	

PHYS, physician; RN, registered nurse; A, attending; R, resident; F, fellow; ED, emergency department; ICU, intensive care unit; VA, venoarterial; VV, venovenous; VAV, veno-arterial-venous.

Table 3. Proportion of students rating themselves as "competent" or better on the confidence assessment

Question	Pre-test	Post-test	Percent difference/ increase (95% CI)
1. Determining which patients would benefit from ECMO	6 (18%)	21 (62%)	44% (27% to 62%)
2. Initiation of IV anticoagulation	18 (53%)	29 (85%)	32% (16% to 49%)
3. Placement of percutaneous cannula using Seldinger technique	13 (38%)	21 (62%)	24% (9% to 39%)
4. Preparing cannulas for connection to ECMO circuit	0 (0%)	23 (68%)	68% (51% to 84%)
5. Connecting patient to ECMO circuit	0 (0%)	21 (62%)	62% (45% to 79%)
6. Securing cannulas	5 (15%)	24 (71%)	56% (36% to 75%)
7. Achieving respiratory and hemodynamic goals	12 (35%)	27 (79%)	44% (25% to 64%)
8. Maintaining ECMO during patient transport	0 (0%)	17 (50%)	50% (32% to 68%)
9. Troubleshooting and managing issues with circuit/equipment	0 (0%)	19 (56%)	56% (38% to 73%)
10. Initiation of ECMO in a critical patient in a deployed setting	0 (0%)	16 (47%)	47% (29% to 65%)

On the assessment, "competent" is defined as "able to mostly recognize and complete the skillset or problem using my own judgment and able to achieve most tasks without additional input."
Values given are counts (percentages out of n=34).

Table 4. Results of troubleshooting complications

Complication	Teams successful	Time to troubleshoot complications
Loss of circuit integrity	15 (88%)	5:00 (2:47-5:46)
Loss of power	15 (88%)	3:26 (2:42-3:43)
Venous air	15 (88%)	4:30 (2:34-5:44)
Arterial air	15 (88%)	4:19 (3:23-5:52)
Chatter/excessive blood flow turbulence	15 (88%)	1:08 (1:03-2:49)

Values given are n (percentages out of n=17) or median time in minutes:seconds (interquartile range).

Table 5. ABGs and vitals for swine at baseline, ECMO initiation, and end of lab

Variable	Baseline	ECMO Initiation	End of Lab
Labs/ABGs			
pH	7.47 (7.44-7.49)	7.51 (7.47-7.55)	7.32 (7.23-7.41)
pH*	7.46 (7.43-7.48)	7.51 (7.47-7.55)	7.33 (7.24-7.42)
pCO_2	41.58 (39.42-43.74)	35.45 (31.68-39.22)	45.84 (40.68-51.00)
pCO_2*	42.97 (40.47-45.47)	35.92 (31.96-39.88)	45.04 (39.80-50.29)
pO_2	206.77 (160.33-253.21)	219.35 (159.61-279.09)	254.32 (141.65-366.98)
pO_2*	210.41 (164.26-256.56)	220.58 (161.14-280.02)	251.92 (140.87-362.96)
cK^+	3.86 (3.63-4.10)	3.93 (3.74-4.11)	4.33 (3.64-5.03)
cNa^+	140.94 (139.66-142.22)	139.40 (138.03-140.77)	140.33 (138.87-141.80)
cCa^{2+}	1.25 (1.21-1.29)	1.23 (1.18-1.28)	2.06 (0.29-3.83)
cCl^-	103.35 (102.13-104.57)	104.27 (102.69-105.84)	107.17 (104.94-109.40)
cGLu	73.82 (63.54-84.10)	74.00 (65.24-82.76)	91.58 (66.74-116.42)
cLac	1.24 (1.04-1.43)	2.21 (1.75-2.66)	4.57 (2.84-6.30)
p50e	24.94 (24.30-25.58)	23.61 (22.56-24.65)	29.13 (26.33-31.92)
cBase(Ecf)c	5.79 (4.60-6.99)	4.86 (3.55-6.17)	-1.72 (-6.18-2.75)
$cHCO_3$-(P,st)e	29.62 (28.49-30.75)	29.32 (28.09-30.55)	22.78 (18.92-26.63)
tHb	9.41 (8.89-9.93)	9.15 (8.61-9.68)	10.94 (10.14-11.74)
O_2Hb	96.63 (96.10-97.16)	96.31 (95.34-97.28)	94.06 (90.88-97.23)
COHb	0.91 (0.41-1.41)	1.17 (0.34-1.99)	2.62 (-0.56-5.80)
MetHb	1.14 (0.79-1.50)	1.21 (0.79-1.63)	1.16 (0.64-1.69)
O_2Ct	12.45 (11.45-13.44)	12.44 (10.83-14.05)	13.70 (12.86-14.54)
Vitals			
HR	88.65 (83.05-94.24)	106.60 (90.19-123.01)	111.21 (95.70-126.73)
SBP	85.71 (77.82-93.59)	84.73 (75.39-94.08)	66.38 (54.16-78.60)
DBP	54.82 (48.21-61.44)	59.33 (53.72-64.95)	37.58 (31.14-44.03)
SPO_2	98.76 (97.70-99.83)	98.27 (96.41-100.12)	94.77 (91.39-98.14)
Temp	37.56 (37.26-37.87)	37.56 (37.17-37.94)	36.88 (36.40-37.36)
RR	12.24 (10.54-13.93)	12.33 (10.35-14.32)	10.79 (9.77-11.80)
ECO_2	43.88 (42.20-45.57)	37.60 (32.94-42.26)	37.50 (30.22-44.78)
Pven	-	-36.77 (-48.14- -25.40)	-99.55 (-129.80- -69.30)
Part	-	168.31 (143.81-192.81)	115.09 (99.50-130.68)
Pint	-	180.58 (153.93-207.24)	119.45 (92.67-146.24)
RPM	-	2685.00 (2545.98-2824.02)	2869.09 (2668.77-3069.41)
LPM	-	180.62 (-204.81-566.06)	24.82 (-23.49-73.13)

Values given are mean (95% CI).
*Values are temperature-adjusted.