Simulating Extracorporeal Membrane Oxygenation Emergencies to Improve Human Performance. Part I: Methodologic and Technologic Innovations

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Background: Extracorporeal membrane oxygenation (ECMO) is a form of long-term cardiopulmonary bypass used to treat infants, children, and adults with respiratory and/or cardiac failure despite maximal medical therapy. Mechanical emergencies on extracorporeal membrane oxygenation (ECMO) have an associated mortality of 25%. Thus, acquiring and maintaining the technical, behavioral, and critical thinking skills necessary to manage ECMO emergencies is essential to patient survival. Traditional training in ECMO management is primarily didactic in nature and usually complemented with varying degrees of hands-on training using a water-filled ECMO circuit. These traditional training methods do not provide an opportunity for trainees to recognize and interpret real-time clinical cues generated by human patients and their monitoring equipment. Adult learners are most likely to acquire such skills in an active learning environment. To provide authentic, intensive, interactive ECMO training without risk to real patients, we used methodologies pioneered by the aerospace industry and our experience developing a simulation-based training program in neonatal resuscitation to develop a similar simulation-based training program in ECMO crisis management, ECMO Sim.

Methods: A survey was conducted at the 19th Annual Children's National Medical Center ECMO Symposium to determine current methods for ECMO training. Using commercially available technology, we linked a neonatal manikin with a standard neonatal ECMO circuit primed with artificial blood. Both the manikin and circuit were placed in a simulated neonatal intensive care unit environment equipped with remotely controlled monitors, real medical equipment and human colleagues. Twenty-five healthcare professionals, all of whom care for patients on ECMO and who underwent traditional ECMO training in the prior year, participated in a series of simulated ECMO emergencies. At the conclusion of the program, subjects completed a questionnaire qualitatively comparing ECMO Sim with their previous traditional ECMO training experience. The amount of time spent engaged in active and passive activities during both ECMO Sim and traditional ECMO training was quantified by review of videotape of each program.

Results: Hospitals currently use lectures, multiple-choice exams, water drills, and animal laboratory testing for their ECMO training. Modification of the circuit allowed for physiologically appropriate circuit pressures (both pre- and postoxygenator) to be achieved while circulating artificial blood continuously through the circuit and manikin. Realistic changes in vital signs on the bedside monitor and fluctuations in the mixed venous oxygen saturation monitor were also effectively achieved remotely. All subjects rated the realism of the scenarios as good or excellent and described ECMO Sim as more effective than traditional ECMO training. They reported that ECMO Sim engaged their intellect to a greater degree and better developed their technical, behavioral, and critical thinking skills. Active learning (eg, hands-on activities) comprised 78% of the total ECMO Sim program compared with 14% for traditional ECMO training ($P < 0.001$). Instructor-led lectures predominated in traditional ECMO training.

Conclusion: Traditional ECMO training programs have yet to incorporate simulation-based methodology. Using current technology it is possible to realistically simulate in real-time the clinical cues (visual, auditory, and tactile) generated by a patient on ECMO. ECMO Sim as a training program provides more opportunities for active learning than traditional training programs in ECMO management and is overwhelmingly preferred by the experienced healthcare professionals serving as subjects in this study. Subjects also indicated that they felt that the acquisition of key cognitive, technical, and behavioral skills and transfer of those skills to the real medical domain was better achieved during simulation-based training.

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ECMO is a form of long-term cardiopulmonary bypass used to treat infants, children, and adults with respiratory and/or cardiac failure despite maximal medical therapy. More than 24,000 patients have been treated with ECMO since its inception over 20 years ago.[1] When managed appropriately, ECMO offers life-saving therapy for patients who would otherwise not survive. ECMO is considered a high-risk pro-

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cedure and technical emergencies on ECMO are associated with a mortality rate of 25%.[1] To date training in the management of potentially life-threatening ECMO emergencies has relied on traditional didactic educational models combined with some type of hands-on practical exercise usually involving a liquid-filled circuit.[2] These teaching strategies overemphasize cognitive skills, underemphasize technical skills, and completely ignore behavioral skills. Trainees are expected to apply the information gathered from didactic instruction and isolated skills stations in an integrated manner when managing real ECMO emergencies.

Human error is one of the leading causes of life-threatening events in high-risk industries such as aviation, the military, and healthcare.[3] The aviation industry developed the principles of Crew Resource Management (CRM) more than 3 decades ago to standardize the manner in which pilots manage emergencies and to reduce pilot error by improving teamwork in the cockpit.[4] There are three primary components that describe effective crew management: safety, efficiency, and morale. Striving to reduce error through CRM occurs on three levels known as the "error *troika*": avoiding error, catching an error before it is committed, and mitigating consequences of errors.[5] In the medical industry, physicians, nurses, and allied health care personnel are expected to make rapid and appropriate decisions in critical situations despite a lack of practical experience. Adapting CRM principles to train medical personnel in dynamic technical, behavioral, and decision-making skills has the potential to mitigate errors in human performance that contribute to adverse patient outcomes, especially in high-risk areas like emergency departments, operating rooms, and intensive care units.

The publication of the Institute of Medicine's report "To Err is Human" led to a national directive to improve patient safety.[6] As a consequence, medical educators have begun to scrutinize the effectiveness of current training methodologies. Educational theory states that adults are more likely to benefit from an active learning environment, yet much of the training in medicine is lecture-based and passive in nature.[7] Acquisition and maintenance of skills are best attained in environments displaying high fidelity to the real working environment.[8] Such training environments incorporate as many visual, auditory, and tactile cues as possible. There are few realistic ECMO training models available and those that exist are expensive (animal models) and/or are used in isolation from the patient (water-filled circuits). We set out to design a highly realistic simulation-based training program in the management of ECMO emergencies that incorporates both the ECMO circuit and the patient. This program is called ECMO Sim.

METHODS

Survey

A survey was developed to determine the current ECMO training practices. A convenience sample was surveyed at the 19th Annual Children's National Medical Center ECMO Symposium using a questionnaire; response rates were tabulated on those surveys returned. The participants were asked to identify their institution and to circle all forms of training used over the past year in their center. Possible methods of training were derived from recommendations from the Extracorporeal Life Support Organization (ELSO) manual and included lectures, water drills, animal laboratory tests, and multiple-choice examinations. We also added a box for simulation with patient manikins to determine whether any group was using simulation in this fashion. Participants could select more than one training method. The surveys were distributed to all attendees; responses were recorded in a confidential fashion and placed in a drop box at the end of the 5-day conference.

Setting

The resources at the Center for Advanced Pediatric Education (CAPE) at Lucile Packard Children's Hospital at Stanford University were used to simulate the physical environment of a neonatal intensive care unit (NICU) (Fig. 1). The simulator room is equipped with functioning medical equipment including a radiant warmer, ventilator, wall suction and gas sources, fully-stocked neonatal and ECMO code carts, and a functional ECMO circuit. Bedside patient monitors, controlled remotely from behind a one-way mirror by handheld computers (Patient Monitor Driver [PMD], Advanced Medical Simulation, Inc., Binghamton, NY), provide information on the infant's vital signs. Changes in vital signs can be entered into the handheld device and register on the bedside monitor as a progressive change over 10 seconds. The traditional ECMO training program was conducted by Lucile Packard Children's Hospital (LPCH) ECMO program staff in the hospital. All ECMO Sim programs were conducted by instructors at CAPE at LPCH at Stanford University in Palo Alto, California. The instructors at CAPE who populate the simulator room include neonatologists, neonatal fellows, neonatal nurse practitioners, and neonatal nurses, all of whom have undergone specialized training in simulation education at Stanford University. All instructors are skilled in creating the human interactions, stressful conditions, and complex environmental cues that exist in a real NICU.

FIGURE 1. The ECMO Sim physical environment at the Center for Advanced Pediatric Education.

Manikin Modification

A neonatal manikin (NRB-1000, Medical Plastics Laboratory, Gatesville, TX) was used to simulate a neonate. The manikin approximates a full-term newborn in size and weight. It possesses a realistic airway that can be intubated, lungs that can be inflated with positive pressure ventilation, and an umbilical cord with one vein and two arteries that can be cannulated. We inserted a 12-Fr arterial and a 14-Fr venous ECMO cannula (Medtronic/Bio-Medicus, Eden Prairie, MN) into the manikin at the right neck and sutured them in place (Fig. 2). The cannulae were connected to one another end-to-end by 8 inches of 0.25-inch Tygon (Norton Performance Plastics Corporation, Akron, OH) tubing, ensuring that all ports on the cannulae were covered. All connections were tie-banded to prevent air entrainment. The circuit tubing was then placed inside the hollow abdominal cavity of the manikin. Within this 8 inches of tubing, a T-connector was spliced and connected to 28 inches of anesthesia tubing that exits the back of the manikin and therefore is hidden from the view of the subjects (Fig. 3). The manikin was intubated with 4.0 cuffed endotracheal tube connected to a ventilator. Replacing the manikin's artificial lungs with balloons of various sizes and elasticity resulted in measurable changes in lung compliance as reported by bedside pressure-volume monitoring, realistically simulating neonatal pulmonary disease. Umbilical arterial and venous catheters were placed in the artificial umbilical stump on the manikin's anterior abdominal wall and intravenous fluids were delivered via infusion pumps into a reservoir within the abdominal cavity. A 12-Fr chest tube was placed in the left thorax and connected to a wall suction evacuation system, simulating ongoing evacuation of a pneumothorax.

Circuit Modification

The ECMO circuit was comprised of the following components connected with 0.25-inch Tygon tubing: a bladder box (OriGen Biomedical, Inc., Austin, TX), roller head pump (Stockert S3 ECMO System, COBE Cardiovascular, Inc., Arvada, CO), oxygenator (Medtronic, Inc., Minneapolis, MN), heat exchanger (CSZ ECMO, Cincinnati Sub-Zero Products, Inc., Cincinnati, OH), and raceway of 0.25-inch Super Tygon tubing (Norton Performance Plastics Corporation, Akron, OH). The circuit was connected to the manikin via the cannulae as described previously. In place of a mixed venous oxygen saturation monitor, we used a pulse oximeter (model NPB-298, Nellcor, Pleasanton, CA) controlled remotely by a PMD. The oxygen saturation monitor was programmed to read a mixed oxygen saturation of 80% at the beginning of each scenario and adjusted in real time in response to the clinical condition of the simulated patient. To create artificial blood we added 15 mL of blue food coloring and 45 mL of red food coloring to the circuit after it was primed with saline. Circuit pressures appropriate for venoarterial ECMO (preoxygenator pressures of approximately 260 mm Hg and postoxygenator pressures of approximately 197 mm Hg) were achieved by adjusting the occlusion of the pump's roller heads. Anesthesia tubing was spliced into the circuit within the abdominal wall of the manikin via a 0.25-inch to 0.25-inch T-connector. This tubing exited the back of the manikin, hidden from view by the bedding, and traveled through a small porthole into the control room behind the one-way mirror. A 30-mL syringe connected to this tubing with a three-way stopcock allowed for the remote addition of air and removal or addition of fluid.

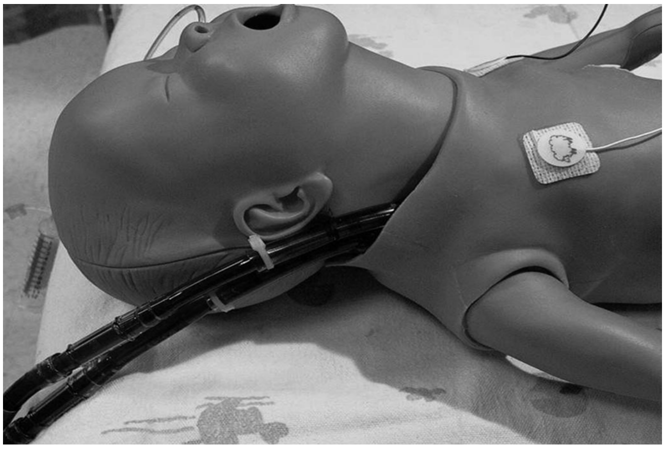

FIGURE 2. ECMO cannula entering the manikin's thoracic cavity, prior to suturing.

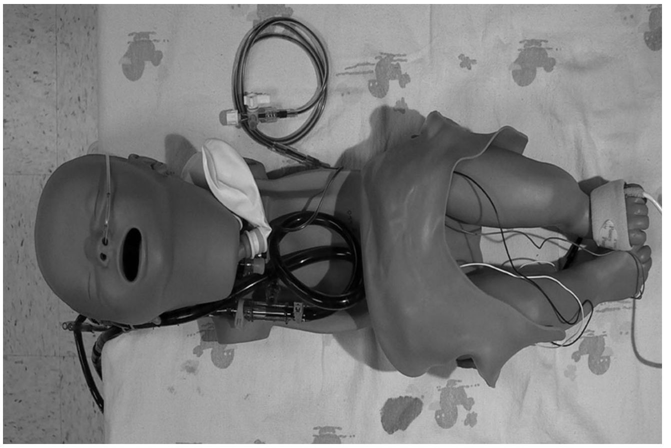

FIGURE 3. Anterior view of the intracorporeal circuit within the thoracic cavity. The white balloon represents the left lung (right lung removed to allow better visualization of the circuit). The cannulae were connected to one another end-to-end by 8 inches of 0.25-inch Tygon tubing.

Simulated Emergencies

By remotely controlling the patient's bedside monitor, the mixed venous oxygen saturation monitor, and the modified ECMO circuit, we were able to simulate multiple ECMO emergencies including hypertension, hypotension, cardiac stun, tachycardia, cardiac tamponade, pneumothorax, acute hypoxemia, air entrainment, decannulation, a clot in the oxygenator, and raceway rupture (Table 1). Because there is no standard calibration of ECMO circuits, we manually adjusted the pressure control display to imply differential pressure across the membrane oxygenator as follows. We set the display screen to "temporary reading" mode, causing the

TABLE 1. ECMO Directions for Simulating ECMO Emergencies

Emergency	Changes Made in Circuit	Changes Made to Monitor
Oxygenator clot; V-V ECMO	Before the scenario: Set internal pump alarm at 450 mm Hg. Manually increase preoxygenator pressure to 350 mm Hg and decrease postoxygenator pressure to 100mm Hg. 2 minutes into the scenario add 50 ml of artificial blood to the circuit via the anesthesia tubing in the control room.	Before the scenario set vital signs for normal newborn on ECMO (HR 135, RR 14, O_2 Sat 96%, MAP 42). 3 minutes into the scenario, the pump will cut out as it senses the excessive preoxygenator pressure. When the pump alarms, increase the HR (150), decrease the O_2 Sat (86%), and decrease the MAP (30).
Hypovolemia;V-V ECMO	Remove 50-100 ml artificial blood (or until bladder collapses and box alarms) from the circuit 2 minutes into the scenario.	Before the scenario set vital signs for normal newborn on ECMO (HR 135, RR 14, O_2 Sat 96%, MAP 42). As the artificial blood is being drawn off the circuit, increase the HR (155), decrease the MAP (34). Continue altering the vitals until the subject responds by giving a bolus of fluid.
Air entrainment;V-A ECMO	Add 20 ml air to the circuit via the anesthesia tubing 2 minutes into the scenario. Continue to add 20 ml aliquots of air until the subject detects decannulation.	Before the scenario set vital signs for normal newborn on ECMO (HR 135, RR 14, O2 Sat 96%, MAP 42). The air will enter on the venous side of the pump and take approximately 45 seconds to reach the patient. The vital signs will remain normal unless the subject stops the pump (decrease HR, decrease, O2Sat, decrease MAP) or until the air enters arterial catheter (decrease HR, decrease MAP).

ECMO, extracorporeal membrane oxygenation; HR, hazard ratio; RR, relative risk; MAP, mean arterial pressure.

circuit to detect the true pressure across the membrane. We then manually increased or decreased the pressure reading using the up and down arrow keys. Once the desired pressure reading was achieved, the display screen was "set," displaying this artificial pressure and effectively allowing creation of high, normal, or low readings and a number of challenging clinical scenarios. For example, a clot in the oxygenator is simulated by increasing the preoxygenator pressure and decreasing the postoxygenator pressure. Adding 50 mL of artificial blood to the circuit increased the pre- and postoxygenator pressures to levels that would set off the preset alarms. Removing 50 mL of artificial blood caused the bladder to collapse and the bladder box to alarm. Adding 20 mL of air to the circuit simulated air entrainment (as from inadvertent decannulation). To enhance the realism of the scenarios, the simulated NICU was populated with CAPE instructors playing the roles of parents and health care professionals.

Traditional Training Program in ECMO

The traditional training program at Stanford is conducted over 2 days and is led by RNs and MDs with varying degrees of experience in ECMO. Trainees receive an ECMO manual assembled by the ECMO coordinator at the beginning of the training session. Day 1 is comprised of seven 55-minute lectures given back to back with a break for lunch. Didactic instruction includes information on hemodynamics, cannula placement, physiology, anatomy of the circuit, and usage of blood products. There is a take-home multiple choice examination given at the conclusion of day one. Day 2 is divided into two 4-hour sessions and the trainees are divided between the two sessions. In each session, the trainees sit in a semicircle around a saline primed circuit while the ECMO Coordinator describes and demonstrates potential problems that can arise on ECMO. The trainees are encouraged to verbally and physically participate in problem solving.

The ECMO Sim Program

ECMO Sim is a full-day training program designed to allow the hands-on management of ECMO emergencies in an environment that poses no risk to patients. Because trainees may be unfamiliar with high-fidelity simulation-based training, an extensive orientation is conducted at the beginning of each ECMO Sim program. This orientation includes a brief (approximately 15 minutes) lecture describing simulation-based training, an interactive review of videotaped examples of crisis management in nonmedical professions, and a detailed hands-on familiarization to all of the physical components of the ECMO simulator. Once this familiarization is complete, trainees actively participate in scenarios designed to simulate real ECMO emergencies. The typical scenario lasts approximately 15 to 30 minutes. All of the events that occur during the scenarios are captured on videotape for playback during interactive debriefings that are facilitated by simulator instructors and occur immediately following each scenario. Debriefings typically last 2 to 3 times the length of the accompanying scenario. Debriefings are conducted in a separate room outside the ECMO simulator so that any emotional or intellectual distress lingering from the scenario is minimized. As many as six scenarios and debriefings may be conducted in a single training program.

Subjects

This study was approved by the Administrative Panels on Human Subjects at Stanford University and written informed consent was obtained from all subjects. A convenience sample of 25 physicians and nurses who actively care for patients on ECMO in the LPCH NICU and who have

TABLE 2. Subject Demographics

Subject	Total	MD	RN
Number of subjects participating	25	7 (28%)	18 (72%)
Years of experience as care provider* (mean ± SD)	3-29 y	12 ± 9.5	15 ± 11.2
Years of ECMO experience (mean ± SD)	1-20 y	6 ± 4.4 y	8 ± 6.8 y
N from Stanford (%)	64 (16/25)	0 (0%)	16 (89%)
Average length of time (months) since subjects' most recent traditional training experience in ECMO (mean ± SD)	4 ± 3.5	6 ± 0	3 ± 1.2

*Care provider to imply years since completion of nursing residency or pediatric residency.

participated in traditional ECMO training attended one of four full-day ECMO Sim training programs.

Qualitative/Quantitative Analysis

Upon completion of the program, subjects were asked, via written questionnaire, to evaluate the components of ECMO Sim using a 5-point Likert scale (1 = poor to 5 = excellent) and to compare their simulation-based training experience with traditional ECMO training. The questionnaire was modified from an existing questionnaire used in the NeoSim program.[9] The mean score for each question was calculated and comparisons were made between the total score for the ECMO Sim course versus the total score for the traditional course using a Student *t* test.

During a 1-year period, one traditional ECMO training course and two ECMO Sim courses were videotaped in entirety and analysis was performed comparing features of the two courses. The videotapes were evaluated by a single, outside reviewer who watched each video twice. The first analysis of each videotape measured time (with a stopwatch) spent in lecture (passive learning activity), and the second analysis measured time spent in hands-on activity (active learning). For both courses, all lecture activity when all the trainees were silently listening was considered passive learning time. Anytime the trainees were involved in discussion (questions, responses, debriefings) or physically interacting with the circuit was measured as active learning time. The results were compared using Student *t* test.

Statistical Analysis

Statistical analysis was performed using SAS for Windows, Version 8 (SAS Institute, Cary, NC).

RESULTS

Survey

Forty-nine surveys were returned, representing 32 different ECMO centers. All centers reported using lectures for training. Water drills (normal saline pumped through a circuit in a closed loop) were used for training in 88% (28/32) of the centers. Fifty-three percent (17/32) of the centers used multiple-choice examinations, and 16% (5/32) used an animal laboratory (an animal was cannulated and placed on the ECMO pump).

None of the surveys reported the use of simulation with a patient manikin for training.

Demographics

Study subjects possessed between 1 and 20 years of clinical ECMO experience (Table 2). The majority were registered nurses from Packard Children's Hospital who had recently undergone traditional ECMO training. In the year prior to the study, Packard Children's Hospital had 12 patients on ECMO for a total of 93 ECMO days and each subject had more than 8 hours of ECMO patient care per 8 weeks throughout the year. The remaining subjects (comprising 36% of the study population) were from an outside institution.

Analysis

All (100%) of the subjects rated the realism of the scenarios and the ability of the instructors to simulate real life roles as good or excellent (Table 3). Open-ended questions elicited commentary that confirmed the realism of the scenarios and the perceived value of the program (Table 4). Feedback from subjects indicates an overwhelming preference for the simulation-based methodology over more traditional training strategies. Using a 5-point Likert scale (1 = poor to 5 = excellent), participants were more likely to describe ECMO Sim as more relevant to their practice than traditional training, mean (± standard deviation), [5.0 (± 0.0) versus 3.1 (± 0.6)] (Table 5). They also scored the ECMO Sim significantly higher on its ability to develop their technical skills [4.8 (± 0.5) versus 2.6 (± 0.7) and on building their confidence in handling ECMO emergencies, [4.9 (± 0.4) versus 2.9 (± 0.6). Moreover they stated that the transfer of these important skills to the real environment was more effectively accomplished via ECMO Sim than traditional training. Overall, ECMO Sim rated significantly higher on the Likert scale than the traditional training course [44.4 ± 0.5 versus 25.6 ± 0.7 ($P < 0.001$)].

All ECMO training courses conducted during the year of the study (one traditional training course and two ECMO Sim courses) were analyzed. The average number of trainees in each ECMO Sim training program was 10; this compares with 37 trainees in the traditional ECMO program. The length of the ECMO Sim program was 7 hours 55 minutes, whereas the traditional ECMO course took 14 hours 50 minutes. Trainees in the ECMO Sim program spent significantly more time practicing ECMO skills than trainees in the traditional course, mean (percentage of total course time), (± standard deviation) [370.5 minutes (78%) ± 14.4 versus 146.6 minutes (14%); $P < 0.001$]. The amount of time spent by

TABLE 3. ECMO Sim Evaluation (n = 25)

	Poor or Suboptimal (%)	Adequate (%)	Good (%)	Excellent (%)
Physical space				
Realism of the simulator	0	12	8	80
Temperature in the simulator	12	8	80	0
Lighting in the simulator	0	28	48	24
Acoustics in the simulator	0	8	44	48
Equipment				
General layout of the simulator	0	16	80	4
Patient monitors	0	16	12	72
Code cart	12	8	80	0
Medication supply	0	16	40	44
Neonatal manikin	0	2	68	4
Scenarios				
Realism of the scenarios	0	4	16	80
Ability of the scenarios to test technical skills	0	0	48	52
Ability of the scenarios to test behavioral skills	0	0	24	76
Overall quality of the scenarios	0	4	20	76
Debriefings				
Ability of the debriefing to clarify issues	0	0	20	80
Ability of the debriefings to allow feedback	0	0	4	96
Ability of the debriefings to address technical skills	0	0	20	80
Ability of the debriefings to address behavioral skills	0	0	0	100
Overall quality of the debriefings	0	0	4	96
Instructors				
Ability of instructors to simulate real-life roles	0	0	20	80
Enthusiasm of instructors	0	0	0	100
Ability of instructors to create a positive environment	0	0	0	100
Overall quality of instructors	0	0	0	100

TABLE 4. Mean Rating (+ SD) of ECMO Sim and Traditional ECMO Training as Scored on a 5-point Likert Scale (1 = Poor to 5 = Excellent)

Question	ECMO Sim	Traditional ECMO Training	*P* Value*
Relevance to my practice in the hospital	5.0 + 0.0	3.1 + 0.6	
Ability to engage my intellect	5.0 + 0.0	3.6 + 0.7	
Ability to develop my behavioral skills	4.9 + 0.4	2.6 + 0.7	
Ability to transfer learned behavioral skills to the real environment	4.9 + 0.5	2.5 + 0.8	
Ability to develop my technical skills	4.8 + 0.5	2.6 + 0.7	
Ability to transfer learned technical skills to the real environment	4.9 + 0.4	2.4 + 0.5	
Ability to develop my critical thinking skills	5.0 + 0.0	3.0 + 0.9	
Ability to transfer learned critical thinking skills to the real environment	5.0 + 0.0	2.9 + 0.7	
Builds my confidence in handling ECMO emergencies	4.9 + 0.4	2.9 + 0.6	
Total score	44.4 ± 0.5 (4.93 ± 0.07)	25.6 ± 0.7 (2.84 ± 0.37)	<0.001

**P* value based on Student's *t* test.

instructors speaking or demonstrating procedures during the traditional ECMO training program was 47 times that of the time spent by trainees asking questions, otherwise speaking or practicing procedures. This is significantly different than the ratio determined for the ECMO Sim training program where the amount of time spent by instructors speaking was only 2.5 times that of the trainee.

DISCUSSION

Simulators have long been used to train professionals in complex, technical, high-risk industries such as aerospace, nuclear power and the military.[10] With the advent of human patient simulators capable of providing key visual, auditory and tactile physiologic cues, simulation-based medical training programs were first developed in adult anesthesia[11] and

TABLE 5. Percentage of Total Course Time Spent in Different Activities in ECMO Sim and Traditional ECMO Training

Activity	ECMO Sim	Traditional ECMO Training	*P* Value*
Active learning (eg, hands-on)	78%	14%	<0.001
Passive learning (eg, lecture)	22%	86%	<0.001

**P* value determined using a Student's *t* test,

more recently in critical care,[12] neonatology,[9] and obstetrics.[13] To the best of our knowledge, this work represents the first simulation-based training program in the management of ECMO emergencies in either pediatric or adult patient populations.

The key to simulation-based training is achieving "suspension of disbelief" (ie, a sense of realism) in trainees. This is accomplished by creating a training environment that has high fidelity to the real environment—in other words, it provides the important visual, auditory and tactile cues to trainees. Using commercially available materials, we were able to realistically simulate the conditions present when a human neonate is on ECMO. This is summarized in Table 3. In their responses to structured and open-ended questions, subjects described the simulated ECMO emergencies as highly realistic, indicating that they effectively suspended their disbelief.

One of the reasons simulation-based training programs like ECMO Sim appeal to trainees is because they provide significantly more active learning experiences than traditional training experiences. This characteristic aligns simulation-based training with the tenets of adult learning as outlined by Bloom.[14] Adult learners are independent, self-directed, internally motivated to learn, seek immediate application of their knowledge and use their accumulated experience to craft their own ongoing intellectual development. Adult learners perform better when they can apply new knowledge and use past experiences to solve problems. Simulation-based training provides them with these opportunities. Cognitive learning theory argues that learning does not automatically occur with the transfer of information from an instructor to a learner. A learner must process and apply the information to learn.[14,15] By giving trainees more time to talk and participate in discussions, ECMO Sim allows this learning to occur. Traditional training tends to overemphasize the role of the instructor via lectures and proctored skills stations where trainees often practice procedures in an assembly line fashion. In contrast, ECMO Sim emphasizes the *learning* environment as opposed to the *teaching* environment and by its design encourages trainees to actively participate in their own education.

Each component of the ECMO Sim training program is designed to enhance the learning experience for the adult trainee as described in the peer-reviewed adult education literature.

This qualitative study of simulation-based ECMO training does have limitations. The subjects in this study were volunteers and may have had an underlying interest in simulation-based training; this could have positively influenced their performance and biased their evaluation of the program. These subjects may have entered the study with a preference for experiential learning methodologies and thus were predisposed to receive benefits (either real or perceived) from participation in simulation-based training exercises. Some of the subjects work in the same NICU as the investigators and professional or personal relationships could also have influenced their perceptions of the fidelity of the training environment. Despite being highly rated by the subjects in this study the neonatal manikin used to simulate the patient on ECMO lacks physiologic authenticity: it does not have spontaneous auscultable breath sounds, heart tones, or palpable pulses nor does it change color to indicate hypoxemia. Because of this trainees may have difficulty in detecting important changes in the simulated patient's physiologic state. We were able to overcome this limitation by driving the readouts on a bedside monitor and using these as surrogates for important cues normally detected by examining the patient; however it could be argued that this may actually reinforce an inappropriate reliance on data obtained from monitors rather than the patient. In addition to the patient simulator other elements of the physical environment such as working medical equipment and human colleagues are necessary to allow realistic simulation of ECMO crises; replication of our results therefore requires ready access to such equipment (as well as the ability to control its function) and trained confederates to create the appropriate environmental cues for trainees.

CONCLUSION

A key to effective medical simulation-based training is the creation of a learning environment that has high fidelity to the real clinical environment. This is accomplished by providing enough of the key visual, auditory and tactile cues to allow trainees to "suspend disbelief" and perform as they would in real life. Feedback obtained from the subjects in this study, all of whom were experienced ECMO specialists, indicates that realistic simulation of ECMO emergencies is possible using currently available medical technologies and validated educational methodologies.

High-fidelity simulation-based medical training offers many advantages over traditional training methodologies. Simulators are controlled settings in which multiple intense clinical scenarios, tailored to the experience level of the trainee, can be conducted in a scheduled manner. Trainees must actively demonstrate technical and behavioral skills rather than simply talk their way through theoretical clinical situations. The use of videotape to document the actions, words and nonverbal communication of the trainees provides an objective, time-coded record and compelling stimulus for learning during facilitated debriefings. Finally, simulation-based training poses no risk to real patients, allowing trainees to safely make and learn from mistakes.

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