Simulating Extracorporeal Membrane Oxygenation Emergencies to Improve Human Performance. Part II: Assessment of Technical and Behavioral Skills

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Background: Healthcare professionals are expected to make rapid, correct decisions in critical situations despite what may be a lack of real practical experience in a particular crisis situation. Successful resolution of a medical crisis depends upon demonstration not only of appropriate technical skills but also of key behavioral skills (eg, leadership, communication, and teamwork). We have developed a hands-on, high fidelity, simulation-based training program (ECMO Sim) to provide healthcare professionals with the opportunity to learn and practice the technical and behavioral skills necessary to manage ECMO emergencies.

Methods: Nine ECMO nurse specialists participated in two sequential randomly assigned simulated ECMO emergencies. The simulated emergencies were captured on videotape and reviewed with the subjects during facilitated debriefings that occurred immediately following each scenario. All videotapes were scored for key technical and behavioral skills by reviewers blinded to the sequence of the scenarios. The ratings of the subjects' technical and behavioral skills in each scenario were compared.

Results: Subjects performed key technical skills correctly more often in the second simulated ECMO emergency. In addition, their response times for three out of five specific technical tasks improved from the first to the second simulated emergency by an average of 27 seconds. Subjects' behavioral skills were rated more highly by masked reviewers in the second simulated ECMO emergency. The improvement in comprehensive behavioral scores from the first to the second scenario reached statistical significance in eight of nine subjects.

Conclusion: After exposure to high-fidelity simulated ECMO emergencies, subjects demonstrated significant improvements in their technical and behavioral skills. ECMO Sim creates a learning environment that readily supports the acquisition of the technical and behavioral skills that are important in solving clinically significant, potentially life-threatening problems that can occur when patients are on ECMO.

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Historically, preparing health care professionals to handle life-threatening emergencies has involved review of pertinent literature, participation in standardized training programs (eg, the Neonatal Resuscitation Program [NRP] of the American Academy of Pediatrics), and assumption of graduated responsibility during immersion into real clinical crises, a process termed by some to be "education by random opportunity."[1–3] The problem with this approach is that healthcare professionals may not learn how to appropriately manage a particular type of medical crisis until faced with the reality of having another human being's life literally in their hands.

Extracorporeal membrane oxygenation (ECMO) is a form of long-term cardiopulmonary bypass and is one of the most intense and technologically complex therapies offered in medicine. Management of ECMO emergencies requires the quick and decisive application of content knowledge as well as technical and behavioral skills to solve the multitude of problems that may arise when a critically ill patient requiring ECMO is in crisis.

ECMO Sim is an immersive simulation-based training program designed to teach the technical and behavioral skills necessary to successfully manage life-threatening crises on ECMO (Table 1). We sought to objectively evaluate the effectiveness of this training program (Table 2).

METHODS

Setting

This study was conducted at the Center for Advanced Pediatric Education (CAPE) at Lucile Packard Children's Hospital (LPCH) at Stanford University in Palo Alto, California. The details of ECMO Sim have been previously described.[4] In brief, the ECMO Sim simulator physically resembles an authentic NICU with real, functioning medical equipment and human colleagues who act as confederates during the training. Inside this physical space is placed a neonatal manikin linked to a standard neonatal ECMO circuit

TABLE 1. Selected Technical Skills Necessary for Successful Management of ECMO Emergencies

Disengage patient from circuit if problem lies within the circuit
Clamp venous cannula above the bridge
Clamp bridge
Clamp arterial cannula above the bridge
Turn the pump flow to OFF (0 L/min)
Remove the oxygen source from the circuit once off of ECMO
Troubleshoot the underlying problem (identify the source of air or bleeding)
Assess the patient
Increase ventilator support when SaO_2's fall
Bag-mask ventilate if necessary
Behavioral skills necessary for successful management of ECMO emergencies
Know the environment
Anticipate and plan
Assume a leadership role
Communicate effectively
Distribute the workload optimally
Allocate attention wisely
Utilize all available resources
Utilize all available information
Call for help early enough
Maintain professional behavior

primed with artificial blood. Physiologically appropriate pressures (both pre- and postoxygenator) are achieved while circulating artificial blood continuously through the circuit and manikin. Realistic changes in vital signs and mixed venous oxygen saturation are made with remotely controlled monitors.

Subjects

This prospective, pre- and postintervention 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 nine consecutive ECMO specialists was chosen. Prior to enrolment in the study, subjects were told only that we were evaluating ECMO skills; the methods of evaluation were not revealed. All subjects were nurses in the LPCH NICU and were considered ECMO "specialists" as they had undergone traditional ECMO training (lectures and water drills) within the month prior to their participation in the study. They also had participated in a simulation-based neonatal resuscitation training course at CAPE sometime in the preceding 3 months. Subjects were randomized as to the order of their simulated ECMO emergencies (air entrainment and inadvertent decannulation with blood loss) and they were unaware of the details of the simulated emergencies prior to entering the simulator.

Intervention

The ECMO Sim training program begins with a detailed orientation, including a brief lecture describing simulation-based training, videotape review of examples of the behavioral and technical skills necessary for successful crisis management in nonmedical domains, and a detailed hands-on familiarization to all of the physical components of the ECMO simulator. Each subject then participated in his/her first randomly assigned simulated ECMO emergency. The subject's performance was videotaped and immediately reviewed during a debriefing facilitated by CAPE instructors possessing clinical ECMO expertise. Each subject then participated in a second simulated ECMO emergency; this simulation was also videotaped and a second facilitated debriefing was held.

Video Analysis of Technical Skills

The videotapes of the simulated ECMO emergencies were reviewed by four CAPE instructors (not authors) with expertise in simulation and ECMO training. All reviewers were blinded to the sequence of the simulated emergencies.

The following three technical skills were evaluated using a 2-point (yes-no) scoring tool:

1. Searching for and identifying of the source of the problem (air entrainment or inadvertent decannulation with bleeding) 2. Using the correct sequence of steps to isolate the patient from the ECMO circuit
   a. Clamping the venous side above the bridge that unites the venous and arterial sides of the circuit
   b. Unclamping the bridge
   c. Clamping the arterial side above the bridge
3. Removing the oxygen source from the ECMO circuit once the patient is off of ECMO

These skills were chosen because they are deemed to be critically important by experienced ECMO clinicians for the successful resolution of ECMO crises. The percentage of subjects performing each technical skill correctly was calculated for scenario 1 (predebriefing) and scenario 2 (postdebriefing).

TABLE 2. Technical Performance Markers II: Time Required for Successful Performance Pre- and Postsimulation/Debriefing (Mean Time, in Seconds ± SD)

Technical Skill	Simulation 1 (Predebriefing)	Simulation 2 (Postdebriefing)	Gain	*P* value*
Coming off ECMO once emergency recognized	50.8 + 72.6	13.5 + 13.4	−37.3 + 62.3	0.11
Removing the oxygen source from the circuit once off ECMO	34.9 + 35.4 (n = 6)	14.0 + 18.7 (n = 8)	−17.1 + 45.3 (n = 5)	0.11
Increasing the ventilator settings once off ECMO	50.7 + 58.1	25.0 + 16.9	−25.7 + 50.5	0.17

*Based on paired *t* test.

Using a stopwatch, response times were measured for the following tasks:

1. Calling for back-up assistance (a physician) once an emergency is recognized
2. Separating the patient from the ecmo circuit once an emergency is recognized
3. Once the patient is off of ECMO:
   a. Calling for a respiratory therapist
   b. Adjusting the ventilator settings
   c. Removing the oxygen tubing from the circuit.

The mean time for each task was calculated for each scenario and compared using paired *t* tests.

Video Analysis of Behavioral Skills

A tool was created to score the behavioral performance based on a group of local experts (Fig. 1). Consensus was achieved regarding the important outcome measures. The tool was piloted until scorers could reliably achieve the same score. Four outside reviewers were trained to review the videotapes; all four reviewers independently reviewed each tape, and all reviewers were blinded to whether the tape was pre- or postintervention. Interrater reliability between the reviewers was calculated with a correlation coefficient. The internal consistency of the tool was measured by Cronbach's alpha. A 5-point Likert scale (Fig. 1) was used. Subjects were rated on 10 different behavioral items on a scale of 1 (poor) to 5 (excellent) for a possible total score of 50 points. The subjects' scores were compared between scenarios using paired *t* tests. Although each individual value of a Likert scale is technically ordinal data, the summed score can be treated as interval data, provided the scale item has at least five categories.[5,6]

KNOW YOUR ENVIRONMENT		
Seems confused in the environment, unfamiliar with the circuit, unable to find clamps and/or syringes	1 2 3 4 5	Recognizes the circuit alarms, quickly finds and uses the clamps
ANTICIPATE AND PLAN FOR CRISES		
Seems slow to anticipate problems, slow to recognize the need for respiratory support once off bypass	1 2 3 4 5	Anticipates the plan, when off bypass promptly recognizes the need for respiratory support
ASSUME A LEADERSHIP ROLE		
Seems timid and unable to take control of the situation	1 2 3 4 5	Assumes a leadership role, \takes charge of the crisis
COMMUNICATE EFFECTIVELY		
Mumbles, speaks quietly, gives open air commands; is unable to explain the problem to the incoming personnel	1 2 3 4 5	Communicates effectively, gives clear, concise, well directed commands; is able to quickly explain the problem to the incoming personnel
DISTRIBUTE WORKLOAD OPTIMALLY		
Gets pulled away from the pump, does not assign tasks, gets distracted with menial tasks	1 2 3 4 5	Distributes the workload optimally, is not the phone caller when should be the pump nurse, gives the bedside nurse a job, assigns a job to the RT
ALLOCATE ATTENTION WISELY		
Gets distracted by the patient and pump alarms, is unable to troubleshoot the problem with the pump	1 2 3 4 5	Allocates his or her attention wisely, focuses on the pump and the patient, is not distracted by alarms or panicking personnel
UTILIZE ALL AVAILABLE INFORMATION		
Ignores the provided history (patient moving or pump bumped), doesn't listen to bedside nurse	1 2 3 4 5	Utilizes all available information, including the history and the changing information provided by the patient and the pump
UTILIZE ALL AVAILABLE RESOURCES		
Ignores other personnel, doesn't elicit help from the team.	1 2 3 4 5	Utilizes all available resources, including the other members of the team.
CALL FOR HELP EARLY ENOUGH		
Doesn't call for help in a timely manner, doesn't make use of all available resources	1 2 3 4 5	Uses all resources; calls for help early, asks for the RT, the ECMO doctor, the surgeon
MAINTAIN PROFESSIONAL BEHAVIOR		
Behaves inappropriately or unprofessionally	1 2 3 4 5	Maintains professional behavior, uses appropriate terminology

FIGURE 1. Scoring tool for behavioral markers of performance.

Statistical Analysis

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

RESULTS

Demographics

All nine subjects had RN degrees, possessing 1 to 13 years of ECMO experience. The mean age was 32 years (range 26 to 44 years) and all subjects worked in the Neonatal Intensive Care Unit at Packard Children's Hospital. Eighty-nine percent (8/9) were female. They averaged 8 years of neonatal nursing experience (range 1 to 17 years). Each subject had more than 8 hours of ECMO patient care per 8 weeks throughout the year prior to the study. In the year prior to the study, Packard Children's Hospital had 12 patients on ECMO for a total of 93 ECMO days.

Technical Skills

Subjects made numerous technical errors in their first simulated ECMO emergency (Fig. 2) compared with the second. The mean time elapsed between when an action was needed until when it was completed decreased after the intervention, but did not achieve statistical significance (Table 3). For example, the mean ($\pm$ standard deviation) time to coming off ECMO once an emergency was recognized decreased from 50.8 ($\pm$ 72.6) seconds versus 13.5 ($\pm$ 13.4)

Expected performance = 100%.

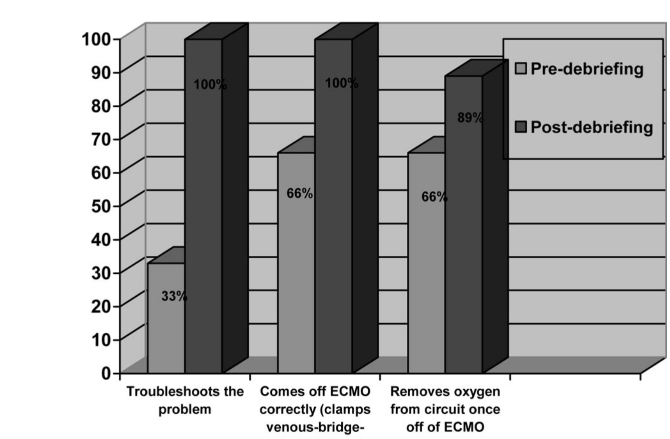

FIGURE 2. Technical performance markers I: Frequency of successful performance pre- and postsimulation/debriefing. Expected performance = 100%.

TABLE 3. Behavioral Performance Markers: Cumulative Ratings Pre- and Postintervention

Subject	Simulation 1	Simulation 2	Gain	*P* value
1	48.5 (±1.9)	50.0 (±0.0)	1.5 (±1.6)	
2	27.3 (±1.5)	42.0 (±2.5)	14.8 (±1.3)	
3	34.8 (±2.6)	47.8 (±1.9)	13.0 (±1.2)	
4	25.3 (±2.2)	41.3 (±3.0)	16.0 (±5.0)	
5	19.8 (±3.9)	39.3 (±1.7)	19.5 (±5.2)	
6	31.3 (±2.5)	43.8 (±2.2)	12.5 (±3.0)	
7	14.0 (±1.4)	39.8 (±2.6)	25.8 (±1.9)	
8	38.5 (±2.7)	47.8 (±2.2)	9.3 (±4.4)	
9	20.3 (±2.7)	42.5 (±3.3)	22.3 (±5.6)	
Total	259.8 28.8 (±10.5)	394.3 43.8 (±4.2)	14.9 (±7.6)	<0.001

P value based on paired *t* test. Ten behavioral markers were rated on a Likert scale of 1 to 5; best possible score = 50.

seconds ($P = 0.11$). The mean time to removing the oxygenator from the circuit once off ECMO decreased from 34.9 (± 35.4) seconds versus 14.0 (±18.7) seconds ($P = 0.11$), and the mean time to increasing the ventilator settings once off ECMO decreased from 50.7 (± 58.1) seconds versus 25 (± 16.9) seconds ($P = 0.17$).

Behavioral Skills

The behavioral scoring tool (Fig. 1) had an internal consistency as measured by Cronbach's alpha of 0.93; a modified version of this tool has been validated in two other unpublished studies with Cronbach's alpha measuring 0.97 and 0.91 (Judy LeFlore, unpublished data, 2006; JoDee M. Anderson, unpublished data, 2004). The interrater reliability of the scoring tool was calculated at 0.96. Subjects' behavioral skills improved between the two scenarios (Table 3).

DISCUSSION

Subjects in this study demonstrated clinically significant improvements in their technical skills and statistically significant improvement in their behavioral skills after exposure to high-fidelity simulation of ECMO emergencies. This indicates that ECMO Sim is a valid training program that produces improvements in the technical and behavioral skills of ECMO specialists.

Human performance degrades in the face of significant stress. Studies have shown that in a relaxed environment, clinicians can choose the correct medication off the shelf 99.9% of the time, but with a "blue" patient on the floor, the error rate may be as high as 25% in performing the same task.[7] All of the subjects in this study had prior recent exposure to traditional training in ECMO emergency management and actively care for patients on ECMO at their home institution; yet a sizable percentage of these experienced ECMO specialists either failed to perform a critical technical task during their first emergency or required a prolonged period of time before accomplishing such a task. For example, only two-thirds of subjects responded correctly to the need to disconnect the patient from the ECMO circuit when circumstances dictated that this was necessary in the first simulated ECMO emergency. Although the differences in performance were not statistically significant, the fact that these subjects failed to perform critical tasks despite recent exposure to traditional training programs in ECMO management is concerning and raises serious questions about the efficacy of traditional training methodologies in preparing healthcare professionals to manage those rare but life-threatening emergencies that can and do occur. Any training experience, when it occurs in isolation from real clinical conditions (changing patient physiology, increasing time pressure, etc.), is limited in its ability to achieve optimal acquisition of important cognitive, technical and behavioral skills by trainees.

Analysis of the time taken by subjects to perform critical tasks was interesting but limited by our small sample size. Subjects in their first simulated ECMO emergency took an average of 50.8 seconds to disconnect the patient from the ECMO circuit once they recognized that an emergency condition, such as the presence of an air embolus in the circuit, existed. Subjects reduced this time to an average of 13.5 seconds during the second simulation. Depending on the rotations-per-minute (RPMs), an air embolus on the venous side of the pump would reach the patient in our simulated circuit within 30 seconds; there are a number of factors that determine how quickly the air embolus will traverse the oxygenator. We were unable to detect statistically significant time maneuvers due to our small sample size; with a sample size of 9, assuming alpha 0.05, and a standard deviation of ± 50 seconds pre and post intervention, we had 80% power to detect a difference of 53 seconds. The significance of the apparent improvement in behavioral response should be regarded with caution, as the wide range of values, the very large standard deviation, and the very small sample size limit the usefulness of this information. In addition, only a portion of the learners actually completed some of the tasks, this is a significant limitation given the sample size. Clinically, subjects reported being better prepared after ECMO Sim than after the traditional training; it would be interesting to determine whether this sense of preparedness results in statistically significant improvements in response times with a larger sample size. For many ECMO emergencies (air entrainment), faster response times may result in better clinical outcomes.

Traditional medical education and training focuses primarily on cognitive and technical skills; very little attention is paid to the development of effective behavioral skills. It was first identified in the aviation industry and later noticed in medicine that human behavior is a potential source of catastrophic errors.[8–10] Behavioral skills are an important component of the ECMO Sim training program. In regard to our use of a paired *t* test to compare behavioral scores, which assumes interval data, with ordinal Likert scale items, in a recent review of the literature on this topic, Jaccard and Wan summarize, "for many statistical tests, rather severe departures (from intervalness) do not seem to affect Type I and Type II errors dramatically."[5,6] All but one of the nine subjects showed statistically significant improvement in behavioral skill acquisition after participation in one simulated emergency and facilitated debriefing. Subjects' communication during their initial scenarios was often inappropriate and ineffective, resulting in an inability to coherently and concisely summarize pertinent data, use of thin-air commands (orders not directed to specific targets) and the spread of confusion among team members. Presented with the opportunity to watch their performance on videotape and speak in a confidential and frank manner with their colleagues during constructive debriefings about what went well and what did not go well during the initial simulated emergency, subjects were able to recognize shortcomings and correct them in the subsequent simulation. Many experts in education argue that this type of self-realization encourages deeper learning.[11]

This study was designed to determine if the technical and behavioral skills necessary for effective resolution of medical crises can be acquired via high fidelity simulation-based training. This is a short-term outcome study and no effort was made to determine the rate of skill degradation or extinction. Studies have shown that skills learned in traditional resuscitation courses degrade over 3 to 6 months[12] and our data demonstrate a similar trend for traditional ECMO training. One may argue that the subjects may have performed poorly during their initial simulated emergency because they were unfamiliar with either the simulation-based methodology employed or with the physical environment itself. However most of the subjects had recently participated in a similar simulation-based training program in neonatal resuscitation, giving them familiarity with both the methodology and the simulator environment. All subjects underwent an extensive familiarization (prior to participation in any simulated emergencies) on the day of the study, during which they were introduced to all elements of the physical environment. It may also be hypothesized that subjects suffered from "stage fright" and were intimidated by the realism and intensity of the initial simulated emergency; once this initial performance anxiety abated they were able to perform at a higher level. Indeed, we have observed and others have described a type of "immunization effect" where repeated exposure to critical incidents acts to blunt the emotional response to such events. However, it seems unlikely that a single exposure (during the first simulated emergency) is sufficient to produce this effect; the improved performance in technical and behavioral skills seen in this study is more likely due to other factors. Knowledge that one's performance is being recorded on videotape for review by peers may also have an influence on that performance. Yet we have been told on numerous occasions by trainees that they are unaware of the presence of cameras once they enter the simulator and "suspend their disbelief" as they attempt to resolve the simulated crisis unfolding before them. In addition, the cameras at CAPE are mounted on the ceiling under opaque acrylic domes and the microphones are hung from the ceiling (not the subjects' clothing). All of the recording technology used in this study was therefore unobtrusive and nearly invisible to those in the simulator. All subjects, instructors, and investigators in this study were required to sign written agreements stating that all discussion of a subject's performance will be kept strictly confidential. Finally, all of the subjects in this study were volunteers and there is no way to disprove that this cohort of volunteers may have perceived a lack of ECMO emergency experience on their part and therefore represented a sample of subjects prone to making more mistakes. Nevertheless, even if this was true, the improvement in performance noted in these subjects argues for the validity of the training methodology.

Although we did not evaluate performance during crises involving real patients on ECMO, it is our belief that events witnessed during simulated emergencies may be predictive of performance in the actual clinical environment with real human patients. Although the gold standard of any education/training intervention remains assessment of the effect on patient outcome, we feel that the use of skill acquisition as a proxy is a reasonable intermediate step in evaluation.

CONCLUSION

ECMO is a classic low-volume, high-risk procedure. The number of patients requiring EMCO support is declining yearly and those requiring support are the "sickest of the sick." As the need for ECMO diminishes, the opportunity to gain actual clinical experience in the management of life-threatening ECMO emergencies also decreases. Thus it is imperative to find effective methods of acquiring and maintaining the skills necessary for successful resolution of ECMO crises. ECMO Sim creates a learning environment that readily supports the acquisition of the cognitive, technical, and behavioral skills that are vital in solving clinically significant, potentially life-threatening problems that occur when patients are on ECMO. To our knowledge, this work represents the first time that high fidelity simulation-based training has been applied to ECMO and is one of the few examples of the use of this methodology in the pediatric sciences.

REFERENCES

1. Schull MJ, Ferris LE, Tu JV, et al. Problems for clinical judgement: 3. Thinking clearly in an emergency. *CMAJ* 2001;164:1170–1175.
2. Allen SS, Bland CJ, Harris IB, et al. Structured clinical teaching strategy. *Med Teach* 1991;13:177–184.
3. Halamek LP, Kaegi DM, Gaba DM, et al. Time for a new teaching paradigm in pediatric medical education: teaching neonatal resuscitation in a simulated delivery room environment. *Pediatrics* 2000;106:E45.
4. Anderson JM, Boyle K, Murphy AA, Halamek LP. Toward a new standard in extracorporeal membrane oxygenation (ECMO) training. *Pediatr Res* 2003;53:99A.
5. Jaccard J, Wan CK. LISREL approaches to interaction effects in multiple regression.Thousand Oaks, CA: Sage Publications; 1996.
6. Kim JO. Multivariate analysis of ordinal variables. *Am J Sociol* 1975; 81:261–298.
7. DeVita MA, Schaefer J, Lutz J, et al. Improving medical crisis team performance. *Crit Care Med* 2004;32(2 Suppl):S61–S65.
8. Helmreich RL, Merritt AC, Wilhelm JA. The evolution of Crew Resource Management training in commercial aviation. *Int J Aviat Psychol* 1999; 9:19–32.
9. Sexton JB, Thomas EJ, Helmreich RL. Error, stress, and teamwork in medicine and aviation: cross sectional surveys. *BMJ* 2000; 320:745–749.
10. Benner P. Creating a culture of safety and improvement: A key to reducing medical error. *Am J Crit Care* 2001; 10:281–284.
11. Knowles MS, Holton E, Swanson R. The Adult Learner. Houston: Gulf Publishing Company, 1998.
12. Chamberlain D, Smith A, Woollard M, et al. Trials of teaching methods in basic life support (3): Comparison of simulated CPR performance after first training and at 6 months, with a note on the value of re-training. *Resuscitation* 2002; 53:179–187.