

Technique Article

Development of the Orpheus Perfusion Simulator for Use in High-fidelity Extracorporeal Membrane Oxygenation Simulation

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Abstract: Despite its life-sustaining potential, extracorporeal membrane oxygenation (ECMO) remains a complex treatment modality for which close teamwork is imperative with a high risk of adverse events leading to significant morbidity and mortality. The provision of adequate training and continuing education is key in mitigating these risks. Traditional training for ECMO has relied predominantly on didactic education and hands-on water drills. These methods may overemphasize cognitive skills while underemphasizing technical skills and completely ignoring team and human factor skills. These water drills are often static, lacking the time pressure, typical alarms, and a sense of urgency inherent to actual critical ECMO scenarios. Simulation-based training provides an opportunity for

staff to develop and maintain technical proficiency in high-risk, infrequent events without fear of harming patients. In addition, it provides opportunities for interdisciplinary training and improved communication and teamwork among team members (1). Although simulation has become widely accepted for training of practitioners from many disciplines, there are currently, to our knowledge, no commercially available dedicated high-fidelity ECMO simulators. Our article describes the modification of the Orpheus Perfusion Simulator and its incorporation into a fully immersive, high-fidelity, point-of-care ECMO simulation model. **Keywords:** simulation, ECMO (extracorporeal membrane oxygenation), patient safety, pediatric, circulatory assistance, temporary. *JECT. 2012;44:250–255*

Extracorporeal membrane oxygenation (ECMO) is a modified form of cardiopulmonary bypass used to provide prolonged tissue oxygen delivery in patients with respiratory and/or cardiac failure. It has become an accepted therapeutic modality for neonates, children, and adults with cardiac and/or respiratory insufficiency secondary to potentially reversible disease processes, which have failed conventional therapy. Despite its life-sustaining potential, ECMO remains a complex treatment modality with high

risk of adverse events leading to significant morbidity and mortality. The quoted mortality rate in ECMO-related adverse events is as high as 25% (1). The Extracorporeal Life Support Organization (ELSO) has set out guidelines for training and continuing education of ECMO specialists along with guidelines for ECMO center standards (2).

There are, however, a number of centers that, despite not being recognized ECMO referral centers, still offer postcardiotomy salvage ECMO. For these centers there are a number of issues that can make the safe provision of ECMO difficult. Non-ECMO referral centers typically experience far fewer ECMO runs than a referral center, leading to the inevitable deterioration of the whole teams skill levels and expertise. In the absence of a fully immersive, high-fidelity ECMO simulation model, current practice is for nurses and other staff to be seconded to

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ECMO centers for short periods of time to gain hands-on experience. Obtaining funding for such secondments has become increasingly difficult in the current financial climate and although staff gain hands-on experience in the day-to-day care and maintenance of the ECMO circuit, they seldom get to manage adverse events during these attachments. For these reasons, the authors believe this model to be suboptimal and unfit for purpose. It risks failure to prepare staff for the competent management of adverse events, leading to further increase in risk of patient harm as a result of errors and adverse events. Given that the most common contributory factors for these errors and adverse events are poor interdisciplinary communication and teamwork, to increase patient safety, the optimal educational model needs to facilitate the prevention and management of adverse events while reflecting both the social team-oriented and cognitive individual-oriented aspects of human factors.

With the emergence of new technologies, simulation has become widely accepted in the training of practitioners in many fields including delivering training in human factors and team management (3–5). Although wet laboratories can be used cost-effectively to provide deliberative practice with achievement of competence in technical skills such as setting up an ECMO circuit and component change-out, they do not reproduce patient management issues or elucidate the human factors and team management elements associated with delivery of ECMO care.

Although there are some software-based ECMO programs aimed at individual cognitive technical skills training, for instance ECMOjo (Telehealth Research Institute, John A. Burns School of Medicine of the University of Hawaii) and MSE adult perfusion simulator (MSE [Australia] PL), to our knowledge, there are currently no commercially available ECMO simulators suitable for the delivery of fully immersive high-fidelity simulation (6,7). A few groups have described the incorporation of ECMO simulation models into critical event simulation training. Current described models incorporate a mannequin with a modified ECMO circuit displaying patient parameters through simulation software platforms, e.g., SimBaby (Laerdal Medical Limited, Orpington, Kent, UK) leading to a disconnect between the patient parameters, as displayed on the patient monitoring, and those displayed on the ECMO console, leading to poor contextual reality for candidates (5,8).

The Orpheus perfusion simulator (Ulco Technologies, Marrickville, NSW, Australia) is a high-fidelity perfusion simulation system fundamentally comprising a hydraulic simulator interfaced with a computer running associated real-time computerized models. Purposely designed for use with a standard heart–lung machine (HLM) and a standard cardiopulmonary bypass circuit consisting of an oxygenator and venous reservoir, to deliver training and continuing education to perfusionists, it was never

intended to deliver ECMO training using an ECMO circuit, which is a closed system (9).

In this article we describe how we modified the Orpheus Perfusion Simulator to allow its incorporation into a fully immersive, high-fidelity, point-of-care ECMO simulation model. Through creation of this model, we have been able to reproduce realistic ECMO parameters for all staff involved in a range of common patient management scenarios and a number of low-volume high-risk events they may experience during ECMO delivery, therefore allowing us to achieve our goal of delivering an optimal educational model that facilitates the prevention and management of adverse events while reflecting both the social team-oriented and cognitive individual-oriented aspects of human factors.

DESCRIPTION OF THE MODEL

The model comprises an Orpheus perfusion simulator with a modified resuscitation mannequin (simulated patient) incorporated between the hydraulic module of the Orpheus simulator and our standard ECMO system (Figure 1). We describe the adaptation of the elements of our fully immersive, high-fidelity, point-of-care ECMO simulation model to achieve optimal realism.

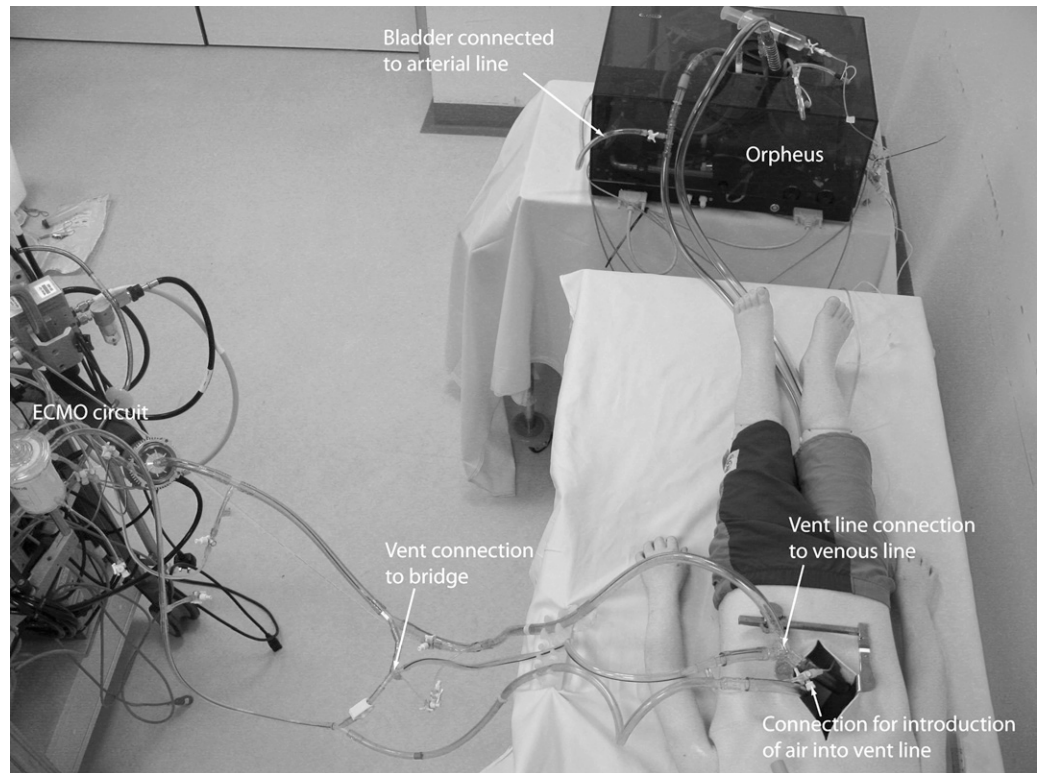
The Mannequin

We set out to modify a low-fidelity resuscitation mannequin, ResuciJunior (Laerdal, Norway) to optimize the contextual reality of our model. Our center delivers almost exclusively transthoracic ECMO in a setting of postcardiac surgery rescue ECMO. Our clinical care delivery model was taken into consideration during the design process of our simulated patient to ensure a high standard of technical reality was achieved. The modifications made to the mannequin were as follows: to allow realistic, undetected entry of the polyvinyl chloride (PVC) tubing from the Orpheus simulator into the ResuciJunior mannequin, we introduced holes into the underside of the mannequin. The chest plate was then modified to allow the tubing to exit and be connected to the ECMO circuitry. To allow intubation and ventilation of the mannequin, lungs were reconstructed and attached to the simulated patient's airway. The technical reality was further enhanced by moulage of the mannequin through the incorporation of an arterial line and central venous catheter. The central venous catheter model was designed to allow the administration of fluid boluses and drugs.

Hydraulic Module

The function of the hydraulic system of the Orpheus simulator is to replicate the physiological attributes of a patient's circulatory system. It is physiologically analogous to the capacitance of the venous system, the native heart,

Figure 1. The system is made up of the Orpheus perfusion simulator incorporating a modified resuscitation mannequin between the Hydraulic module of the Orpheus and the extracorporeal membrane oxygenation system.



and the arterial system programmed to behave according to the Frank-Starling relationship. When connected to a HLM with standard cardiopulmonary bypass configuration, the volume in the venous capacitance reservoir empties into the cardiotomy reservoir, reducing the venous pressure within the system. As soon as the hydraulic module detects a venous pressure below 1 mmHg, the simulator changes the model's native heart function from producing a pulsatile pressure to a constant head of pressure, thus providing systemic vascular resistance (SVR).

This change in venous pressure is difficult to achieve when combining the hydraulic system with an ECMO circuit because it is a closed system with no venous capacitance. In our model, we lower the venous pressure by incorporating a bladder into the arterial line of the simulator (Figure 1). This allows the volume of the hydraulic system to be manipulated by removing or adding volume to the model. Additionally, the pressure in the venous capacitance system can be adjusted as to simulate a patient being on full or partial ECMO support. Once on ECMO, the Orpheus simulator allows for some manipulation of cardiovascular models allowing for further adjustment of contractility and SVR. To connect our hydraulic module to our ECMO system, we incorporated $\frac{3}{8}$ " arterial and $\frac{1}{2}$ " venous PVC tubing, which were fed through holes made on the underside of the low-fidelity resuscitation mannequin.

Extracorporeal Membrane Oxygenation System

As per our standard clinical practice, an ECMO circuit consisting of a Levitronix Centrimag pump (Levitronix GmbH, Zurich, Switzerland), a Medos Hilite 2400LT membrane oxygenator (Medos Medizintechnik AG, Willkommen, Germany), and $\frac{3}{8}$ " \times $\frac{3}{8}$ " PVC tubing was connected to the relevant tubing in the mannequin's chest. As we wanted to model venoarterial (V-A) ECMO, we incorporated a left ventricular vent by inserting an extra $\frac{1}{4}$ " PCV tubing through a Y connector into the $\frac{1}{2}$ " venous line within the mannequin's chest. This left ventricular vent line was then connected back into the drainage line of the ECMO circuit as per normal practice in our institution (Figure 1).

The development of the model, described previously, we are able to achieve realistic age-specific circuit and patient parameters on commencement of ECMO (Table 1) and a combination of common adverse events and high-risk low-volume events.

Following the creation of a successful model, we set out to develop the model further to allow the simulation of a number of the most common clinical scenarios encountered while caring for a patient on ECMO and high-risk, low-volume adverse events. This would allow our team to train to excellence through deliberate practice of the management of these events. We created the simulated clinical

Table 1. Circuit and patient parameters while on extracorporeal membrane oxygenation.

Flow (LPM)	2.5–3.5
Centrifugal pump (RPM)	4000–6000
Inlet pressure (mmHg)	0 to –10
Preoxygenator pressure (mmHg)	140–180
Postoxygenator pressure (mmHg)	160–200
Arterial pressure (mmHg)	35–55
Central venous pressure (mmHg)	–4 to 10

scenarios by combining the existing programmed models in the Orpheus software with various interactions with the ECMO circuit (Table 2). Subsequently we have described some of the techniques used to achieve realism of these scenarios.

Simulated Clinical Scenarios

Circulating Volume Loss: Bleeding is a very common adverse event on initiation of ECMO, especially in the setting of postcardiotomy ECMO support. This requires the team to rapidly and effectively evaluate the patient and circuit parameters to correctly diagnose the problem and make the correct adjustment by administering volume to the patient.

We were able to simulate volume loss through two mechanisms. First, the Orpheus has the ability to lose volume into a separate reservoir or volume can be lost by removing it through the bladder; we attached to the arterial line at the outlet of the Orpheus simulator. The observed net effect of either of this was true to a real clinical event. As the circulating volume is lost from the system, the patient central venous pressure (CVP) reduces and eventually becomes negative. This leads to a cascade of events. The inlet pressures into the pump become more negative and the arterial flow is reduced despite increasing the pump revolutions per minute (RPM) leading to a reduced patient arterial blood pressure. Such realism was achieved that when the Levitronix RPM increased excessively, the CVP observed in the Orpheus system was low

enough for small amounts of air to be entrained, observed as cavitation. The administration of volume corrected all of these parameters.

Tamponade: Tamponade can be very common in trans-thoracic delivered V-A ECMO and is often confusing leading to its mismanagement. In this clinical scenario you would expect to observe similar parameters to the clinical scenario of the loss of circulating volume but with a raised patient CVP. In our model this was modeled by losing volume from the circuit; all the other parameters follow with changes as described in the circulating volume loss scenario. As the Orpheus produces the patient pressure monitoring, an increase in the observed patient CVP was easily manipulated. These changes allowed our scenario to achieve technical realism.

Oxygenator Failure: In our experience, oxygenators either fail quickly on initiation of ECMO as a result of a manufacturing fault or over time attributable to progressive deterioration in the oxygenation capacity of the membrane resulting from clot or protein buildup. In our scenario we model oxygenation failure resulting from clotting of the oxygenator. We restricted the arterial outlet from the Orpheus, which led to a cascade of events. The following changes were observed: an increase in both pre- and postmembrane pressures, decrease in pump flow, decrease in arterial pressures, and positive pump inlet and CVP. All of these changes are what one would expect to observe in a real-life clinical event apart from the postmembrane pressure, which should be reduced, thus increasing the transmembrane pressure gradient. A decrease in the postmembrane pressure was produced by a line connected into the pressure transducer at the level where it is measured on the Levitronix. The link was disguised and linked back to the operator at the Orpheus where it was manipulated to give the required decrease in postmembrane pressure.

Kinked Arterial Line: This scenario was simulated using the native Orpheus software to occlude the arterial line;

Table 2. Patient and circuit normal parameters and parameters after manipulation of the model.

	Normal	Loss of Circulating Volume	Tamponade	Oxygenator Failure Resulting from Clotting	Obstructed Arterial Line	Obstructed Venous Line
Centrifugal pump (RPM)	6000	6000	6000	6000	6000	6000
Flow (LPM)	3.5	3.0	3.0	2.0	1.0	1.0
Inlet pressure (mmHg)	–7	–20	–20	0	0	–30
Preoxygenator pressure (mmHg)	200	180	180	240	260	100
Postoxygenator pressure (mmHg)	180	160	160	100	250	90
Arterial pressure (mmHg)	60	50	50	30	20	20
Central venous pressure (mmHg)	10	2	10	10	11	11

however, more progressive constriction was achieved by partial clamping of the arterial outlet from Orpheus by the operator. All patient and circuit parameters follow with the same characteristics observed while on ECMO.

Obstructed Venous Line: Again this scenario was simulated using the native Orpheus software to achieve this in an acute manner. It is important to note that more progressive restriction of the venous line at the level of the Orpheus produces slower effects as observed with slow volume loss.

Air Entrainment: The Orpheus has the capability to allow air to be entrained into the venous line, simulating for example a cannula becoming loose. To entrain air specifically into the vent line rather than the venous line, we used a separate line as shown in Figure 1.

Other Capabilities: The Orpheus has a number of cardiovascular and physiological parameters that you are able to manipulate and incorporate into the previously described scenarios. For instance, changes in heart rate and electrocardiogram can be used to great effect in increasing realism of the scenario.

DISCUSSION

ECMO is a challenging clinical practice and patients requiring ECMO are often totally dependent on the mechanical life support. ELSO reports 18,044 incidents in 22,346 ECMO supports (10). Anderson et al. (1) report that those incidents have an associated mortality rate of 25%. Maintaining technical, behavioral, and critical thinking skills are essential for the timely management of ECMO emergencies, which in turn are critical for patient survival. Incorrect troubleshooting and diagnosis of basic patient management issues may exacerbate the clinical situation leading to compromised patient safety. For non-referral ECMO centers, maintaining these skills may be challenging. The gold standard for these centers is to create opportunities for learners to learn these skills in an interactive environment without risk to real patients.

Simulation offers safe, reproducible, and planned rehearsal of both the common problems and the rare high-risk, low-volume problems seen on ECMO. Studies have shown that training is of most benefit when delivered to the full complement of the multidisciplinary team in their native clinical area or a realistic clinical environment (1). The Orpheus simulator introduces changes to parameters in a manner allowing teams to detect changes through situational awareness in a realistic manner. Mobile audio-visual recording technology is used to record these sessions for review by the candidates following the simulated ECMO scenarios during the structured conversational debriefs using advocacy inquiry methodology.

Limitations of the Model

The Orpheus perfusion simulator has been designed for patients above 25 kg and therefore designing and delivering realistic simulation scenarios for neonates is problematic. We have run ECMO simulations with neonatal ($\frac{1}{4}'' \times \frac{1}{4}''$) and pediatric ($\frac{1}{4}'' \times \frac{3}{8}''$) circuits but have found the model to work optimally with the $\frac{3}{8}'' \times \frac{3}{8}''$ circuit. We questioned whether the model using the $\frac{3}{8}''$ tubing when used with the child mannequin would achieve contextual realism. Feedback from participants confirmed that this departure from our standard practice did not affect their perception of reality.

The Orpheus' blood gas model is displayed on the perfusionists' user interface. On initiation of the oxygen transfer failure model, realistic changes to the oxygen saturations and partial pressures are generated; however, the model does not produce realistic changes in the displayed carbon dioxide blood gas. It is not current practice in our institution to use an in-line arterial saturation monitor on the ECMO circuit. We therefore chose to deliver our simulated clinical events without the use of the perfusionists' user interface. Because Orpheus does not give oxygen saturations on the patient monitor, we displayed changes in patient saturations through a separate monitor connected to a laptop running PowerPoint with slides available for a range of representative saturation values.

CONCLUSION

The model we have developed is mobile allowing us to run simulated ECMO scenarios in a number of clinical settings and nonclinical settings. We have successfully delivered simulated ECMO training in the point-of-care setting in the bed spaces where the ECMO patient would normally be cared for in the Bristol Medical Simulation Center and through workshops in nonclinical external environments.

The Orpheus perfusion simulator in conjunction with our interventions allowed us to deliver ECMO simulation scenarios that achieved contextual reality for all members of the multiprofessional team that care for these complex patients. We were able to design a curriculum that allowed candidates to achieve competence through a process of deliberate practice of commonly encountered patient circuit management issues, ranging from the basic event of slow volume shifts to the more complicated scenarios involving changes in multiple parameters.

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