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ECMO Simulation-Based Training: Methods, Drawbacks, and a Novel Solution

Abstract

Introduction: Patients under the error-prone and complication-burdened extracorporeal membrane oxygenation (ECMO) are looked after by a highly-trained, multidisciplinary team. Simulation-based training (SBT) affords ECMO centers the opportunity to equip practitioners with the technical dexterity required to manage emergencies. The aim of this article is to review ECMO SBT activities and technology and suggest a novel solution to current challenges.

ECMO Simulation: The commonly-used simulation approach is easy-to-build as it requires a functioning ECMO machine and an altered circuit. Complications are simulated through manual circuit manipulations. However, scenario diversity is limited and often lacks physiological and/or mechanical authenticity. It is also expensive to continuously operate due to the consumability of highly-specialized equipment.

Technological Aid: Commercial extensions can be added to enable remote control and automate circuit manipulation but do not improve on the realism or cost effectiveness.

A Modular ECMO Simulator: To address those drawbacks, we are developing a standalone modular ECMO simulator that employs affordable technology for high-fidelity simulation.

Keywords

ECMO, ECLS, medical simulation, medical training, simulation technology.

Introduction

Advances in the technology and increasing evidence of the efficacy of extracorporeal membrane oxygenation (ECMO) has skyrocketed its worldwide adoption.[1] ECMO is an intensive care procedure that supports patients' cardiopulmonary functions during their recovery.[2] There are two basic ECMO configurations: veno-arterial (VA), and veno-venous (VV). VA ECMO supports both cardiac and respiratory functions, where high pressure oxygenated blood is returned to the arterial system for systemic circulation.[2] VV ECMO provides partial or complete respiratory support, blood is pumped back to the venous system to be circulated through the body via the heart.[2] Also, an advanced configuration, veno-venous-arterial (VVA), is established by a second cannula for venous blood drainage.[3] Patient's vital dependence on the machine makes its uninterrupted and smooth operation of utmost importance.[4] Unfortunately, the technique is prone to mechanical and patient-related complications that can occur suddenly, have catastrophic consequences, and call for an immediate and quick intervention of a multidisciplinary nature.[5,6] To provide quality clinical care to ECMO patients, ECMO specialists are expected to master specialized clinical and technical skills, be able to identify problems and intervene quickly, communicate effectively, and develop the confidence necessary to rapidly manage emergencies that may arise.[7,8]

Highly trained and cohesive multidisciplinary teams are generally a by-product of strong theoretical understanding coupled with the experience of interacting with patients and dealing with critical situations.[9,10] However, ECMO is error-prone, sparsely used, and is can be associated with severe complications[11]. This makes it unlikely for specialists to encounter all types of ECMO emergencies more than once during their career as an ECMO specialist and become proficient at dealing with them solely from real clinical experience.[12–14] This is especially problematic in low-volume ECMO centers, which have been shown to have higher rates of patient mortality.[15] It can even be difficult for experienced ECMO team members to retain their technical dexterity the less they are exposed to challenging ECMO complications.[16]

To satisfy the incompatible needs of quality clinical care and of training novice practitioners, educators employ simulation-based training (SBT) to supplement or replace real medical experiences with intensified and immersive simulation-based activities.[17] SBT offers a safe environment where teams and individuals can rapidly understand ECMO-patient interactions, instill technical skills, communicate with members of different clinical professions, and develop crisis resource management skills expected of ECMO practitioners.[18,19] For instance, a study on junior-level baccalaureate nursing students showed that employing SBT in the curriculum leads to improved skills performance[20]. For ECMO centers, SBT provides an opportunity to objectively evaluate the performance of clinicians under stress and time pressure, test their readiness for rare complications, and develop improved problem-solving procedures and emergency codes without interfering with the quality of patient care.[21,22]

The majority of ECMO centers affiliated with the extracorporeal life support organization (ELSO) in the United States have an active or are developing a mannequin-based ECMO simulation program.[13] As the adoption of ECMO grows internationally, so is the incorporation of ECMO SBT. Although still in its infancy, there is a need to identify the best practices of ECMO SBT while keeping costs in check. This article reviews the methods and technologies used to simulate ECMO emergency scenarios and examine the degree of realism, cost-effectiveness, and sustainability they offer to ECMO specialists and teams. We also introduce our solution to ECMO simulation and how it addresses the drawbacks identified in literature. The literature review was performed using an exhaustive screening process of over forty publications on ECMO, SBT, and ECMO SBT using the PubMed database and Google Scholar.

ECMO Complications

By studying ECMO complications, their symptoms, and the corresponding required interventions, we emphasize the necessity for ECMO SBT and highlight simulator features that should be ideally present.

Usually unpredictable, ECMO complications can be circuit or patient related and their indications come in the form of visual, auditory, or haptic cues. Life-threating events related to the circuit are oxygenator failure, pump failure, circuit blood clots, air embolism, and cannula issues.[11,12,23] On the other hand, pathological and cannulation site bleeding are the most common patient-related complications.[24] A systematic review of 1,042 adults treated with VV ECMO reports that complications occurred in $25-56\%$ of cases and links them with up to 11% of patient mortality.[25] Similar complication rates can be observed in different age groups and pathologies, and in special cases such as ECMO patient transportation.[6,26,27] A compiled summary of cues, corresponding complications, and possible interventions are presented in Table 1.

Table 1: Summary of common ECMO cues and their corresponding complications and interventions.[12,23,24,27–29]

Cues	**Complications**	**Interventions**
Low arterial oxygen saturation (SaO_2)	• Inadequate circuit flow • Increased oxygen consumption (VV) - patient • Declining lung function (VV) - • Upper body hypoxia (VA)	• Adjust circuit flow • Diagnose/treat underlying causes • Sedate/cool the patient • Switch to VV or VVA ECMO
Low drainage limb oxygen saturation	• Inadequate circuit flow • Increased oxygen consumption • Increased cardiac output	• Adjust circuit flow • Diagnose/treat underlying causes • Sedate/cool the patient
High drainage limb oxygen saturation	• Recirculation (VV)	• Confirm and adjust cannula position • Change cannula type • Perform echocardiogram • Adjust pump flow • Administer fluids • Change to VA ECMO
Loss of circuit flow	• Pump failure • Circuit airlock • Circuit blood clots • Obstruction in the blood path	• Perform CPR with chest compression • Use manual handcrank and replace pump • De-air the circuit • Replace the circuit • Check tubes for kinks
Fall in tidal volume and/or a deteriorating chest radiography	• Declining lung function • Inflammatory response to ECMO	• Increase circuit flow • Restrict fluids and wait for improvements

	• Infection • Left ventricular distention (VA)	• Diagnose/treat infection • Decompress/vent the left ventricular
Low return limb oxygen saturation and no blood color difference between circuit limbs	• Disconnected gas supply • Oxygenator capabilities exceeded • Oxygenator failure	• Perform CPR with chest compression • Check connections • Add another oxygenator in parallel • Replace oxygenator
Low circuit flow, high negative drainage limb pressure, shattering of drainage limb and/or hypotension	• Obstruction of the drainage cannula due to position or blood clots • Hypovolemia • Tamponade (VV) • Pneumothorax	• Address cannula issues • Check blood volume/administer fluids • Perform pericardiocentesis or pericardial window • Insert thoracostomy or drain tube • Use needle decompression
Low circuit flow, high plasma in blood, change in pump sound, visible dark/white spots in pump head/oxygenator/circuit tubes, and/or increasing pressure difference across oxygenator	• Blood clots in the circuit	• Increase anticoagulation • Change pump/oxygenator or the entire circuit

As mentioned earlier, troubleshooting ECMO complications demands well-coordinated teamwork. During SBT activities, an emergency scenario often begins after the bedside clinician notices a particular cue, identifies the potential complication, and calls for help. The interprofessional ECMO team then splits roles between patient stabilization and circuit management. Practitioners responsible for stabilizing the patient are tasked with initiating ventilator support, controlling patient temperature, administering drugs or fluids, adjusting patient position (e.g. the Trendelenburg position), etc. In parallel, other team members are addressing the underlying cause of the complication, which sometimes entails a procedurally complex circuit change or circuit de-airing.[23] Those procedures require all team members to agree on the sequence of events to mitigate errors and optimize for procedural speed.[24] If the patient is completely dependent on extracorporeal support, the team have to restore ECMO support within minutes.[6] In addition to time pressure, the multi-person nature of ECMO interventions coupled with the generally limited space makes performing optimally quite challenging.[7,30,31] This is not limited to ECMO emergencies, but also includes situations where ECMO is deployed on the spot such as in extracorporeal cardiopulmonary resuscitation (ECPR),[32] rewarming of severe or accidental hypothermia,[33,34] or maintaining organs alive for donation after circulatory death.[35,36]

ECMO Simulation

Thankfully, SBT offers a safe venue to practice those complex interventions. In fact they have been shown to improve participants' knowledge,[16] confidence,[37] behavioral skills,[31] and technical dexterity.[19,38] To simulate ECMO emergencies with high-fidelity, SBT must take place in-situ or in an environment that resembles an intensive care unit (ICU) or an emergency room. This environment should have all the equipment used in real-world ECMO cases. Ideally, an ECMO simulator should be able to present learners with realistic hydraulics (pressures, flow rates, and pump speeds) and blood parameters (oxygen saturations, hemoglobin levels, hematocrit, blood temperature, etc.) typically displayed on the ECMO machine console or inline monitors. To simulate complications, the simulator should be able to generate realistic visual, auditory, and/or haptic cues (e.g. pressure changes corresponding to a failing pump or a deoxygenated blood color due to an oxygenator failure.) Lastly, interactivity is essential to allow learners to diagnose by themselves the problem and perform troubleshooting actions accordingly.

Still being in its infancy, ECMO SBT offers a sparse collection of full-fledged simulators. To this day, many teams simulate ECMO using an approach reminiscent of Anderson *et al*. Developed over a decade ago, Anderson et al.'s approach does not require any specialized tools and can be constructed using readily available medical equipment (ECMO machines and circuits, cannula, tube, saline bags, bladders, etc.).[39,40]

Anderson and her colleagues set up their ECMO SBT in a simulation room equipped with functioning ventilators and a radiant warmer, an ECMO code cart, a functional ECMO circuit, and a low-fidelity neonatal mannequin.[39] The ECMO circuit consisted of a roller pump, oxygenator, heat exchanger, and a bladder box interconnected using a ¼" Tygon tubes filled with food-colored saline to simulate blood.[39] "Blood" circulation was achieved by connecting the venous and arterial cannula, inserted into the mannequin's neck using a tee-connector.[39] To increase realism, a balloon was connected to the mannequin's trachea in its chest cavity to simulate lung compliance and an infusion pump was used to simulate fluid delivery to the patient.[39] Patient's physiological parameters were displayed on a remotely-controlled bedside monitor and pulse oximeter.[39] Complications were simulated by manual manipulations of the circuit and changes to the parameters on the patient monitor. For example, hypovolemia is simulated by withdrawing fluid from the circuit and lowering the blood pressure, and similarly, air embolism is simulated by injection of air into the circuit.[39]

Anderson et al.'s ECMO simulation approach quickly gained in popularity and was gradually adapted by other teams. A common alteration is to complement the ECMO circuit loop with a reservoir (typically a saline bag or a bladder) inside the mannequin's abdominal cavity connected to a syringe. In cases where the mannequin cannot be modified, drilled, or is vulnerable to water damage (e.g. due to electronic components inside the mannequin), the ECMO circuit is connected directly to the reservoir (without cannula) and placed away from mannequin.[41] Figure 1 shows a modern ECMO simulation setup. It is currently used with modern centrifugal pump based ECMO circuits such as Maquet Rotaflow pump, Maquet CardioHelp system, Thoratec's CentriMag, and a plethora of basic to advanced mannequins such as the Laerdal's ResuciJunior, SimMan, SimBaby, and Nursing Kelly, CAE's PediaSim, and Gaumard's Hal 3201.[5,38,41–44]

[insert Figure 1]

Figure 1: A Modern ECMO simulation setup.[42]

Manual circuit manipulations are used to generate complications' cues, of which the most basic form is the withdrawal and addition of fluid, or the injection of air. Withdrawing liquid from the circuit, for example, causes the inlet pressure to become more negative and reduces the flow rate regardless of the pump speed. Correspondingly, this triggers the ECMO console's pressure and flow rate alarm, and with the help of the remotely controlled patient monitor, hypovolemia and tamponade can be simulated. Different ECMO centers improvise new circuit manipulations or topologies to create new scenarios or enhance existing scenarios for higher fidelity. For example, from our experience at Hamad Medical Corporation (HMC), blood clots in the membrane are simulated by injecting finely shredded animal liver parts into the venous line. Subsequently, this puree gets stuck in the membrane causing the trans-membrane pressure to rise and giving appearance of a dark clots on the membrane. Royal Brompton Hospital simulation team developed a novel circuit topology to simulate open chest cardiac tamponade.[19] Attached to a neonatal mannequin's chest is a saline bag (the circuit's reservoir) with a silicone tube loosely wrapped around its center and another saline bag connected to a syringe on top (Figure 2).[19] Both bags are covered with a sheet of mannequin skin with a silicone rubber membrane-window in the middle. During the simulation, the top saline bag is filled with red colored liquid to compress the silicone tube and restrict venous outflow the circuit flow and pressures to drop. The filled saline bag also bulges out of the silicone rubber window, simulating open chest bleeding.[19] Table 2 presents common methods used to simulate ECMO emergency scenarios.

[insert Figure 2]

Figure 2: Royal Brompton Hospital open chest cardiac tamponade simulation method.[19]

Unfortunately, in many scenarios the displayed circuit and blood parameters and simulated complication cues are not realistic in relation to the enacted scenario. As ECMO circuits migrated from roller to centrifugal pumps, ECMO simulation lost its ability to set realistic circuit pressures—prior to the start of the session—using the pump occlusion. Circuit manipulations that affect the circuit (e.g. fluid volume) do not necessarily simulate authentic abnormal pressure values but induce values that are high or low enough to trigger the ECMO console alarm.

Moreover, in the case of oxygenator failure, the pressure changes produced (rise in pre- and post-membrane pressures) do not reflect the realistic cue (rise in trans-membrane pressure) of the complication. Other parameters are generally uncontrollable remotely or via circuit manipulations, for example, pump speed and sweep gas flow rate have to be manipulated discretely by a confederate nurse and blood parameters (e.g. blood gases, hematocrit, hemoglobin, and activated clotting time (ACT)) on modern ECMO consoles and inline monitors cannot be controlled. This leaves participants having to imagine and pretend during simulations, not only in scenarios where the generated cues do not match that of the expected complication but also in scenarios where cues are generated by confederate actors. For example, an actor nurse turns off the pump to simulate pump failure and participants have to pretend that the pump has failed.

Table 2: Simulated ECMO scenarios, methods of simulation, induced cues, and gaps and drawbacks.[5,38,39,41–45]

Scenarios	Methods	Cues	Gaps and drawbacks
Pump or power failure	Confederate nurse turns off the pump.	Loss in circuit flow and pump's rotation per minute.	Checking the status of the pump is a part of troubleshooting pump failure. Participants have to pretend the pump is not turned off.
	Confederate nurse turns off the power.	Battery alarm triggers if the battery was drained beforehand. If the battery is completely drained, the pump and console will turn off.	Similar to the above, participants have to pretend the power is not disconnected/turned off. Furthermore, console battery must be drained before simulation and the scenario must begin shortly after to prevent it from charging back up.
Oxygenator failure or membrane clots	Adding fluid into the circuit or partially clamp the arterial line.	Rise in pre-and-post membrane pressure and fall in circuit flow rate.	*Incorrect cues*: the emergency is characterized by the rise of trans-membrane pressure. *Missing cues*: visible clots on the membrane, no blood color change representing hypoxemia, unrealistic blood parameters (blood gases, hematocrit, hemoglobin, and activated clotting time) on modern ECMO consoles (e.g. CardioHelp) or inline monitors. *Contextual authenticity:* rapid oxygenator failure is extremely rare.[46] Clots typically build up, and hence, a more realistic scenario would start with indicators of oxygenator failure such as low oxygenation efficiency and high trans-membrane pressure that are not

			sufficient to trigger alarms but still indicate potential failure. Additionally, it is difficult to discretely clamp the circuit lines.
	Injection of animal liver puree into the venous line of the circuit.	Rise in trans-membrane pressure (rise in pre- and fall in post-membrane pressure), fall in circuit flow rate, and the appearance of dark spots on the membrane.	Address the incorrect pressure cues and missing visible clots in the method above. However, it can be performed only once per oxygenator as the liver cannot be removed afterwards. It is inconvenient and expensive to replicate.
Hypovolemia, cardiac tamponade, access insufficiency, or hypotension	Withdrawing fluid from the circuit. Optional: **(a)** partial clamp near the pump inlet or a confederate nurse discretely shaking the venous line. **(b)** pushing blood colored liquid to a chest drain set near the mannequin using a syringe.	Fall in pre-and-post membrane pressure and circuit flow rate. Optional: **(a)** Line shattering of the venous line. **(b)** Appearance of blood colored liquid in the chest drain, simulating bleeding.	*Missing cues*: line shattering and visible bleeding (depending on the simulated scenario) unless options (**a**) and (**b**) are used, providing additional cues but increasing scenario operation and coordination complexity.
	Partial clamp of the venous line or Royal Brompton Hospital's double saline bag method.	Fall in pre-and-post membrane pressure and circuit flow rate and shatters in the drainage line.	Address the missing line shatters but still misses the visible bleeding unless option (**b**) of the first method is used. It is also difficult to discretely clamp the circuit lines. Royal Brompton Hospital's method adds complexity.
Hypertension or volume overload	Adding fluid into the circuit or partial clamp of the arterial line.	Rise in pre- and post-membrane pressure and fall in circuit flow rate.	It is difficult to discretely clamp the circuit lines.
Kink in circuit	During a	Depending on the	It is difficult to discretely kink the

lines	transportation/bed transition scenario a confederate nurse kinks the venous or return lines under the mannequin's legs or back	kink location pre-and-post membrane pressures will fall (venous line kink) or rise (arterial line kink).	circuit lines.
Air entrainment	Injection of air into the circuit.	Noise of air in the pump head and triggering of the bubble sensor or a complete airlock and loss of circuit flow depending on the volume of air injected.	None.

Advantages of this medium fidelity method is its simple construction, non-complex operation, and physical realism. Any ECMO center with a vacant room and a mannequin can assemble and operate this ECMO simulator. Moreover, novice practitioners can interact with the real circuit and improve their psychomotor or technical skills during simulations. However, the approach suffers from many drawbacks. As mentioned earlier, the authenticity of simulated scenarios is weak and are detached from reality. This means that it is difficult for learners to suspend their disbelief and fully immerse in simulations. Due to the limited and binary (e.g. high or low pressure) control over the simulator, instructors are forced to simulate emergencies with pressure changes as the primary cue. Hence, simulated emergencies are not diverse in their difficulties and underlying causes limiting the amount of critical thinking required to identify the simulated problem. For example, the failure of the blood oxygenation is almost always simulated as clots in the membrane with an incorrect pressure cue and no visible clots. Learners who have experienced the scenario before can identify the simulated scenario without engaging their full critical thinking abilities. SBT in general is very costly to facilitate even with a low-fidelity setup.[47] The cost aspect is exacerbated in ECMO SBT as the setup relies on an ECMO machine and expensive consumable circuit components. Ng *et al*. reported the replacement of twenty-six ECMO circuits, forty-six cannula, and other consumables over the span of two years in the context of SBT activities.[42] Furthermore, due to the nature of how simulations are operated (by manual manipulations and confederates, ECMO simulations have to be operated by a well-briefed and coordinated team of clinicians or simulation specialists, increasing the cost of human resources. Subsequently, the cost of ECMO simulations is very high, hence limiting or prohibiting opportunities for training, reducing the frequency of simulations, and prohibiting its use for mastery or deliberate practice.

Technological Aid

In recent years, technology has been used in ECMO SBT to elevate some of its limitations and drawbacks. This includes setting specific pressure and blood flow values, automating some manual and laborious tasks performed by confederates, and enabling remote control of the simulator.

We have observed at HMC the use of the built-in audio-visual (AV) capabilities of simulation rooms to visualize the pressure changes induced by volume adjustments done from the control room. This was achieved by focusing a camera on the ECMO machine console and accessing its video via a computer linked on the networked AV system, and so it could also be viewed from the observation room. In the in-situ or ECMO transport contexts, they also use a mini-camera with Wi-Fi connectivity (e.g. GoPro) positioned directly on the ECMO machine console and view the live video stream on a tablet or smartphone in the control room. The device screen was itself shared via their integrated AV system so it could be displayed into the observation room.

Lansdowne *et al.* incorporated the Orpheus Perfusion Simulator, a device originally designed for use with a heart-lung machine, into ECMO circuits (Figure 3).[5] Currently produced by Terumo, the Orpheus has an hydraulic model which replicates the behavior of patient circulation using venous and arterial capacitance, native heart, venous and arterial valves, and also based on the Frank-Starlin model.[48,49] It also comes with a perfusionist touchscreen interface to display blood gases, blood pH, ACT, and allow learners to administer drugs (e.g. anticoagulants) digitally.[48] Parameters displayed on the screen react to changes in the circuit hydraulics and digitally administer drugs using computerized models.[48] In ECMO SBT, the Orpheus connects to an ECMO circuit in series (i.e. between the arterial and venous lines).[5] In Lansdowne's implementation, the circuit lines were passed to the Orpheus through drilled holes in the backside of a basic mannequin. Complications are simulated using the same methods listed in Table 2. Oxygenator failure, for example, is simulated using the Orpheus's ability to obstruct the arterial line which in addition to pressure changes, produces realistic blood gas changes on the learner's interface.[5]

[insert Figure 3]

Figure 3: Orpheus Perfusion Simulator in ECMO SBT (modified with permission).[5]

Advantages of using the Orpheus are the more realistic circuit hydraulics and the automation it provides. Hence, scenario management is more convenient and requires lower number of personnel. However, it does not address the realism gaps in simulation scenarios and the costs associated with the ECMO console and consumable circuit components, or provide unique mechanics to simulate missing visual or auditory cues (e.g. blood hypoxemic color, blood clots, or clotted pump head noise). Blood parameters are displayed on a separate screen instead of existing ECMO console/inline monitors, which creates a contextual disconnect between real ECMO and simulated ECMO. Furthermore, instructors cannot directly control blood parameters and the used computerized model only reacts to hydraulic changes and administered drugs, and hence, realistic blood parameters corresponding to complications with no hydraulic cues (e.g. recirculation or low oxygen saturation due increased metabolic activity) cannot be simulated. It also reinforces trainee’s reliance on obtaining information from displayed data rather than cues from the patient or the circuit; a problem that also exists in standard ECMO simulation.

In addition to the Orpheus, there are other commercially available ECMO simulators such as the Curtis Life Research's EigenFlow and the Chalice Medical's Parallel Simulator.[50,51] Both devices enable remote venous and arterial line obstruction, circuit volume removal, and injection of air. Their obstruction of the circuit line is variable (using variable valves) which theoretically allows any pressure or circuit flow value to be obtained. However, to obtain specific values, instructors must be able to obtain feedback from the ECMO console by manually calibrating the corresponding pressure and flow values per level obstruction. The EigenFlow is controlled using an iPhone application and comes with a 10" LCD screen displaying blood parameters. Meanwhile, the Parallel simulator comes with two tablet computers, one given to instructors for control and the other displaying both patient vitals and blood parameters. The Parallel's control software gives instructors the option to pre-program scenarios (e.g. parameter or circuit changes in a particular sequence) and execute them when needed. This can be beneficial for standardization purposes, however, it can make scenarios feel more staged and unnatural as the pre-programmed scenario can proceed without consideration of the trainee's actions. Unlike the Orpheus, those simulators do not possess hydraulic or blood parameter models, and hence, the parameters displayed are not dynamic and need to be changed at the instructor’s discretion. On top of that, since simulated ECMO emergencies are preplanned and those interfaces feature no computerized models but are simply screens with numbers on them, this functionality could more cost-effectively replaced by a computer, PowerPoint slides, and a clicker.

Table 3 summarizes the advantages and disadvantages of aforementioned ECMO simulation devices.

In a collaborative effort, HMC and Qatar University are working towards a more realistic, cost-effective, and user-friendly ECMO SBT that addresses the aforementioned gaps and drawbacks. We started developing a simulator that behaves, looks, and feels realistic, but does not rely on a real ECMO machine and oxygenator. This was done through the design of independent modules, each responsible for producing a particular ECMO visual, audio, or haptic cue.[52,53] Those modules are then interconnected using a local wireless network and can be fully controlled remotely using a tablet instructor application.[54] The simulator is centered around an “ECMO circuit” module which relies on a thermochromic fluid and continuous temperature adjustment to simulate blood oxygenation and deoxygenation (Figure 4A).[55] Instead of a real oxygenator and pump head, 3D printing was utilized to replicate circuit components used to circulate the thermochromic fluid to maintain circuit continuity (Figure 4C). A line shattering module is hidden under the bedding and connects to the circuit generating shatters in the drainage (Figure 4D). The system provides bleeding on-demand from a separate tank and a pump (Figure 4E). We have also replicated the ECMO console interface used at HMC which learners can interact with (Figure 4F). Modules and the interface are remotely controllable via a tablet application that features a live control panel (Figure 4G) from which commands are sent in real-time. In addition, it includes a sequence manager so scenarios can be pre-programmed and executed during simulations (Figure 4B).[45] Despite the high research and development costs, the modules themselves are cost-effective. The ECMO circuit module hardware costs 300 USD and is reusable, which could result in an increased frequency of SBT opportunities. Instructors have complete control over the system. The main disadvantages of our system are the slight loss of physical (i.e. weight, size, texture) realism as it is difficult to 3D print components and cases that are exact replicates of the real-ones.

Table 3: Advantages and disadvantages of commercial ECMO simulators.[5,48–51]

Device	Advantages	Disadvantages
Terumo Orpheus Perfusion Simulator	• Simulates patient circulatory behavior and allows ECMO consoles to display realistic and age-specific hydraulic parameters. • Enables remote obstruction of arterial and venous lines, draining of circuit volume, and injection of air into the circuit. • Provides an interactive learner interface displaying blood parameters based on a computerized model with the ability to administer drugs. • Reduced manpower costs associated with operating ECMO SBT.	• Simulates patients above 25kg and works best with 3/8" tubes, which limits simulating neonatal scenarios. • Hydraulic parameters are only realistic under normal conditions (i.e. no complications simulated), abnormal hydraulic parameters (required to simulate complications) can be unrealistic. • Does not provide any additional or more emergency cues, simulated emergencies inherent drawbacks from manual methods. • Disconnect between parameters displayed on real devices and inline monitors and ones simulated on the learner's interface. • Reinforces learner reliance on displayed parameters. • Modeled blood parameters are not always realistic with respect to the enacted scenarios and instructors do not have the option to change parameters manually during a scenario. • Control is performed using a laptop mounted on top of an electronic control unit, which is less mobile in comparison to the tablet/phone applications used with the other solutions. • Increased equipment and maintenance costs. • Does not resolve costs related to use of real ECMO circuit and their consumables.
EigenFlow and	• Enables remote	• Does not generate realistic circuit

Parallel Simulators	obstruction of arterial and venous lines, draining of circuit volume, and injection of air into the circuit. • Specific pressure and flow values can be obtained by variable obstruction. • Provides a learner interface displaying blood (EigenFlow and Parallel) and patient (Parallel) parameters. • Displayed parameters are selected manually, removing restrictions of Orpheus' model based approach. • System is remotely controlled through tablet (Parallel) and mobile (EigenFlow) applications, improving mobility and convenience. • Parallel: remote control application allows for a sequence of commands and parameter changes to be pre-programmed, saved, and retrieved. • Reduced manpower costs associated with operating ECMO SBT.	hydraulics. • Does not provide any additional or more emergency cues, simulated emergencies inherent drawbacks from manual methods. • Setting realistic circuit hydraulic through the simulator variable venous and arterial obstruction requires instructors to visualize the ECMO console to obtain feedback on pressure and flow changes. • Disconnect between parameters displayed on real devices and inline monitors and the ones simulated on the learner's interface. • Learner interface is not interactive and is simply a tablet that displays values adjusted remotely by instructors. This function can be cost-effectively replicated in-house. • Reinforces trainee reliance on displayed parameters. • Parallel: Pre-programmed scenarios can feel staged and unnatural. • Increased equipment and maintenance costs. • Does not resolve costs related to the use of real ECMO circuit and consumables.

[insert Figure 4]

Figure 4: Components of the modular ECMO simulator.

Conclusions

Existing ECMO simulation solutions are all based on a functioning ECMO machine to ensure a high level of realism yet rely on an altered circuit requiring operator manipulations in order to create or simulate complications. Although this approach offers a quick and generally accessible simulation solution, it is unable to recreate all possible ECMO complications with high-fidelity, cannot be remotely controlled, and most importantly, is linked to a high equipment setup and maintenance costs. Commercial simulation products provide the missing remote control capabilities and automate circuit manipulations although inherits much of the realism gaps from the aforementioned approach and do not mitigate the costs associated with ECMO machine and consumables. Hence, ECMO still necessitates a cost-effective, yet high-fidelity simulation solution that does not rely on the use of real equipment but also do not present of risk of confusing learners due to unusual circuit alterations. These factors motivated the development of our own modular and standalone simulator that will offer a comprehensive, realistic, cost-effective, and user-friendly solution for ECMO SBT.

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Declaration of Conflicting Interests

The Authors declare that there is no conflict of interest.

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