A Thermochromic Ink Heater-cooler Color Change System for Medical Blood Simulation

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Keywords: Simulation-based Training (SBT), Extracorporeal Membrane Oxygenation (ECMO), Blood Oxygenation, Thermochromism, High-fidelity Simulation, Temperature Control.

Abstract: Extracorporeal membrane oxygenation (ECMO) is a modified form of CPB that supports intensive care patients' vital functions during recovery from cardiac or pulmonary trauma. ECMO, although lifesaving, is vulnerable to a plethora of mechanical complications which can cause mortality. This is why developing advanced training systems is of crucial importance. In this paper, as part of an ECMO simulator for training management, a novel thermochromic heater-cooler system is presented. The need of such contribution arises from the lack of high-realism blood simulation methodologies Hence, developed upon thermochromic ink, cost-effective blood simulation is achieved by temperature adjustment, simulating oxygenation and hypoxemia. The system has been developed as a prototype with successful and reversible transitions between dark and bright red blood color. After addressing the limitations, the heater-cooler will be integrated with the ECMO simulator, allowing unprecedented cost-efficient simulation possibilities.

1 INTRODUCTION

Cardiopulmonary bypass (CPB) is technique that is employed to take over a patient's blood circulation and oxygenation functions, and is commonly used during open-heart surgery; allowing surgeons to easily operate on a beat-less heart (*What Is Cardiopulmonary Bypass?*, 2004). Extracorporeal membrane oxygenation (ECMO) is a modified form of CPB that supports intensive care patients' vital functions during recovery from cardiac or pulmonary trauma (*What Is Cardiopulmonary Bypass?*, 2004). Patients are connected to ECMO via cannula and tubes and their deoxygenated blood is drained and pushed through an oxygenation membrane using a pump ("What Is ECMO?," 2016). The membrane facilitates blood oxygenation, and the pump draws and returns the blood to the patient; replacing the patient's lung and/or heart function ("What Is ECMO?," 2016).

Recent technological advancements in ECMO have made it a simpler and safer procedure; boosting survival rates up to 70%, across age groups and making ECMO an increasingly adopted technique (MacLaren et al., 2012; Nichani, 2011). Consequently, the demand for highly trained individuals that can operate the machine has increased. ECMO, although lifesaving, is vulnerable to a plethora of mechanical complications which can cause mortality. Common ECMO complications on the machine side are air entrainment, oxygenator failure, pump failure, and blood clots (Lafçı et al., 2014). Such high risk emergencies require ECMO staff to process critical problem identification skills, make quick interventions, have common behavioral patterns to work as an effective team, and good communication skills to decrease ECMO support suspension; hence avoiding mortality (Peets & Ayas, 2013).

ECMO educators have used simulation modalities to create realistic and high risk scenarios to instill positive technical and behavioral patterns in their trainees (Brazzi et al., 2012; Chan et al., 2013). However, due to lack of support, ECMO simulation methods are still relatively primitive. They consist of modifying a mannequin to enable circulation, connecting the mannequin to a colored water filled ECMO circuit, and using workarounds like manually injecting air into the circuit to trigger alarms and initiate the simulated emergency (Anderson et al., 2006; Ng et al., 2016). Current ECMO simulation practices suffer from high initial and reoccurring costs due to the use of medical equipment and

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expensive circuit consumables such as the oxygenation membrane. It also offers little fidelity and interactivity relative to the cost; the circuit does not visually simulate blood oxygenation color differentials unless they use real blood and deoxygenate the it with carbon dioxide (CO_2) through a modified circuit, but the display of custom information on the ECMO console often remains a challenge.

Thermochromic ink is a special ink with a chemical composition that reacts to temperature by changing its hue (Abdullah Alsalemi, Aldisi, et al., 2017). The ink can be customized to switch between two colors at a set temperature; for example, going from red to invisible when a pizza box is under 40°C. On the other hand, the blood oxygenation process is where the lung (or ECMO oxygenator) exchanges blood $CO_2$for oxygen (O_2). The oxygenation process is visually represented with a clear blood color differential; blood changes from dark red to red as it loses CO_2 and gains O_2. Blood color differentials serve as an important diagnostic tool for ECMO staff; indicating lack of oxygen in the circuit.

Thermochromic can be used to simulate blood oxygenation by customizing it to shift between dark red and red and placing it within a system that continuously manipulates its temperature above and below a defined threshold. Incorporating thermochromic ink into current ECMO simulation practice means increased fidelity; by introducing the oxygenation visual effect, and reduced cost; by getting rid of expensive consumables that do not introduce any actual functionalities to the simulation environment.

In order to operate thermochromic ink in ECMO simulations, a temperature control system is needed. It also needs to be compact, efficient, and controllable. In this paper, we are presenting a novel heater-cooler system for thermochromic ink control, where oxygenation and deoxygenation can be simulated.

The remainder of this paper is organized is follows. Section 2 describes the overall simulation system. Section 3 elaborates on the design of the heater-cooler system. Section 4 presents and discusses preliminary results of the first prototype. The paper is concluded with future work in Section 5.

2 OVERVIEW OF THE MODULAR ECMO SIMULATOR

This section describes the research and development processes behind the proposed ECMO training system. The training system is focused on practically training practitioners for ECMO on adult patients (A. Alsalemi, Al Disi, et al., 2017). The system is expected to be used alongside a strong theoretical course to develop a solid foundation. Figure 1 depicts the proposed system's block diagram comprising three physical subsystems: the patient unit, the ECMO unit, and the oxygenator all centered around the thermochromic loop. Each unit includes simulation modules as shown in the diagram. To control the operation of those modules, a communications system is developed, and connected to a tablet application for instructors to steer the training experience for a smooth learning experience.

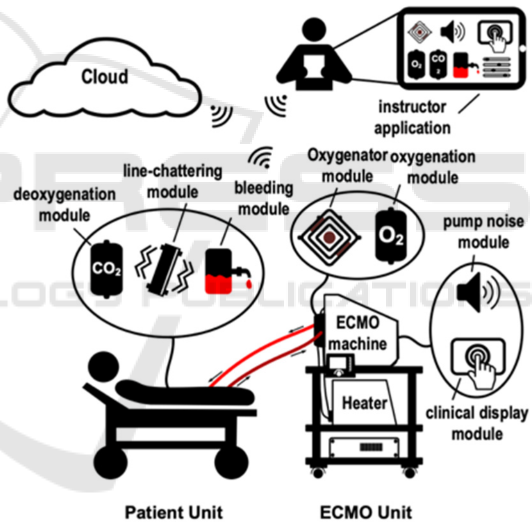

Figure 1: Overview of proposed training system.

The thermochromic loop is a system designed around using thermochromic ink to simulate basic ECMO functionalities; circulation and oxygenation. The patient unit contains a tank that houses a thermochromic ink mixture diluted in water and includes red and black. The black ink can be deactivated and activated above and below 30°C respectively. The thermochromic mixture is pushed through the circuit using a brushless DC pump. It goes out of the patient unit and heads towards a mock oxygenator which bypasses it to the heater unit below. The heater unit heats the mixture causing it to lose its dark color; simulating oxygenation. The mixture then returns to the patient station where it is cooled down;

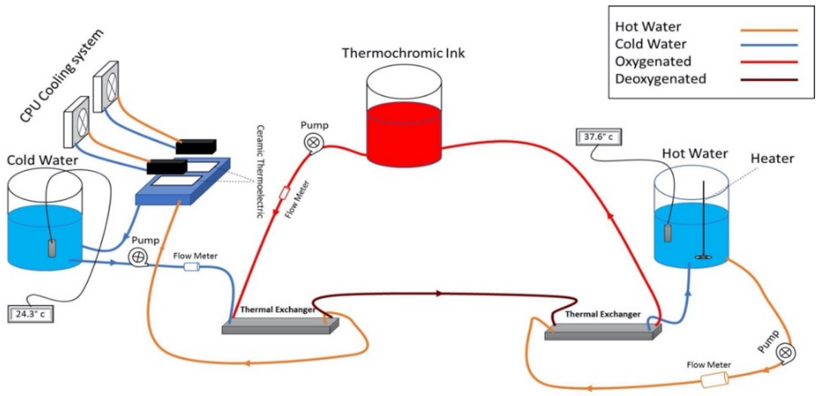

Figure 2: Block diagram of the thermochromic heater-cooler system.

gaining its dark color back and simulating deoxygenation.

The loop function relies on continuously adding and removing heat in and out of the mixture; making the appropriate design of the heat exchange process of utmost importance.

The proposed system is constituted of the primary and secondary loop. The primary loop is where the thermochromic mixture flows; it includes two heat exchangers (one with a cold-water stream and another with a hot-water stream), a pump, and a reservoir tank placed inside the patient unit. The secondary loop is between the source of the water streams and the heat exchangers (Al Disi et al., 2018).

In addition, the simulator contains a variety of simulation modules, each specially designed to physically, audibly, or haptically imitate a certain ECMO phenomena. Examples include line breakage, patient bleeding, head pump noise, among others (Al Disi et al., 2017).

Moreover, the simulator system has been holistically thought out in the point of views of both the learner and the instructor (Alhomsi et al., 2018; Abdullah Alsalemi et al., 2018; Abdullah Alsalemi, Homsi, et al., 2017). The teaching aspect has been supported by the development of two innovative software components: the instructor tablet application. The application is comprised of two parts: the scenario designer and the live control panel, both connected to a CouchDB cloud server for parameter and wireless scenario transmission (Al Disi et al., 2019).

3 METHODS

3.1 Thermoelectric Module

The fundamental underlying operation of the thermochromic loop is heat exchange; increasing/decreasing temperature to above/below the ink's specific deactivation temperature. The ink mixture used is a combination of black and red, with deactivation temperatures of 31°C and 47°C respectively. In this case, the ink used has a transitional region between 27℃ to 32℃; where the liquid color moves between light and dark red. Thus, the heat exchange process is required to cool/heat the liquid below/above the transitional region.

A thermoelectric module is a transducer that can generate electricity by applying heat and vice versa (i.e. the Peltier effect). Indeed, by injecting current to the thermoelectric module, heat can be produced. Therefore, when the current is fed to thermoelectric module, it flows through two different semi-conductors, and consequently, the heat or the cold will be generated. In the other words, a thermoelectric module has two faces, once one of them gets cold, the other face become hot. Furthermore, the performance of cooling side is directly related to the heating face, which means that, by decreasing the temperature of the heating side, the performance of cooling side will increase significantly.

3.2 System Design

In order to demonstrate the visual effect of blood color change, the color of thermochromic ink in the simulator needs to simulate the different states of human blood. Thus, the heater-cooler prototype has been designed and developed in order to satisfy the simulator's needs.

Therefore, the prototype is split into three main subcomponents: A) main tank for supplying blood, B) the cooling unit, and C) the heating unit.

3.2.1 Main Tank

In this stage, blood is transmitted into the next stage (the cooling unit) by a controllable pump, and eventually, passed to the last stage (the heating unit) when returning back to the same tank.

3.2.2 Cooling Unit

As illustrated in Figure 2, the cooling unit consists of the following components.

- Thermal exchanger
- Ceramic thermoelectric
- CPU cooling module
- Tank (Koolance BDY-TK120X70) and pipes
- Water or coolant
- Aluminum water/coolant cooling block
- Pump (Koolance PMP-300)
- Flow Meter (Koolance INS-FM14)
- Temperature sensor

As shown in Figure 2, the thermal exchanger has 4 ports: IN1, IN2, OU1, and OUT2. Accordingly, the blood is delivered to IN1, and goes out from OUT1. Meanwhile, the cooling unit affects the blood entering to IN2, and then goes out from OUT2. Indeed, by placing two thermoelectric modules on the aluminum water/coolant cooling block, the temperature of the water/coolant inside this block will decrease. It will also circulate, by a controllable pump, between the cooling tank and the thermal exchanger unit. In the other hand, two CPU cooling modules decrease the temperature of the heating side of the thermoelectric module. The unit components have been selected from the same manufacturer to ensure compatibility and fitting.

Moreover, due to the considerable effect of flowrate on the cooling performance, several flowrate meters have been implemented in the circuit after each pump. In the other words, by increasing the flowrate, the cooling effect dramatically decreases for the cooling unit. However, flowrate is a significant key factor in this prototype, and it is not negligible. Therefore, by finding the trade-off between the flowrate and appropriate temperature, the overall performance can be optimized.

3.2.3 Heating Unit

As illustrated in Figure 2, a heating unit consists of the following components:

- Tank (Koolance BDY-TK120X70) and pipes
- Pump (Koolance PMP-500)
- Heater module
- Flow meter (Koolance INS-FM14)
- Thermal exchanger (Koolance HXP-193)
- Water

The heating unit includes almost the same cyclic process as the cooling unit. However, in order to heat up the tank's water, a heating element is used. Indeed, in order to optimize the performance in the compact size, the 3D printer's hot-end heater has been employed in this prototype. Hence, by placing the heater inside the water tank, water's temperature will increase. Likewise, the unit components have been selected from the same manufacturer to ensure compatibility.

The tanks are: the thermochromic ink's tank, cold water's tank, and hot water's tank. Furthermore, three pumps correspond to each tank. Indeed, the thermochromic ink's tank contains the bright ink all the time. Therefore, by injecting ink to the cooling unit, the ink's color will turn to dark red.

At this point, the ink will transfer to the heater unit to turn the color back to light red. The entire liquid flow is circulating via those three pumps explained earlier. Due to the proportional effect of flow and the performance of the heater/cooler, three flowrate meters have been implemented in the circuit in order to control flowrate, and eventually, improve the entire process to operate autonomously.

In addition, power supply is also provided in order to supply power to pumps, CPU cooling systems, heater, flowrate meters, and the thermoelectric modules. Moreover, the flowrate of motors can be controlled by voltage adjustment.

4 RESULTS AND DISCUSSION

In this section, light is shed on preliminary results of the prototype thermochromic heater-cooler system. The prototype was developed at Qatar University. It is worth noting that, in this initial version, thermoelectric modules were used in both the cooling and heating units. Also, the system has been initially tested with successful color transformation of blood color from dark bright (cold) to bright red (hot). This is shown in Figure 3. More specifically, bright red simulated blood refers to oxygenation, which is the normal and healthy state for human organ function. On the other hand, simulating dark red refers to deoxygenation, which is a hypoxemic, unhealthy state. To achieve the oxygenation state, the fluid temperature has to exceed 35°C, conversely, hypoxemia can be simulated when cooling the fluid to under 25°C.

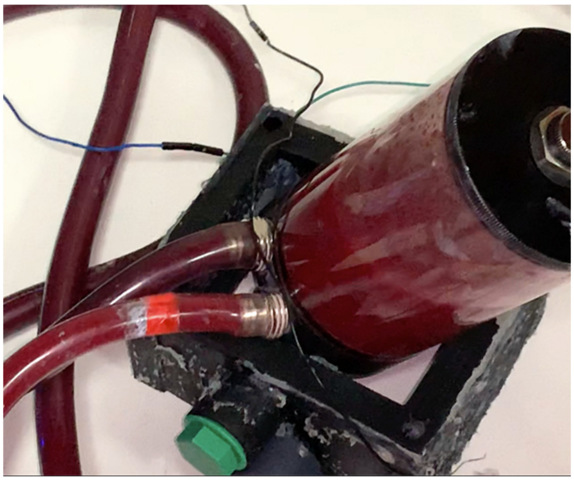

Figure 3: Color change effect achieved by heater-cooler system prototype.

With several tests undertaken on the cooling unit, the following results are attained. By increasing the flow rate to approximately 5 L/min, and raising the temperature to 35°C degrees, it is evident that color of the thermochromic ink turns to bright red. On the flip side, by dropping the flow rate to approximately 3 L/min or less, the temperature can drop readily to below the temperature to 25°C degrees, showing dark red simulated blood. We have observed an inverse relation between flow rate and cooling efficiency, i.e., the lower the flow rate, the faster the fluid cools down, achieving simulated hypoxemia.

Figure 4 shows the current prototype of the thermochromic heater-cooler system. For simplified analysis the system has been minimized to a single, closed loop. It is also worth noting that the tests conducted proved that the two color states are reversible, with average transition time of 25 sec.

The system includes a number of limitations. First, a single, closed loop was deployed, however, higher heating and cooling efficiencies can be achieved by separating the units, enabling independent heating and cooling functionalities. Second, proper more effective heating modules should be used to significantly increase the heating efficiency. Third, an automated control system is to be developed to enabled dynamic adjustment of flow rate to achieve the desired effect without human intervention.

From a cost-effectiveness standpoint, the current prototype can be developed with an equipment cost of less than 500 USD. Compared to using an actual ECMO machine with real blood (i.e. more than 100,000 USD depending on the machine brand), the proposed solution is a powerful alternative for simulations.

In the next prototype of the system, the heater-cooler will be integrated with the simulator's patient unit, allowing it to be controlled by the instructor tablet application. Also, the aforementioned limitations are to be addressed as well as packaging the system as a compact module for increase portability.

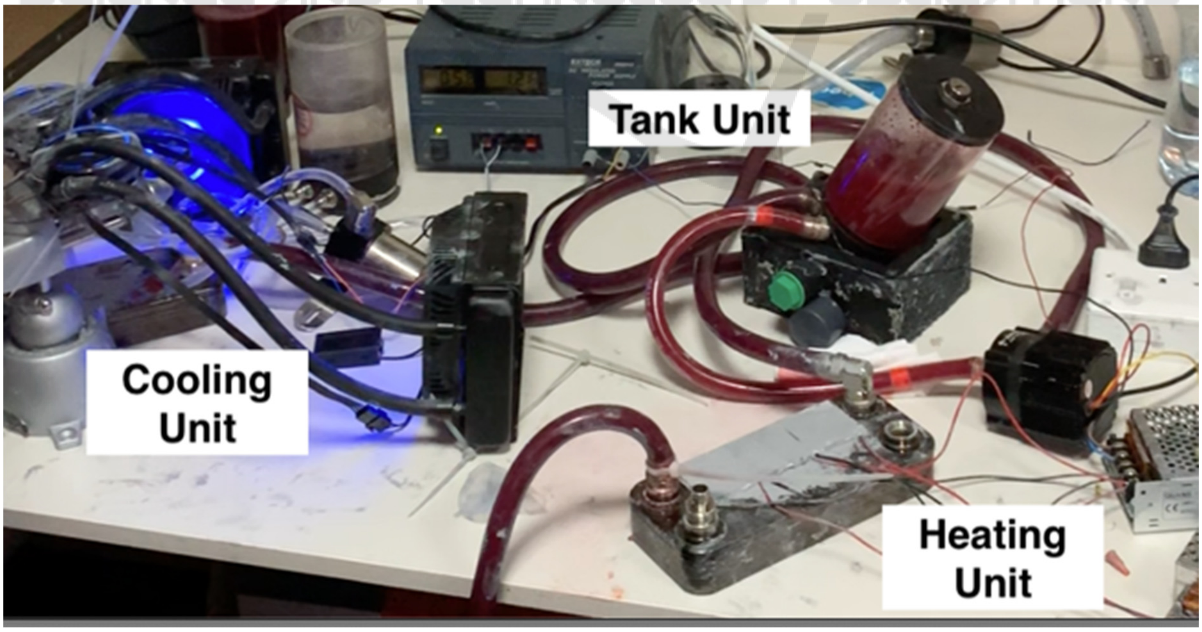

Figure 4: Current prototype of thermochromic heater-cooler system.

5 CONCLUSIONS

In this paper, a novel thermochromic heater-cooler system is presented as part of the modular ECMO simulator. Developed upon thermochromic ink, cost-effective blood simulation is achieved by temperature adjustment, simulating oxygenation and hypoxemia. The system has been developed as a prototype with successful and reversible transitions between dark and bright red blood color. After addressing the limitations, the heater-cooler will be integrated with the ECMO simulator, allowing unprecedented cost-efficient simulation possibilities.

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REFERENCES

Al Disi, M., Alsalemi, A., Alhomsi, Y., Bensaali, F., Amira, A., & Alinier, G. (2017). Revolutionizing ECMO simulation with affordable yet high-Fidelity technology. *The American Journal of Emergency Medicine*. https://doi.org/10.1016/j.ajem.2017.11.036

Al Disi, M., Alsalemi, A., Alhomsi, Y., Bensaali, F., Amira, A., & Alinier, G. (2018). Using thermochromism to simulate blood oxygenation in extracorporeal membrane oxygenation. *Perfusion*, 0267659118798140. https://doi.org/10.1177/0267659118798140

Al Disi, M., Alsalemi, A., Alhomsi, Y., Bensaali, F., Amira, A., & Alinier, G. (2019). Extracorporeal membrane oxygenation simulation-based training: Methods, drawbacks and a novel solution. *Perfusion*, *34*(3), 183–194. https://doi.org/10.1177/0267659118802749

Alhomsi, Y., Alsalemi, A., Al Disi, M., Bensaali, F., Amira, A., & Alinier, G. (2018). CouchDB Based Real-Time Wireless Communication System for Clinical Simulation. *2018 IEEE 20th International Conference on High Performance Computing and Communications; IEEE 16th International Conference on Smart City; IEEE 4th International Conference on Data Science and Systems (HPCC/SmartCity/DSS)*, 1094–1098. https://doi.org/10.1109/HPCC/SmartCity/DSS.2018.00182

Alsalemi, A., Al Disi, M., Ahmed, I., Alhomsi, Y., Bensaali, F., Amira, A., & Alinier, G. (2017). *Developing cost-effective simulators for patient management: A modular approach*. 1–4. https://doi.org/10.1109/ICABME.2017.8167552

Alsalemi, Abdullah, Aldisi, M., Alhomsi, Y., Ahmed, I., Bensaali, F., Alinier, G., & Amira, A. (2017). Using thermochromic ink for medical simulations. *Qatar Medical Journal*, *2017*, 63. https://doi.org/10.5339/qmj.2017.swacelso.63

Alsalemi, Abdullah, Disi, M. A., Alhomsi, Y., Bensaali, F., Amira, A., & Alinier, G. (2018). Enhancing Clinical Learning Through an Innovative Instructor Application for ECMO Patient Simulators. *Simulation & Gaming*, *49*(5), 497–514. https://doi.org/10.1177/1046878118794984

Alsalemi, Abdullah, Homsi, Y. A., Disi, M. A., Ahmed, I., Bensaali, F., Amira, A., & Alinier, G. (2017). Real-Time Communication Network Using Firebase Cloud IoT Platform for ECMO Simulation. *2017 IEEE International Conference on Internet of Things (iThings) and IEEE Green Computing and Communications (GreenCom) and IEEE Cyber, Physical and Social Computing (CPSCom) and IEEE Smart Data (SmartData)*, 178–182. https://doi.org/10.1109/iThings-GreenCom-CPSCom-SmartData.2017.31

Anderson, J. M., Boyle, K. B., Murphy, A. A., Yaeger, K. A., LeFlore, J., & Halamek, L. P. (2006). Simulating Extracorporeal Membrane Oxygenation Emergencies to Improve Human Performance. Part I: Methodologic and Technologic Innovations: *Simulation In Healthcare: The Journal of the Society for Simulation in Healthcare*, *1*(4), 220–227. https://doi.org/10.1097/01.SIH.0000243550.24391.ce

Brazzi, L., Lissoni, A., Panigada, M., Bottino, N., Patroniti, N., Pappalardo, F., & Gattinoni, L. (2012). Simulation-Based Training of Extracorporeal Membrane Oxygenation During H1N1 Influenza Pandemic: The Italian Experience. *Simulation in Healthcare: The Journal of the Society for Simulation in Healthcare*, *7*(1), 32–34. https://doi.org/10.1097/SIH.0b013e31823ebccb

Chan, S.-Y., Figueroa, M., Spentzas, T., Powell, A., Holloway, R., & Shah, S. (2013). Prospective Assessment of Novice Learners in a Simulation-Based Extracorporeal Membrane Oxygenation (ECMO) Education Program. *Pediatric Cardiology*, *34*(3), 543–552. https://doi.org/10.1007/s00246-012-0490-6

Lafçı, G., Budak, A. B., Yener, A. Ü., & Cicek, O. F. (2014). Use of Extracorporeal Membrane Oxygenation in Adults. *Heart, Lung and Circulation*, *23*(1), 10–23. https://doi.org/10.1016/j.hlc.2013.08.009

MacLaren, G., Combes, A., & Bartlett, R. H. (2012). Contemporary extracorporeal membrane oxygenation for adult respiratory failure: Life support in the new era. *Intensive Care Medicine*, *38*(2), 210–220. https://doi.org/10.1007/s00134-011-2439-2

Ng, G. W. Y., So, E. H. K., & Ho, L. Y. (2016). Simulation Training on Extracorporeal Membrane Oxygenation. In M. S. Firstenberg (Ed.), *Extracorporeal Membrane Oxygenation: Advances in Therapy*. InTech. http://www.intechopen.com/books/extracorporeal-membrane-oxygenation-advances-in-therapy/simulation-training-on-extracorporeal-membrane-oxygenation

Nichani, S. (2011). An overview of extracorporeal membrane oxygenation (ECMO). *Paediatrics and Child Health*, *21*(4), 170–176. https://doi.org/10.1016/j.paed.2010.09.006

Peets, A. D., & Ayas, N. T. (2013). Simulation in Pulmonary and Critical Care Medicine. In A. I. Levine, S. DeMaria, A. D. Schwartz, & A. J. Sim (Eds.), *The Comprehensive Textbook of Healthcare Simulation* (pp. 525–536). Springer New York. https://doi.org/10.1007/978-1-4614-5993-4_37

What is Cardiopulmonary Bypass? (2004, September 1). Perfusion.Com. http://www.perfusion.com/cgi-bin/absolutenm/templates/articledisplay.asp?articleid=1549#.WK09dRDmQ_U

What is ECMO? (2016). *American Journal of Respiratory and Critical Care Medicine*, *193*(6), P9–P10. https://doi.org/10.1164/rccm.1936P9.