Al Disi M, Alsalemi A, Alhomsi Y, Bensaali F, Amira A, Alinier G. Revolutionizing ECMO simulation with affordable yet high-Fidelity technology. American Journal of Emergency Medicine (in press, 11-2017)

Revolutionizing ECMO Simulation with Affordable yet High-Fidelity Technology

Simulation-based training (SBT) is becoming a necessity in educating healthcare professionals who work in high-risk environments, such as the intensive care unit (ICU) [1]. This applies to extracorporeal membrane oxygenation (ECMO), a complication-burdened life support ICU modality employed to treat patients with circulatory and/or respiratory failure. Additionally, ECMO can quickly restore perfusion, and hence, used in the pre-hospital or emergency setting as an extracorporeal cardiopulmonary resuscitation (E-CPR) strategy or to maintain donors' organs after circulatory death [2,3]. Different ECMO simulation models have been reported in the literature. It ranges from simple mannequin and circuit modification with manual control [3,4], to hydraulically capable, remotely controlled mannequins [5,6], and high-fidelity simulators [7]. However, the common factor in the incumbent practices is the reliance on a functioning ECMO console and circuit components, which introduces a colossal cost barrier and requires active spending to replace ECMO consumables [8]. Reliance of such specialized and potentially scarce pieces of equipment also significantly reduces training opportunities. Furthermore, attempts to improve the simulation paradigm are faced with ever-increasing technical difficulties. For example, basic objectives such as controlling the displayed circuit pressures requires creating a sophisticated hydraulic model. It becomes even more problematic when considering higher level objectives such as simulating blood oxygenation color differentials, or remotely controlling blood gas parameters, displayed on in-line monitors. Hence, there is a need for lower cost, high-fidelity simulation systems with more customization capabilities that meet the expectations and increasing demand for ECMO therapy [9].

Qatar's Hamad Medical Corporation (HMC) have partnered with Qatar University to develop a standalone ECMO simulator based on the philosophies of physical fidelity and modularity. Physical fidelity deals with simulating the visual and audio cues of a given phenomenon while not necessarily producing it physiologically [10,11]. Modularity, on the other hand, focuses the design process on implementing mechanisms that recreate the ECMO systems phenomena using affordable, extensible, independent components. The fundamental ECMO functions were first pursued. Blood oxygenation and circulation is simulated by streaming thermochromic fluid through two heat exchangers using a commercial pump. Thermochromic ink is a substance with a special chemical composition that allows it to change its color based on temperature adjustment. Heating and cooling the fluid at different parts of the “ECMO circuit” continually shifts its color between light and dark red, simulating blood oxygenation and circulation [12]. A replica of the circuit’s oxygenator was 3D printed, externally resembling the look of the MAQUET HLS oxygenator. From the inside, it contains a bypass tube, circulating the thermochromic fluid from the access to the return ports. Concluding the fundamental functions, the ECMO console interface is emulated on a single-board computer connected to a touchscreen. The parameters visible on the “ECMO screen” are stored in a real-time cloud remotely accessible by instructors using a tablet application. This enables on-the-spot adjustment of circuit and blood parameters and controlling the system modules. In addition, the instructor tablet application offers a sequence designer that allows instructors to create and store simulation scenarios for blueprinting a standardized training curriculum and automate some parametric changes on a timeline or as desired by the instructor. Fig. 1 showcases prototyping results of the simulator.

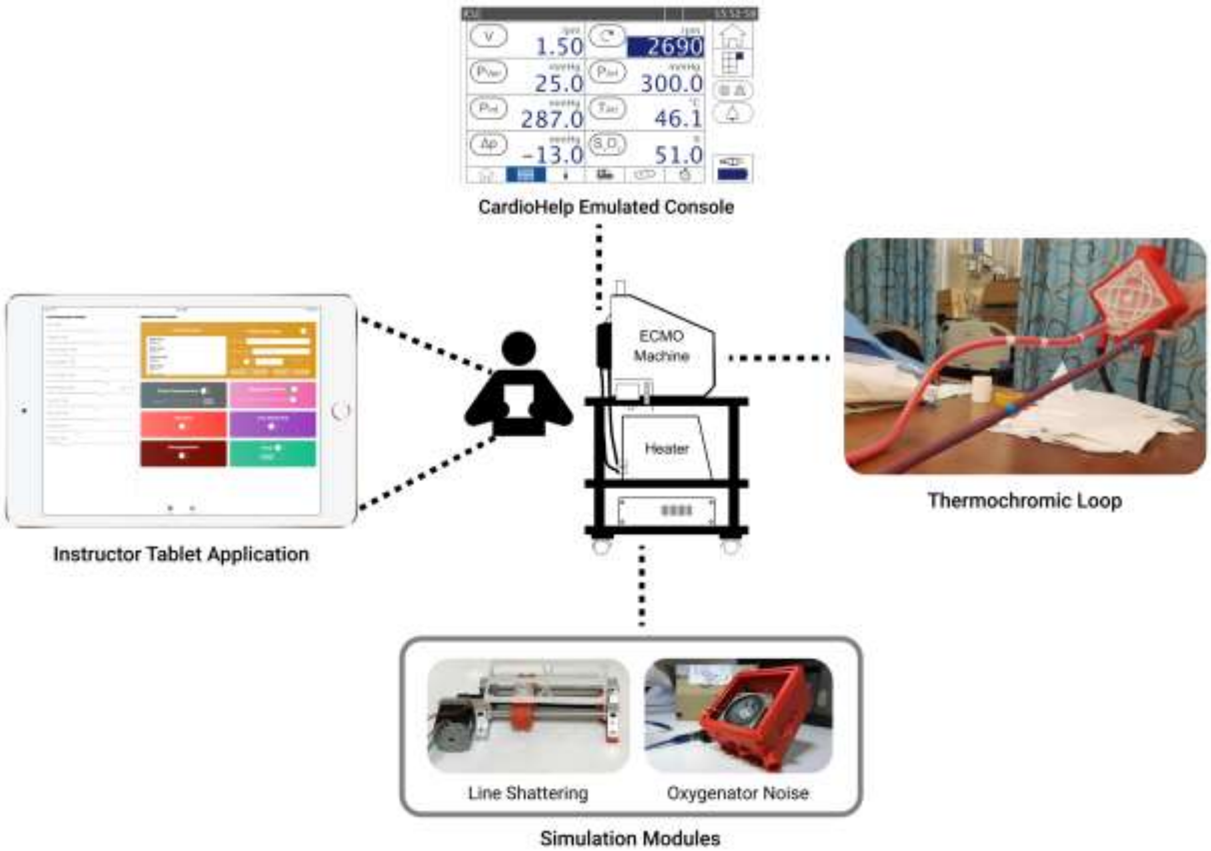

Fig. 1. Simulator prototyping results.

On top of the fundamental layer of the simulator, additional wirelessly controlled modules are added to simulate visual or audio effects of specific ECMO emergencies. A linear motion device is used to create vibrations within the drainage tube, simulating line-shattering. A bleeding module can discharge blood-like liquid anywhere on the mannequin, simulating patient bleeding. Valves are used to disable temperature change in the thermochromic fluid, creating a mono-colored circuit, simulating hypoxemia or recirculation. Table 1 summarizes the simulator modules and the potential cases when they would be used.

Table 1: HMC ECMO simulator modules and the associated clinical cases when they

would be used [14–16]

In addition to providing a realistic and versatile platform for ECMO simulation, the simulator is

Module	Description	Potential scenarios
ECMO console interface	A single-board computer connected to a touchscreen displaying all relevant parameters, and an application enabling the control of all the interconnected modules and displayed parameters	• Applicable to all ECMO scenarios
Thermochromic loop	Thermochormic fluid is circulated, heated, and cooled to create oxygenation color differentials. Mono-colored circuits can be achieved by disabling heating/cooling	• Normal operation • Successful oxygenation in ECMO cardiopulmonary resuscitation • Oxygenator failure • Disconnected gas supply • Declining lung function • Recirculation
Bleeding	A pump that drains a reservoir filled with blood-like liquid	• Pericardial tamponade (chest bleeding) • Surgical/cannulation site bleeding
Line shattering	A linear motion device that oscillates the drainage line at a pre-programmed rhythm	• Hypovolemia • Pneumothorax • Pericardial tamponade
Pump noise	A speaker embedded in a 3D-printed mock oxygenator that produces different pump audio cues	• Pump head clots • Pump air bubbles
Clotting	A LED matrix that creates visible dark or light spots on the oxygenator	• Oxygenator clots

considered affordable in comparison with other high-fidelity solutions. System modules are built from commercially available components (pumps, heat-exchangers, microcontrollers, etc.) It is also enclosed by low-cost 3D-printed casing. The simulator hardware is estimated to cost a total of 3,000 USD.

SBT provides a safe, lifelike environment where trainees can quickly and effectively understand

ECMO-patient interactions and communicate with members of the multi-professional clinical team [17,18]. Compared to other existing systems in place, our simulator mitigates the prohibitive cost imposed by the use of medical equipment, and provides instructors with an easy to use but powerful wireless interface, not to mention the high customizability that allows the creation of a vast amount of ECMO emergencies with varying degrees of criticality. Current progress includes the development of the thermochromic system, simulation modules, and the instructor tablet application. Future development plans focus on performance optimizations of the modules and the instructor application. This will also include blending the whole system with the ICU environment, establishing unprecedented realistic and immersive integration of an ECMO simulator.

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