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6

7

8 **Using Thermochromism to Simulate Blood**
9 **Oxygenation in Extracorporeal Membrane**
10 **Oxygenation**

11 **Abstract**

12 **Introduction:** Extracorporeal membrane oxygenation (ECMO) training programs
13 employ real ECMO components, causing them to be extremely expensive while
14 offering little realism in terms of blood oxygenation and pressure. To overcome
15 those limitations, we are developing a standalone modular ECMO simulator that
16 reproduces ECMO's visual, audio, and haptic cues using affordable
17 mechanisms. We present a central component of this simulator capable of
18 visually reproducing blood oxygenation color change using thermochromism.

19 **Methods:** Our simulated ECMO circuit consists of two physically distant modules
20 responsible for adding and withdrawing heat from a thermochromic fluid. This
21 manipulation of heat creates a temperature difference between the fluid in the
22 drainage line and the fluid in the return line of the circuit, and hence a color
23 difference.

24 **Results:** Thermochromic ink mixed with concentrated dyes was used to create a
25 recipe for a realistic and affordable blood-colored fluid. The implemented "ECMO
26 circuit" reproduced blood's oxygenation and deoxygenation color difference or
27 lack thereof. The heat control circuit costs 300 USD to build and the
28 thermochromic fluid costs 40 USD/L. During a ten-hour in-situ demonstration,
29 nineteen ECMO specialists rated the fidelity of the oxygenated and
30 deoxygenated "blood" and the color contrast between them as highly realistic.

31 **Conclusions:** Using low-cost yet high-fidelity simulation mechanisms, we
32 implemented the central subsystem of our modular ECMO simulator which
33 creates the look and feel of an ECMO circuit without using an actual one.

34
35 **Keywords**

36 Simulation-based training (SBT), extracorporeal membrane oxygenation (ECMO),
37 blood oxygenation, thermochromism, high-fidelity simulation.

38

39

40 **Introduction**

41 Among the many sophisticated pieces of technology found in the intensive care
42 unit (ICU), the extracorporeal membrane oxygenation (ECMO) machine is arguably
43 the most complex.¹ It is used as an invasive life-sustaining device that provides
44 cardiopulmonary support for patients during recovery of their diseased lung or
45 heart or while awaiting for a transplant.² Patients' vital dependence on ECMO
46 makes its uninterrupted and smooth operation of paramount importance.
47 Unfortunately, ECMO is burdened with many complications caused by the patient's
48 pathology, mechanical failures of the equipment, or clinical error and inexperience
49 of the clinical care team.^{3,4} ECMO's vulnerability to human errors and its technically
50 challenging nature requires ECMO practitioners to come equipped with adequate
51 technical, behavioral, and crisis resource management skills.⁵ Since ECMO is a
52 relatively low-volume and high-risk procedure that permits no room for learning
53 from errors, training novice practitioners and maintaining competencies without
54 compromising patients' safety must preferably be done through simulation-based
55 training (SBT).⁶⁻⁹

56 Most ECMO centers offering SBT use different variations of the simulation
57 model described by Anderson and her colleagues in 2006.^{10,11} The model consists
58 of an ECMO circuit filled with red-colored saline and connected to itself through a
59 reservoir (e.g. bladder) featuring a hidden connection to a syringe which facilitates
60 circuit volume adjustment and injection of air.¹¹ Emergency scenarios are
61 simulated by discreet manual adjustments made to the circuit as the simulation
62 session begins.^{11,12} For example, hypovolemia can be simulated by withdrawing
63 fluid from the circuit while a confederate nurse sways a thread attached to the
64 tubing to create shatters in the drainage line.^{11,12}

65 Although realistic from an equipment point of view, using an ECMO circuit
66 and machine for simulation purposes has major drawbacks. First, many simulated
67 emergency scenarios are detached from reality or require trainees to imagine and

68 pretend. In an oxygenator failure scenario, for example, it is not possible to
69 increase the delta-pressure across the oxygenator, produce deoxygenated blood
70 color in the return line, or manipulate blood gas saturations displayed on modern
71 ECMO consoles or in-line monitors without complex circuit modifications or using
72 real blood. Many other scenarios suffer from the same issue, which is mainly
73 caused by the simulator's inability to control circuit and blood parameters, or
74 reproduce relevant visual/audio cues. Some commercial ECMO simulators address
75 some of those issues by providing instructors with a wirelessly controlled screen to
76 display relevant parameters.^{13,14} Still, there remains a disconnect between the
77 parameters that are displayed on the real ECMO system and the ones displayed
78 on the emulated screens. Second, disposable ECMO circuit components such as
79 the oxygenation membrane, are expensive, making continuous replacement for
80 training purposes limiting or prohibitive.¹⁵

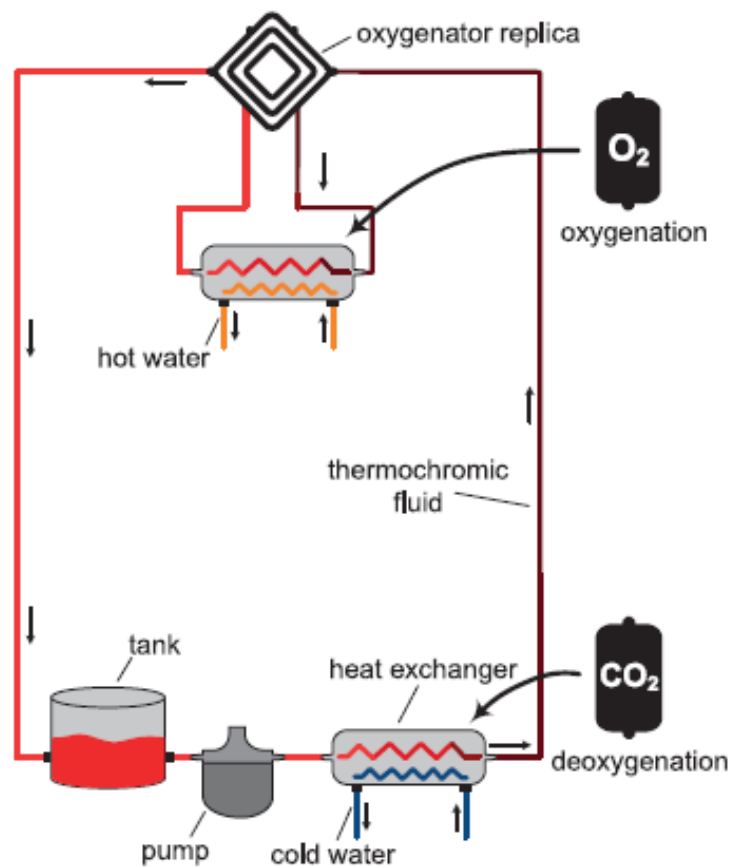
81 Motivated by the aforementioned drawbacks, we are developing a
82 standalone ECMO simulator that does not require the presence of a real ECMO
83 machine or its expensive circuit components. The core principle is to recreate an
84 ICU ECMO environment which instructors can fully and remotely control and
85 learners can interact with. This is done by designing affordable but high-fidelity
86 modules capable of reproducing ECMO visual, audio, and tactile cues (e.g. blood
87 color, air entry pump noise, and line-shattering) without their physical or
88 physiological requirements.^{16,17} These modules are then enclosed within 3D
89 printed cases that resemble real ICU or ECMO components. Naturally, our initial
90 development efforts were drawn to simulating the most observable and indicative
91 ECMO visual cue: blood oxygenation color change. Blood color transitions from
92 dark-red to red as it gains oxygen (O_2) and loses carbon dioxide (CO_2). It is a
93 critical diagnostic tool that indicates normal operation, successful ECMO initiation,
94 low-oxygen saturation in the return line, and recirculation. This article describes the
95 use of thermochromism in the development of the oxygenation and deoxygenation
96 modules used in our ECMO simulator with the objective of reproducing a realistic
97 oxygenated-deoxygenated blood color difference and building a standalone
98 "ECMO circuit".

99

100 **Methods**

101 Thermochromism is a property of a substance that allows reversible color change
102 with temperature. Thermochromic inks and powders are products designed to
103 transition between two distinct states (colors) above and below a fixed transition
104 temperature (T_t).¹⁸ Our simulated ECMO circuit exploits this property by circulating
105 a thermochromic fluid (diluted thermochromic ink mixed with other dyes) through
106 two physically-distant modules responsible for adding or withdrawing thermic
107 energy (heat). Heat manipulations drive temperature change in the fluid, triggering
108 it to change state. The circuit design is presented in Figure 1. Besides the "patient"

109 location sits a reservoir containing the thermochromic fluid that is pumped through
110 a heat exchanger (HE), cooling it below its T_t . On the opposite side of the circuit, a
111 3D printed “oxygenator” conceals the bypassing of the fluid to another HE, which
112 heats it above its T_t . The continuous change of the fluid temperature—in two
113 separate locations—creates a noticeable color difference pre-and-post oxygenator
114 (and pre-and-post patient), hence simulating observable blood oxygenation color
115 difference.
116



117

118

Figure 1: Simulated ECMO circuit design.

119

120 Thermochromic Fluid

121 Many fluid colors can be achieved by mixing thermochromic inks with other
122 variants or coloring products. Our aim was to find an affordable, yet optimal mixture
123 that visually resembles blood. Initially, red and black thermochromic inks (SFXC,
124 East Sussex, UK) were mixed and diluted in distilled water. Considering that the
125 black thermochromic ink becomes invisible when heated to 31°C, the premise was

126 for the black thermochrome to be cooled to introduce a dark tint onto the red and
127 heated to eliminate itself, creating a dark-red to red color difference. Unfortunately,
128 diluting the inks in water caused a subtle gray-shift in their colors (black → gray,
129 and red → pink) resulting in a purple to pink thermochromic fluid. An attempt to
130 color-correct the purple into red was pursued by mixing in yellow and red
131 concentrated dyes (Mayhems Solutions, Darlington, UK). However, it proved
132 impractical as it was necessary to add large amounts of dye to make a noticeable
133 difference, raising the overall cost of the simulated blood. This was addressed by
134 eliminating the red thermochromic ink from the mixture, allowing lower amounts of
135 dye to produce a more potent effect. Diluting the ink in water was also observed to
136 cause the black ink to change state between 27°C to 32°C rather than the
137 advertised 31 °C. This temperature transition region was kept in mind during the
138 design process of the circuit. The final fluid recipe is presented in Results.
139

140 **Heat Exchange**

141 Each of the two modules contains a plate heat exchanger (PHE) chosen on the
142 virtue of its compactness and efficiency. PHEs take two liquid streams (primary
143 and secondary) and facilitate heat transfer from the hot stream to the colder one
144 through thermal conductive plates. In both modules, the primary stream is the
145 thermochromic fluid and the secondary stream is hot or cold water supplied by a
146 heater-cooler machine. The aim of this section is to describe the selection of a flow
147 rate for the primary stream and flow rates and temperatures for the secondary
148 streams which will result in a sufficient (thermochromic state-altering), balanced
149 (between the two modules), and bounded (by the capacity of the heater-cooler
150 machine) heat exchange process.

151 The relationship between the heat exchanged between the two streams,
152 their input temperatures, and their flow rates is summarized in (1).¹⁹ Where Q is the
153 heat transferred between the two streams (in W), T_{in} and T_{out} are, respectively, the
154 fluid's temperature into and out of the HE (in °C), F is the fluid's flow rate (in L/min),
155 U is the heat exchange coefficient (in $W \times m^{-2} \times ^\circ C$), and A is the heat exchange
156 area (in m^2). The subscripts h and c are used to refer to the warmer or colder
157 streams with respect to the other as seen at the input of the HE (i.e. the
158 thermochromic fluid is considered a hot stream when compared to cold water and
159 a cold stream when compared to hot water).

$$\begin{aligned}\Delta T_{in} &= T_{h,in} - T_{c,in} \\ T_{out} &= T_{in} + \frac{60 Q}{4180 F}\end{aligned}\tag{1}$$

$$Q = UA \frac{\Delta T_{in} - \left[\left(T_{h,in} + \frac{60(-Q)}{4180 F_h} \right) - \left(T_{c,in} + \frac{60 Q}{4180 F_c} \right) \right]}{\ln(\Delta T_{in}) - \ln\left(\left[\left(T_{h,in} + \frac{60(-Q)}{4180 F_h} \right) - \left(T_{c,in} + \frac{60 Q}{4180 F_c} \right) \right] \right)}$$

160 Since the final equation in (1) is non-linear and has many variables, an
 161 iterative empirical approach is used to determine the appropriate temperature and
 162 flow rate values. The procedure is applied per module and is as follows:

- 163 1. Select a PHE and find the constant UA using its physical properties and
 164 properties of distilled water.²⁰
- 165 2. Select an operational temperature range for the thermochromic fluid.
 166 Estimate the initial temperature values allowed into the tank before the
 167 system startup (common to both modules).
- 168 3. Assume a flow rate for the thermochromic fluid (common to both modules).
- 169 4. Assume a temperature and flow rate for the secondary stream (hot or cold
 170 water depending on the module). This is typically found in the heater-cooler
 171 machine specifications.
- 172 5. Find Q using a non-linear solver such as MATLAB's *fsolve()* function.
- 173 6. Check if Q causes sufficient temperature change to output the desired
 174 thermochromic state (in this case $T_{out} < 27$ when cooling and $T_{out} > 32$
 175 when heating).
- 176 7. Check if the maximum Q transferred is within the heating/cooling capacity of
 177 the heater cooler-machine.
- 178 8. Repeat steps 3, 4, and 5 until 6 and 7 are met.
 179

180 Circulation and Flow Control

181 This section aids in the pump selection process by describing the estimation
 182 method of the required pump head. Head is the positive pressure, exerted on a
 183 liquid, required to overcome the flow resistance caused by circuit components
 184 (tube and HEs, in-line sensors, etc.).

185 The tube-generated head is described in (2), where H_t is the tube's head (in
 186 m), λ is the tube's friction coefficient, L is the tube's length (in m), and d is the tube
 187 inner diameter (in m).²¹ The friction coefficient depends on the tube's wall material
 188 and (3) provides an estimation based on the use of polyvinyl chloride (PVC) tubes,
 189 where Re is the circuit Reynolds number. The additional head generated by other
 190 components (HEs, in-line sensors, etc.) can be found in the corresponding
 191 component's specifications sheet.

$$H_t \approx \frac{2.2975 \lambda F^2 L}{10^{11} d^5} \quad (2)$$

$$\lambda \approx \begin{cases} \frac{64}{Re}, & \text{if } Re < 2000 \\ \left[-2 \log_{10} \left(\frac{2.51}{Re \sqrt{\lambda}} + \frac{0.0015}{3700 d} \right) \right]^{-2}, & \text{if } Re \geq 2000 \end{cases} \quad (3)$$

$$Re \approx \frac{F}{0.037605 d}$$

192 Running any pump at a constant rotation per minute (RPM) will produce a
 193 flow rate proportional to the flow resistance of the circuit it is connected to. In
 194 ECMO, the circuit flow resistance changes significantly based on the patient's size,
 195 age group, and the health condition of the veins and arteries. Hence to maintain
 196 the flow rate required for sufficient heat exchange, the pump's RPM requires
 197 continuous adjustment. Fortunately, brushless direct-current (BLDC) motor pumps
 198 are easy to control, readily available, and inexpensive. A metal-oxide-
 199 semiconductor field-effect transistor (MOSFET) can act as a variable electric
 200 current "valve" when placed in series with the pump's power source. In this
 201 implementation, a microcontroller reads the flow rate from a flowmeter and
 202 subsequently controls the current that goes through the MOSFET. This results in
 203 more or less electric current reaching the pump, hence, varying its power and RPM
 204 to maintain the circuit's flow rate.

205

206 **Thermochromic Circuit Design**

207 Following the design procedure outlined in the previous section, the HXP-193
 208 (Koolance, Auburn, WA) was the selected PHE used to heat and cool the
 209 thermochromic fluid above and below the aforementioned transition region. The
 210 PHE's UA constant was calculated as $(433 \frac{W}{^\circ C})$ and the thermochromic fluid
 211 operational temperature range was set from $21^\circ C$ to $40^\circ C$ and the secondary
 212 streams values (temperature and flow rate) were bound by the Sorin 3T (LivaNova,
 213 London, England) heater-cooler available in our partner hospital. The resultant
 214 configuration is as follows:

215 • Thermochromic flow rate: ≤ 1.6 L/min

216 • Cold water: $25^\circ C$ at 15 L/min (Sorin 3T patient circuit)

217 • Hot water: 35 °C at 9 L/min (Sorin 3T cardioplegia circuit)

218 Using the maximum thermochromic fluid flow rate (1.6 L L/min) and the 3/8"
219 polyvinyl chloride (PVC) tube used in our circuit, λ was estimated to be 0.0388.
220 Consequently, the total circuit head considering a 10 m tube, two heat-exchangers,
221 and a flow sensor is 0.5 m. Koolance's PMP-300 (Koolance, Auburn, WA) BLDC
222 pump was selected since it offers head up to 2.6 m. It was controlled by a Teensy
223 3.2 microcontroller (PJRC, Sherwood, OR) with feedback from an INS-FM14
224 (Koolance, Auburn, WA) flow meter.

225

226 **Assessment**

227 The thermochromic fluid color-temperature characteristics were quantified using a
228 digital camera (Canon EOS 600D, Canon, Tokyo, Japan). Cold thermochromic
229 fluid was filled in a beaker and placed on top of a hot plate to vary its temperature.
230 A camera was fixed 50 cm away looking down into the beaker ($\approx 10^\circ -$
231 20° clockwise) to minimize reflection. Pictures were taken under cool-white
232 fluorescent lighting (≈ 4100 K) and the camera's exposure was fixed with the help
233 of a luminance histogram. To reproduce colors correctly, the photos were digitally
234 white balanced using an objective technique.²² Then, ten-pixel points were
235 sampled from the fluid's surface and the average of the pixels' standard Red-
236 Green-Blue (sRGB) components was considered the quantified color.

237 The circuit was implemented and tested with a convenience sample of
238 ECMO clinicians from Hamad Medical Corporation (HMC), our partner hospital.
239 Nineteen participants from different professions (physicians, perfusionists, nurses,
240 and respiratory therapists) evaluated the thermochromic effect. They, on average,
241 had 4.73 (0.5 – 12) years of ECMO experience and had cared for an average of
242 75 (3 – 150) ECMO patients each. The demographics are summarized in Table 1.
243 Participants were introduced to the circuit and were asked to fill in a questionnaire
244 that included a set of statements about the realism of the "blood" color in its
245 oxygenated and deoxygenated states along with the contrast between the two
246 states using a 5-point Likert scale (1=not realistic at all; 5=very realistic).

247 To assess the thermochromic fluid consumability, samples were taken from
248 the circuit's reservoir every two hours of the circuit's operation as the fluid was
249 continuously circulating through the cooling and heating system. Samples' ink
250 concentration was estimated using a calibrated 400nm absorbance versus
251 concentration plot.

252 Table 1: Demographic characteristics of evaluation participants.

	<i>n</i> (%)
Gender	
Male	14 (73.6%)
Female	5 (26.4%)
Age (years)	
25 – 34	4 (21%)
35 – 44	9 (47%)
45 – 54	4 (21%)
55 – 64	2 (11%)
Profession	
Physician	5 (26.4%)
Perfusionist	5 (26.4%)
Nurse	8 (42.1%)
Respiratory therapist	1 (5.1%)
	Mean (\pm std)
ECMO experience (years)	4.7 (\pm 3.2)
Number of patients cared for	75 (\pm 52)

253

254 **Ethics**

255 The clinicians' evaluation aspect of this research project was approved by HMC's
 256 Medical Research Center (#17231/17) and classified as "exempt" from full ethical
 257 review.

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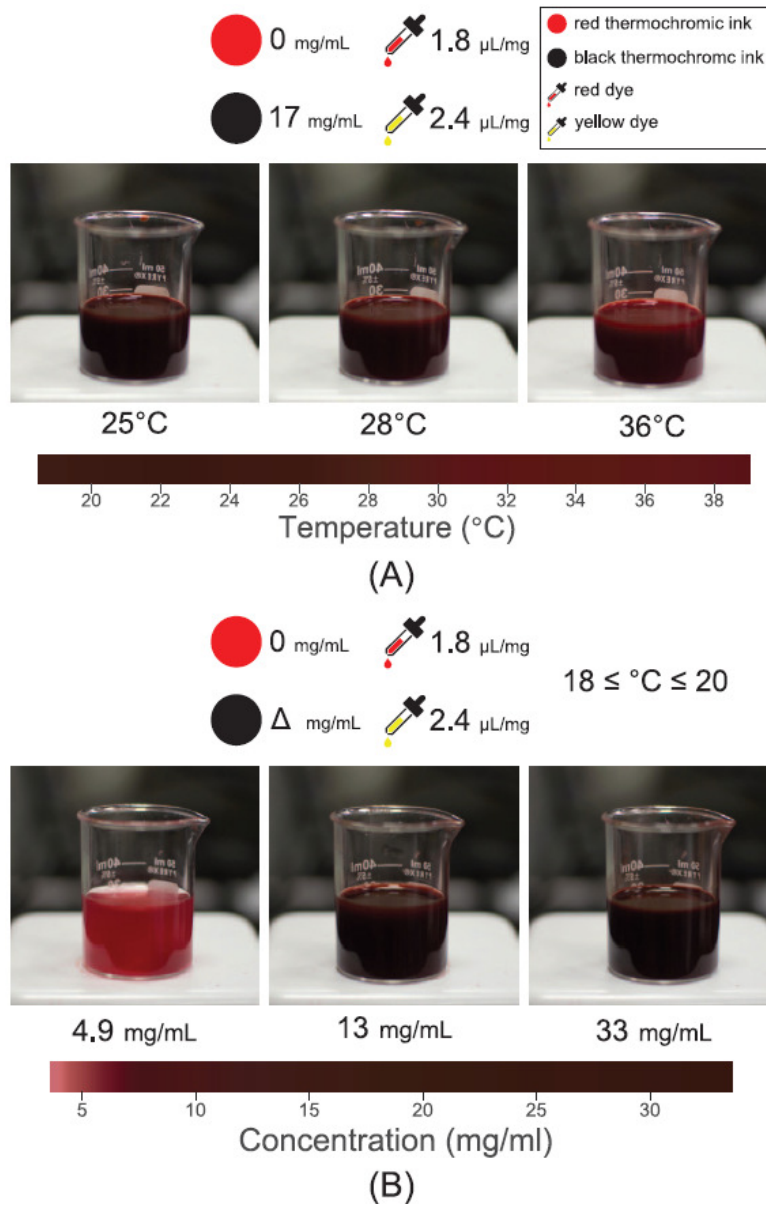
260 **Results**

261 **Thermochromic Fluid**

262 As outlined in Methods, thermochromic ink enables achieving a variety of possible
 263 color variants. Our final recipe consisted of black thermochromic ink with red and
 264 yellow concentrate dyes. The ink was first diluted in distilled water to obtain the
 265 desired concentration. Afterwards, the volume of dyes is determined proportional to
 266 the ink's weight. Figures 2A and 2B show, respectively, how fluid temperature and
 267 ink concentration affect the color of the mixture. The ink's concentration was kept
 268 constant during temperature variations and vice-versa with the dyes' concentration
 269 always proportional to the ink's weight.

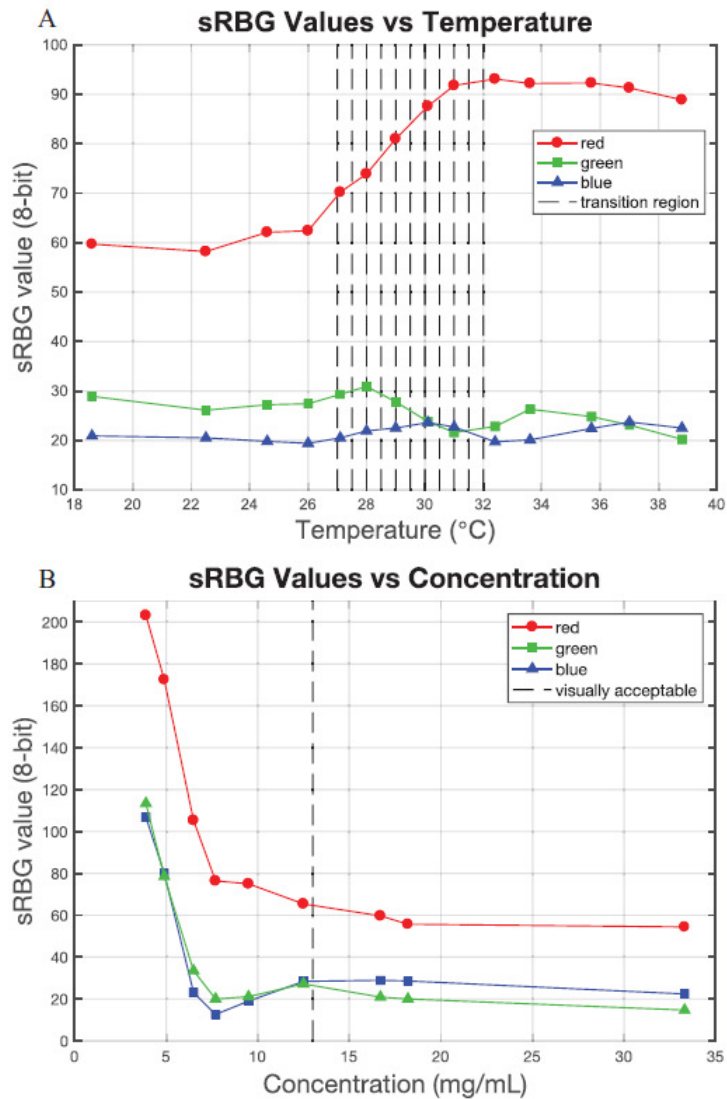
270 sRGB components of the quantified color bars in Figures 2A and 2B are
 271 plotted in Figure 3 where the ink temperature transition region can be clearly

272 observed. Moreover, we found that concentrations lower than 13 mg/mL were too
 273 translucent, and hence a black thermochromic ink of that concentration or higher
 274 was considered visually acceptable.



275
 276
 277
 278
 279

Figure 2: Thermochromic fluid final recipe. (A) The fluid recipe varied over the selected operational temperature range at a fixed concentration (B) The fluid recipe varied over thermochromic ink concentrations.



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Circuit Implementation

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286

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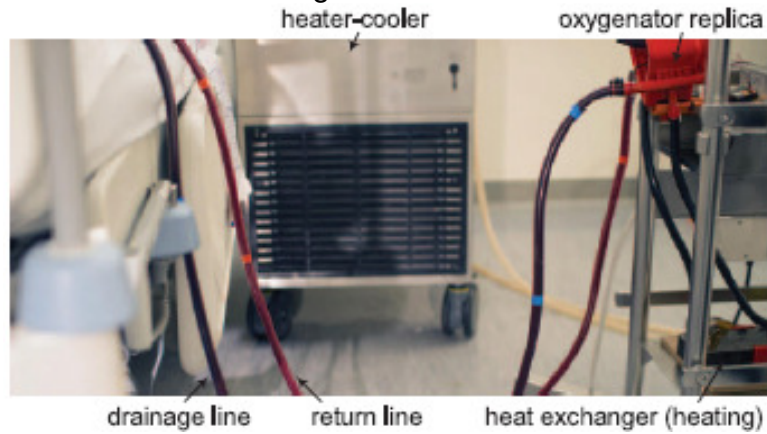
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289

Figure 3: Quantified standard red green blue (sRGB) components. (A) sRGB against temperature variation. (B) sRGB against concentration.

The circuit described in Methods was setup in an intensive care unit at HMC as seen in Figure 4. A prototype mock-up of Maquet’s HLS oxygenator (Maquet, Rastatt, Germany) was 3D printed and used to discreetly bypass the liquid to the oxygenation module (heating unit) and receive it after heating via an opaque PVC tube. The circuit produced three distinct color visual effects as seen in Figure 5:

290 blood oxygenation and deoxygenation, low-oxygen saturation in the return line, and
291 high-oxygen saturation in the drainage line.



292

293

Figure 4: Simulated "ECMO circuit" setup in an ICU.



drainage line (A) return line



(B)



(C)

294

295

296

297

Figure 5: Simulated "ECMO circuit" in its three states. (A) Blood oxygenation and deoxygenation. (B) Low oxygen saturation in return line. (C) High oxygen saturation in the drainage line.

298 The mean rating (out of 5) for oxygenated and deoxygenated blood color realism,
 299 and realism of their contrast were 4.63, 4.79, and 4.53 respectively. Table 2
 300 summarizes the results. Over the period of ten hours, five samples of the
 301 thermochromic fluid were taken from the reservoir and their concentration was
 302 measured. Using a linear fit, we found that the fluid degrades by a 0.38 mg/mL
 303 ($R^2 = 0.84$) per hour. Between the tenth and eleventh hours of operation, the
 304 thermochromic fluid failed whereby the black thermochromic ink stopped
 305 transitioning when heated. None of the participants witnessed the thermochromic
 306 fluid in its non-functioning state.

307

Table 2: Results descriptive statistics

<i>Sample size n = 19</i>	
<i>Oxygenated "Blood" Color Realism</i>	Mean = 4.63 (± 0.482) Min = 4.00 Max = 5.00 Mode = 5.00 Median = 5.00
<i>Deoxygenated "Blood" Color Realism</i>	Mean = 4.79 (± 0.408) Min = 5.00 Max = 4.00 Mode = 5.00 Median = 5.00
<i>"Blood" Color Contrast Realism</i>	Mean = 4.53 (± 0.595) Min = 3.00 Max = 5.00 Mode = 5.00 Median = 5.00

308

309 Discussion

310 High-fidelity simulation sessions aid in achieving suspension of disbelief in trainees
 311 and prevent negative learning, a key to successful SBT.^{24,25} However, high-fidelity
 312 systems and environments are costly and require a significant financial
 313 commitment.²⁶ This is exacerbated with the currently used ECMO SBT

314 approaches. On top of simulation equipment, ECMO centers that offer SBT also
315 rely on a functioning ECMO machine alongside expensive consumable circuit
316 components which offer little in terms of context because the visual/audio cues
317 they produce and parameters they display are generally inconsistent or
318 uncontrollable in relation to enacted scenarios.

319 We sought to address the limitations of the ECMO simulation paradigm by
320 developing a standalone and modular ECMO simulator. In this article, we
321 demonstrated the design and implementation of a patented simulated “ECMO
322 circuit” featuring a unique thermochromic effect that resembles blood oxygenation
323 color change in real ECMO circuits²⁷. The circuit operates on a balanced and
324 continuous heat exchange process, producing a temperature difference between
325 the drainage and return lines, and hence a color difference due to
326 thermochromism. It can create visual cues relevant to many emergency scenarios
327 including oxygenator failure, disconnected gas supply, increased oxygen
328 consumption, decreased lung function, inadequate circuit flow, and recirculation.
329 Nineteen clinicians specializing in ECMO at HMC with varying degrees of
330 experience evaluated the fidelity of the thermochromic effect. On average, the
331 participant rated the effect as highly realistic. The common criticism received was
332 that the oxygenated and deoxygenated “blood” colors were too dark and should be
333 slightly brighter and redder, which can be corrected by changing the concentration
334 of dyes and ink in the fluid mixture.

335 Advantages of an ECMO independent simulator with a modular design
336 approach are the reduced deployment and maintenance cost, customizability and
337 expandability, and full system control. The simulated blood color change circuit
338 components (excluding the heater-cooler) costs 300 USD to build and can be used
339 indefinitely (or until a component is damaged) since components are non-
340 consumable. Our thermochromic recipe costs 40 USD/L with a low (0.38 mg/mL)
341 concentration degradation over time and an operational lifetime of ten hours. It is
342 up to the user to determine whether circuit component costs and the fluid’s realism,
343 cost, and lifetime is acceptable as every component used in the circuit can be
344 substituted by other brands and there are many possible recipes due to the broad
345 selection of thermochromes and dyes in the market. Moreover, our in-house design
346 facilitates ease of use and control since the system electronics are programmable
347 to the user’s preference and can be wirelessly enabled to receive remote
348 commands to perform simulation actions. Overall, many of the existing ECMO
349 related SBT programs could greatly benefit from this innovation to further enhance
350 their participants’ learning.²⁴

351 This study has several limitations. First, we had no access to quantitative
352 color-measuring tools, limiting the color quantification to a digital camera, where it
353 can vary based on the illuminance and the camera exposure settings. We

354 attempted to mitigate this weakness by (i) presenting photos of the fluid in two
355 different environments and illuminants (in-lab and in-situ); (ii) using the camera's
356 luminance histogram to make sure the exposure is set in the middle (not too dark
357 or too bright); and (iii) surveying ECMO specialists about the realism of the color.
358 Second, our assessment of the circuit's efficacy is limited by the prototypic nature
359 of the implementation. Thus, our design can only be truly assessed when the
360 system is complete with a "product level" quality and is compared head to head
361 with the traditional simulation method. Finally, the realism of the simulator is highly
362 dependent on the fidelity of our 3D printed components and casings and how well
363 we can integrate the modules into the ICU environment. Future work includes
364 obtaining a thermochromic fluid with longer operational time and establishing a
365 dynamic relationship between simulated blood color and various ECMO
366 parameters such as hemoglobin and oxygen saturation.

367

368 **Conclusions**

369 A novel system consisting of modules that work together to reproduce ECMO's
370 visual, audio, and haptic cues is proposed. In this article, we presented the use of a
371 low-cost but high-fidelity technology in the design of two modules responsible of
372 creating a simulated ECMO circuit with the ability to reproduce ECMO's blood
373 oxygenation visual cue (or the lack thereof) using the thermochromism properties
374 of a fluid mixture. The two modules work together to create a temperature
375 difference between the drainage and return lines of the "ECMO circuit", resulting in
376 a color difference. ECMO practitioners found the circuit highly realistic and they
377 could easily distinguish the two colors of the simulated blood.

378 We envision that, after completion, our modular ECMO simulator will feature
379 more simulated ECMO cues including drainage line vibrations (line-shattering),
380 patient bleeding, air noise in the pump head, blood oxygenator clotting, and others.
381 Those modules will be wirelessly connected to a tablet application, giving
382 instructors full control of the ECMO environment and facilitating the creation of
383 high-fidelity and immersive simulation scenarios.

384

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490 **Declaration of Conflicting Interests**

491 The Authors declare that there is no conflict of interest.