Advancing Life Support with an Open-Source ECMO Simulation Model

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INTRODUCTON

- Extracorporeal membrane oxygenation (ECMO) provides advanced life support for respiratory or circulatory failure
- Effective ECMO therapy requires managing complex physiological interactions and significant clinical expertise
- Developing a robust digital twin simulation helps explore the effects of support titration and treatment strategies
- In silico evaluation of autonomous life-support strategies for use in austere and pre-hospital settings can inform deployment in challenging environments
- A simulation-based approach can improve ECMO outcomes by enabling:
  - Innovation in device design
  - Development of automated control systems
  - Predictive modeling of patient-specific response and therapy optimization
  - Synthetic data to train AI tools and support clinical decision-making
- Extending the open-source Pulse Physiology Engine [1] to model ECMO hemodynamics and substance transport provides a flexible platform for research, testing, and training

pulse.kitware.com   Pulse Physiology Engine

METHODS

Table 1. Cannulation Site Options

Group	Location
Venous - Central	Right Atrium
	Superior Vena Cava
	Inferior Vena Cava
Venous - Peripheral	Internal Jugular
	Right Femoral Vein
	Left Femoral Vein
	Right Subclavian Vein
	Left Subclavian Vein
Arterial - Central	Ascending Aorta
	Carotid Artery
Arterial - Peripheral	Right Femoral Artery
	Left Femoral Artery
	Right Axillary Artery
	Left Axillary Artery

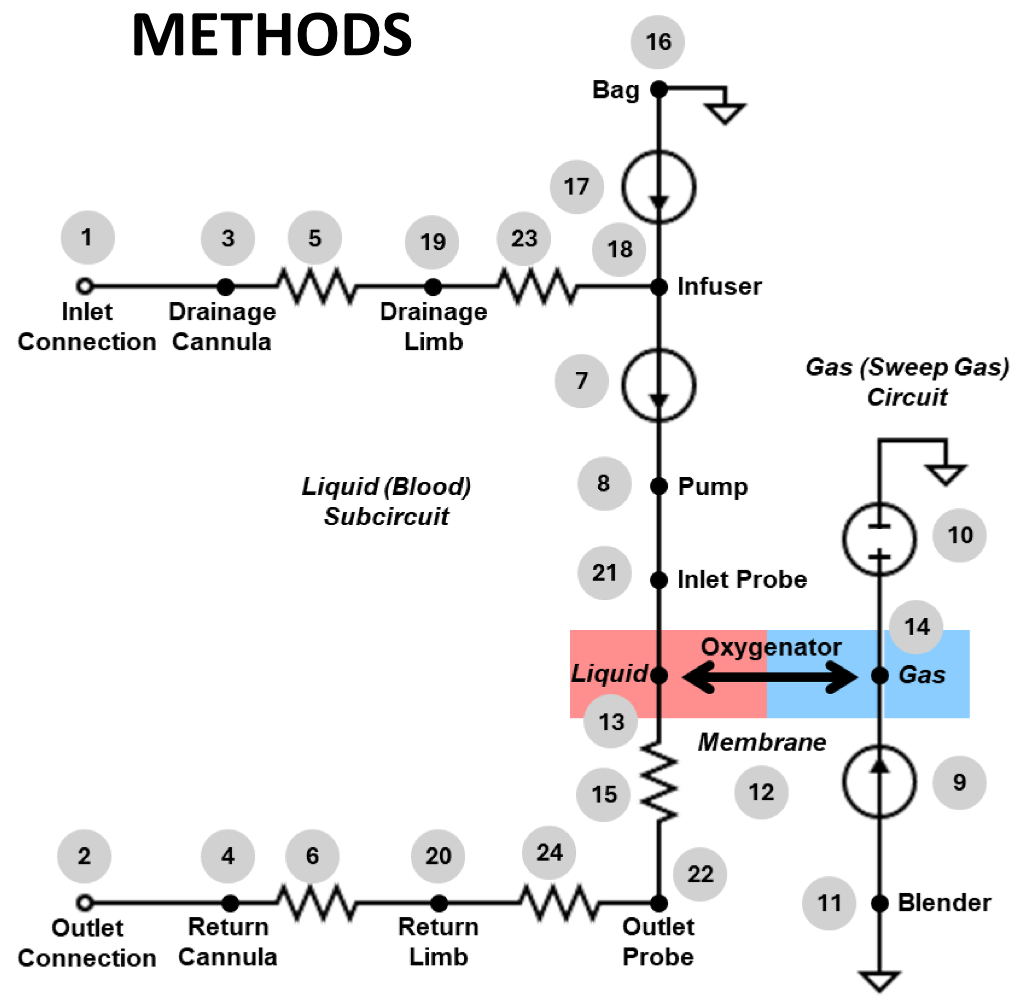

Figure 1. ECMO Device Circuit

- Implemented a physics-based lumped parameter ECMO fluid circuit and transport graph
- Simulated ECMO device is coupled to pulmonary and cardiovascular systems and connects to key anatomical sites
- Supports both respiratory (VV) and circulatory (VA) ECMO configurations, including key device settings
- Supports both multisite and single-site dual-lumen (SSDL) cannulation
- Enables evaluation of device parameters, hemodynamic and gas exchange effects, and automated control algorithm development
- Automated validation capabilities include scenarios for multitrauma and comorbid conditions such as hemorrhage, respiratory distress, and resuscitation
- Synthetic data generation by varying patient parameters, combining insults, and applying interventions

Table 2. ECMO Device Settings

Label	Parameter	Components
1	Inlet Location	Cannulas
2	Outlet Location	
3	Drainage Cannula Volume	
4	Return Cannula Volume	
5	Drainage Cannula Resistance	
6	Return Cannula Resistance	
7	Pump Flow	Pump
8	Pump Volume	
9	Sweep Gas Flow	Oxygenator
10	Supply Pressure	
11	Fraction Of Sweep Gas Oxygen	
12	Oxygen Membrane Diffusing Capacity	
12	Carbon Dioxide Membrane Diffusing Capacity	
13	Oxygenator Liquid Volume	
14	Oxygenator Gas Volume	
15	Oxygenator Resistance	
16	Bag Compound	Fluid Administration
16	Bag Volume	
17	Infuser Rate	
18	Infuser Volume	
19	Drainage Limb Volume	Peripherals
20	Return Limb Volume	
21	Inlet Probe Volume	
22	Outlet Probe Volume	
23	Drainage Limb Resistance	
24	Return Limb Resistance	

RESULTS

Extracorporeal Life Support Organization (ELSO) Guideline-Based Comparison [2, 3]

- Simulated management of a mechanically ventilated patient with severe bilateral ARDS, with and without VV ECMO support
- Femoral vein inlet and internal jugular vein outlet, consistent with ELSO recommendations for adult respiratory failure

Initial Simulation Scenario Segment (Table 3) – No ECMO Support:

- Represents baseline care for a patient meeting criteria for VV ECMO
- Ventilator settings reflect aggressive ARDS management prior to ECMO initiation

Final Simulation Scenario Segment (Table 4) – With ECMO Support:

- VV ECMO initiated using ELSO-recommended parameters
- Ventilator settings adjusted to lung-protective levels per the ELSO lung rest strategy

ECMO Configuration Experimental Data Validation

- Ten mechanically ventilated ARDS patients receiving femoro–jugular VV ECMO were studied by Schmidt et al. [4]
- In the experimental protocol, blood gases were measured after independently varying circuit blood flow or sweep gas flow, with all other settings held at their maximum
- Simulated validation scenarios followed the same approach to evaluate model performance under comparable conditions
- Figures 2 and 3 display whisker plots of measured data (gray) [4] with simulator results overlaid (red)
- Figure 4 presents an example of the automated landing monitor used to support evaluation

Table 3. Initial State Showing Indication for ECMO Initiation

Property Name	Accepted Value	Simulated Value	Pass/Fail
Vent VT Setting for 4-6 mL/kg (mL)	301 - 602 [2]	436	Pass
Vent RR Setting (bpm)	10 - 30 [2]	19.9	Pass
Vent PIP Setting (cmH2O)	< 30 [2]	29	Pass
Vent PEEP Setting (cmH2O)	> 10 [2]	12	Pass
pH indication for ECMO initiation	< 7.25 [2]	7.23	Pass
PaCO2 indication for ECMO initiation (mmHg)	> 60 [2]	63.8	Pass
PaO2/FiO2 indication for ECMO initiation (mmHg)	< 80 [2]	72.8	Pass

Table 4. Final State with ECMO Lung Rest Strategy

Property Name	Accepted Value	Simulated Value	Pass/Fail
Vent VT Setting for 4-6 mL/kg (mL)	301 - 602 [2]	341	Pass
Vent RR setting (bpm)	4 - 15 [2]	10	Pass
Vent I:E Ratio setting	1:1 [2]	1:1	Pass
Vent PIP setting (cmH2O)	< 25 [2]	22	Pass
Vent PEEP setting (cmH2O)	10 [2]	10	Pass
ECMO Blood Flow setting (L/min)	4 - 6 [2]	4.5	Pass
ECMO Sweep Gas Flow setting (L/min)	1 - 10 [2]	3	Pass
Suction Pressure to prevent issues (mmHg)	> -300 [3]	-70.4	Pass
Outlet Pressure to prevent circuit strain (mmHg)	< 400 [3]	155	Pass
MAP for adequate perfusion (mmHg)	> 65 [2]	96.1	Pass
pH for normal range	7.35 - 7.45 [2]	7.38	Pass
PaO2 for target oxygenation (mmHg)	60 - 100 [2]	89.2	Pass
PaCO2 for target CO2 clearance (mmHg)	35 - 45 [2]	43.4	Pass
SpO2 to maintain oxygenation (%)	> 95 [2]	97.1	Pass

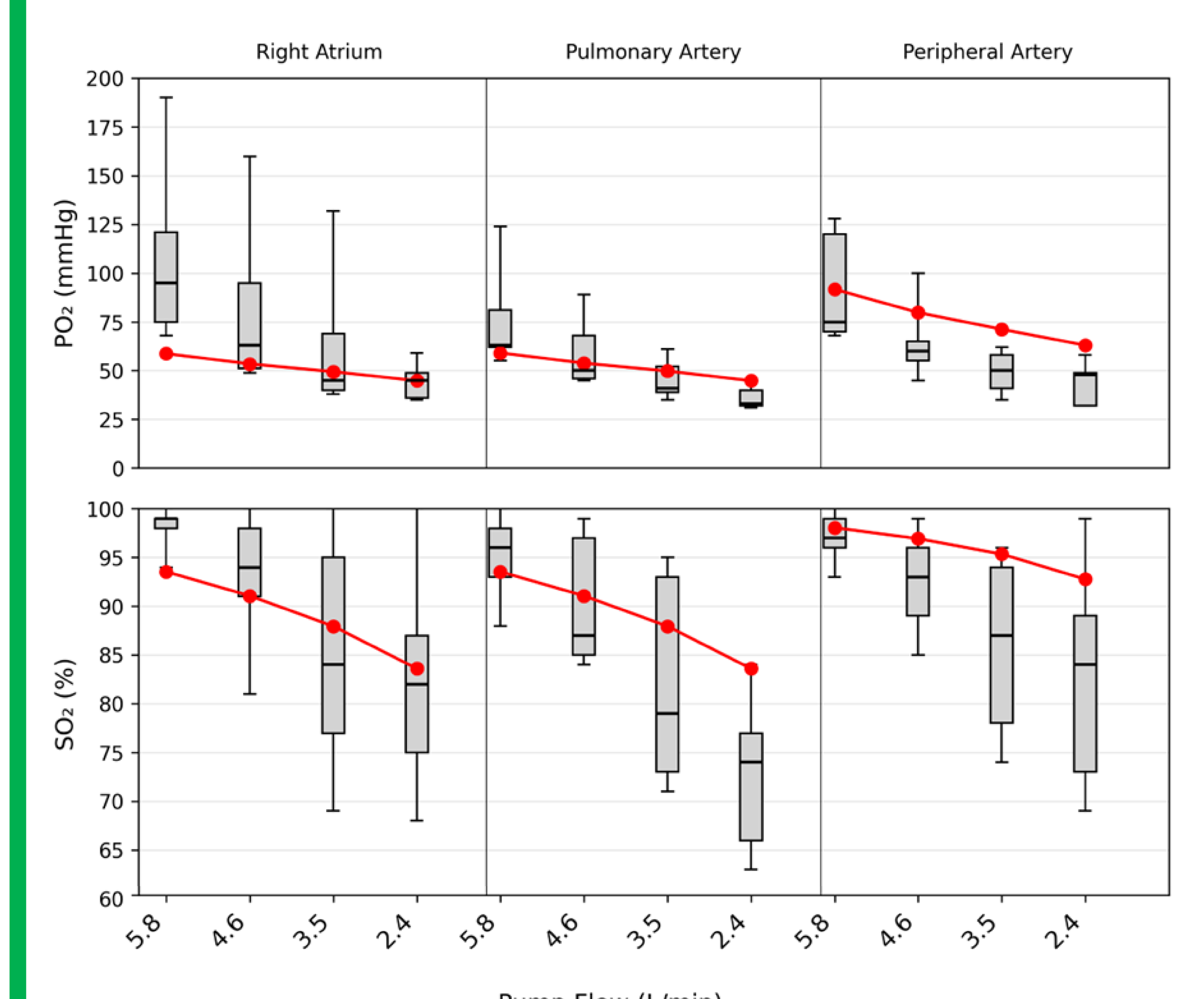

Figure 2. Impact of Pump Flow Reduction

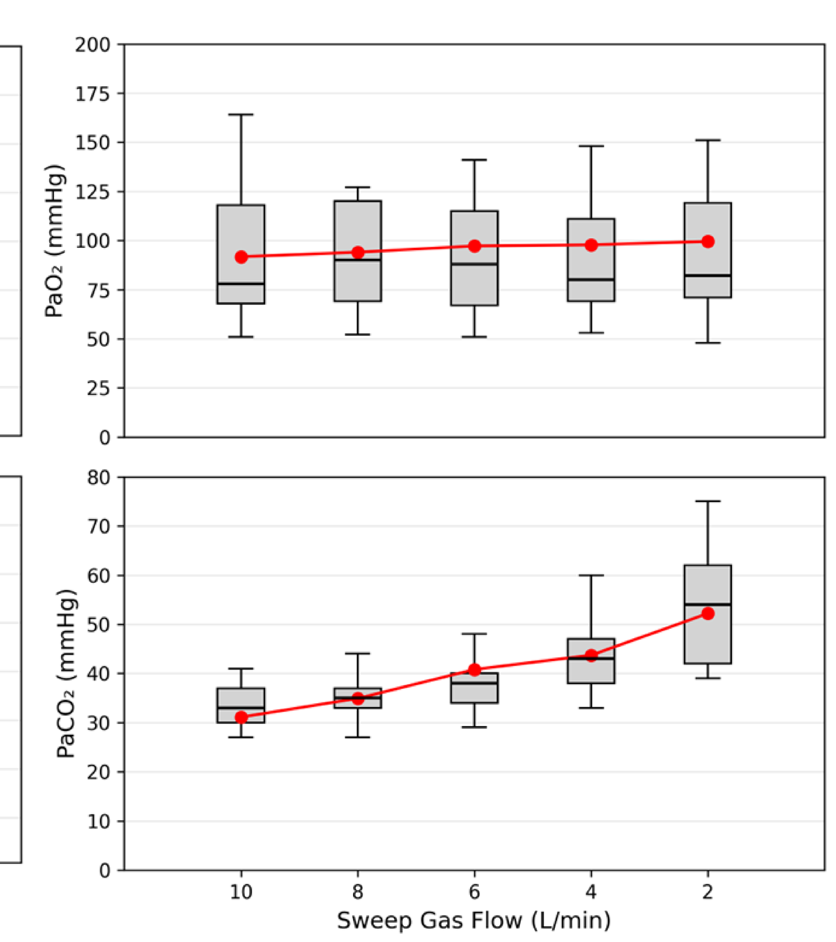

Figure 3. Impact of Sweep Gas Flow Reduction

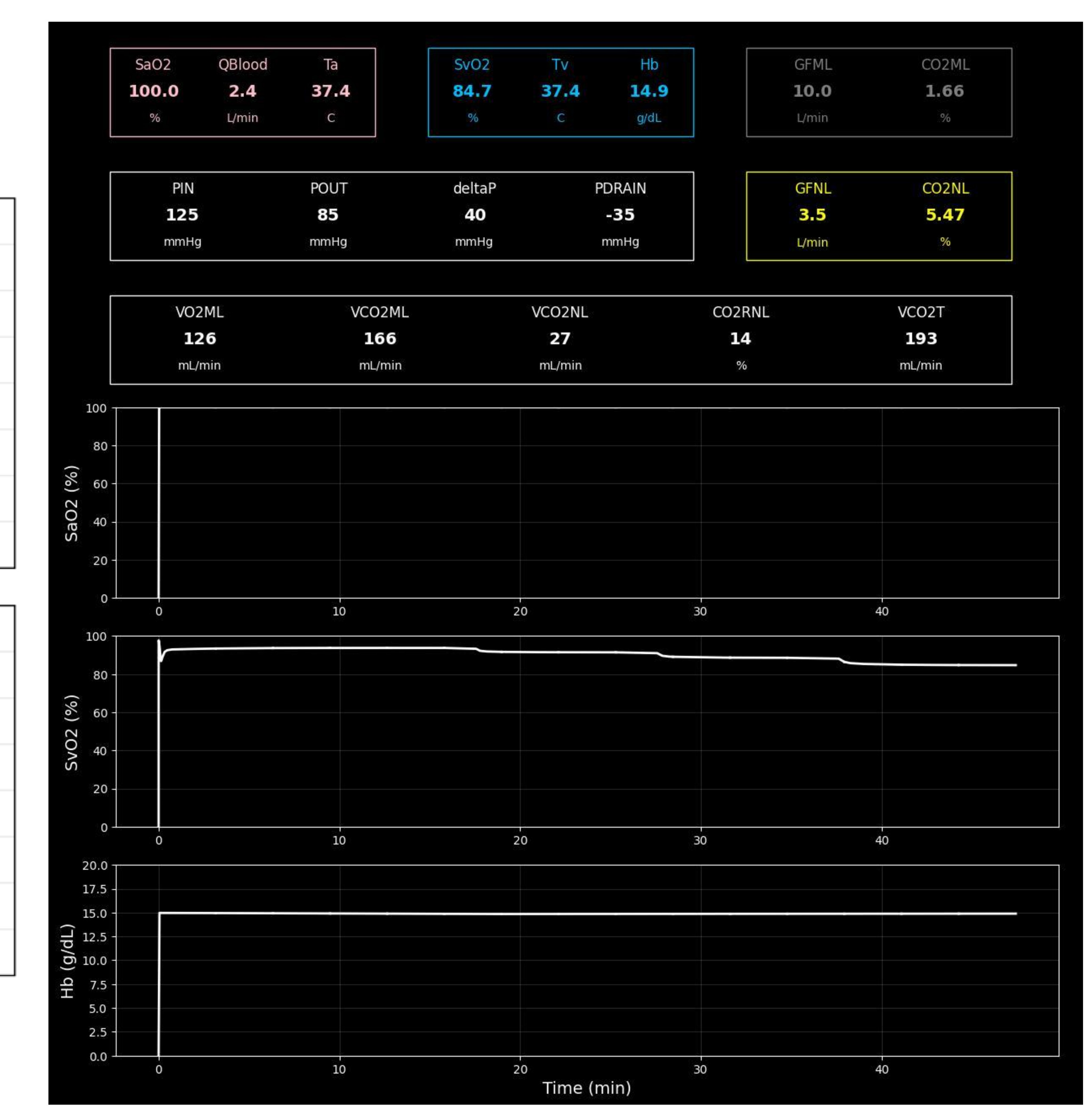

Figure 4. Simulated Landing Monitor

REFERENCES

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DISCUSSION

A new ECMO device model was successfully integrated into the Pulse Physiology Engine whole-body framework and demonstrated effective dynamic coupling with mechanical ventilation in severe respiratory distress. The result is a validated open-source platform to support device development, training, and improved patient care. Simulated responses to changes in ECMO flow and sweep gas matched published patient data. Future work includes further calibration to clinical data, animal model comparisons, and expansion to cyber-physical simulations.

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