Maximum Efficiency of Extracorporeal CO_2 Removal Requires Nine -to-One Sweep Gas Flow to Blood Flow Rates for Metabolic Intervention Benefits

AUTONOMOUS REANIMATION AND AREVA EVACUATION RESEARCH PROGRAM
THE GENEVA FOUNDATION

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Introduction

- High sweep gas flow rates during low-flow extracorporeal carbon dioxide removal ($ECCO_2R$) therapy rapidly remove CO_2 and stabilize pH levels
- High "sweep gas" flow rates lead to high oxygenator membrane ventilation-perfusion (V/Q) ratios, yet optimal V/Q is not well established
- Membrane oxygenator "dead space" is the fraction of the membrane that is ventilated but not perfused, and gas exchange is impeded

Objective

- Investigate the relationship between high V/Q ratios and CO_2 removal efficiency in an *ex vivo* circulation model

Hypothesis

- CO_2 removal becomes inefficient at higher V/Q ratios

Methods

- *Ex vivo* circuit (Figure 1) consists of two sections: **1)** physiological simulator (Cardiohelp + HLS Membrane, Maquet, Rastatt, Germany) to model *in vivo* circulation, and metabolic activity; **2)** Gas-exchange membrane oxygenator (Novalung XLung, Fresenius Medical Care NA, Waltham, MA) with heat exchanger used for $ECCO_2R$
- Exhaust gas sampled and dehumidified (using Nafion sampling line); CO_2 measured using a nondispersive IR sensor (1Hz) (SprintIR®-W; Gas Sensing Solutions Ltd; Cumbernauld, UK)

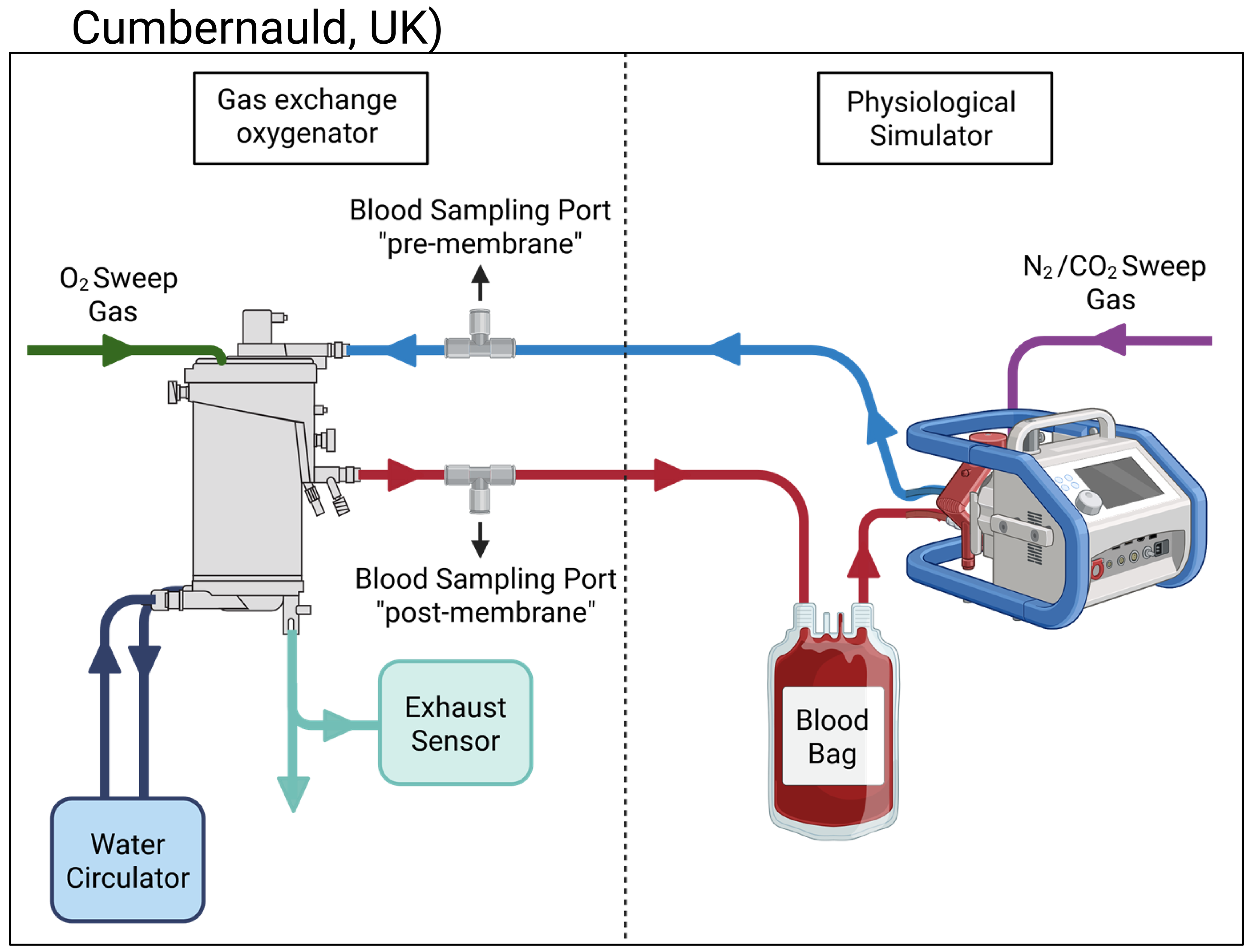

Figure 1: *Ex vivo* circuit design with physiological simulator, ECLS membrane oxygenator, and tubing circulating 2 liters of donor swine blood. Blood was heated to 38 °C using external water heater and heat exchanger in oxygenator. Schematic created with Biorender.com

Methods

- Circuits filled with 2 L heparinized donor swine blood (Animal Technologies Inc., Tyler, TX; USDA EU 142/2011, ISO certified)
- During circulation: a blood flow and sweep gas flow rate target was set:
  - Blood flow targets: Q_b = 0.5, 1.5, and 2.0 L/min
  - O_2 sweep targets: V_g = 3, 10 and 14 L/min
- Target combinations set, allowed 10 min equilibration
- Blood pCO_2 (GEM4000; Instrumentation Laboratories) and exhaust gas CO_2 ($PeCO_2$) analysis performed; new targets selected, process repeats
- V_g / Q_b combinations with > 3 paired measurements were analyzed (Figure 2) resulting in V/Q ratios of 1.50, 6.00, 6.67, 9.33, 20.00, and 28.00; n = 54 paired measurements
- CO_2 exhaust and V/Q ratios were compared using linear regression and Pearson correlation coefficients (PCC)
- Optimal V/Q was assessed with Welch's t-test; p < 0.05
- Oxygenator performance calculations:
  - Ventilation/dilution index $VDI = 1 - PeCO_2 \,/\, pre\ pCO_2$
  - Membrane dead space index $MDSI = 1 - PeCO_2 \,/\, post\ pCO_2$
  - Gas-side CO_2 clearance $\dot{V}CO_2 = PeCO_2 \,/\, [P_{atm} - PH_2O] \times Vg$

Results

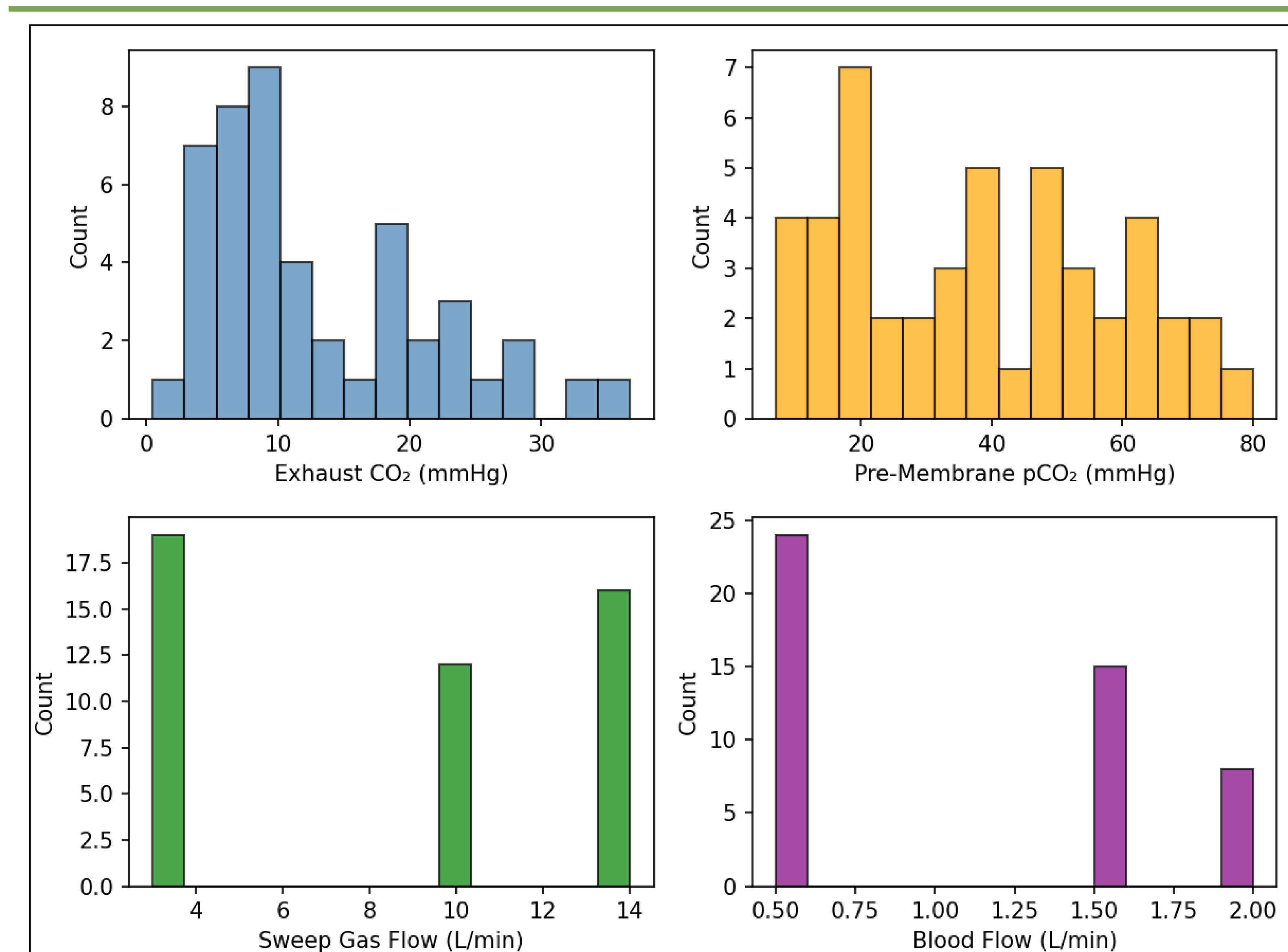

Figure 2: Histograms detailing sample counts for exhaust CO_2, pre-membrane CO_2, sweep gas flow, and blood flow.

Results

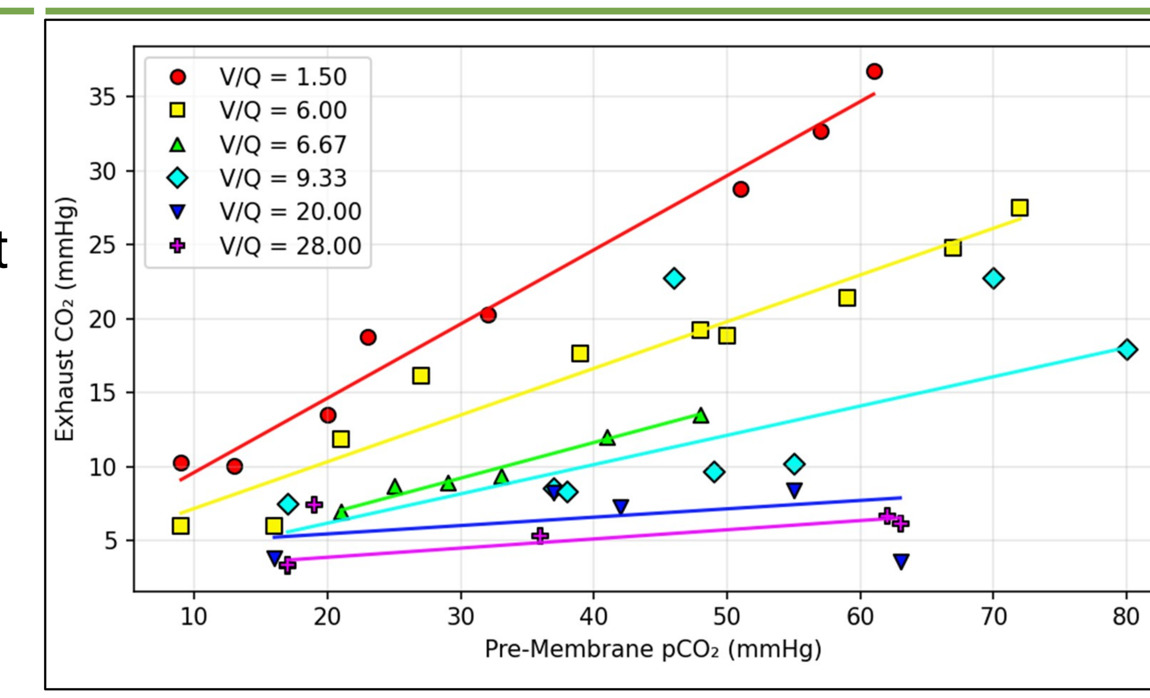

Figure 3: $PeCO_2$ vs pre-membrane blood pCO_2 at various V/Q ratios.
- $PeCO_2$ scaled linearly with pre pCO_2
- Slope decreased from 0.50 to 0.06 as V/Q increased from 1.50 to 28.0
- PCC decreased as V/Q increased (see table)

V/Q	n	slope	ρ (PCC)
1.50	8	0.501	0.990*
6.00	11	0.304	0.963*
6.67	7	0.251	0.993*
9.33	8	0.198	0.652
20.00	5	0.057	0.805
28.00	8	0.066	0.086

* p<0.05

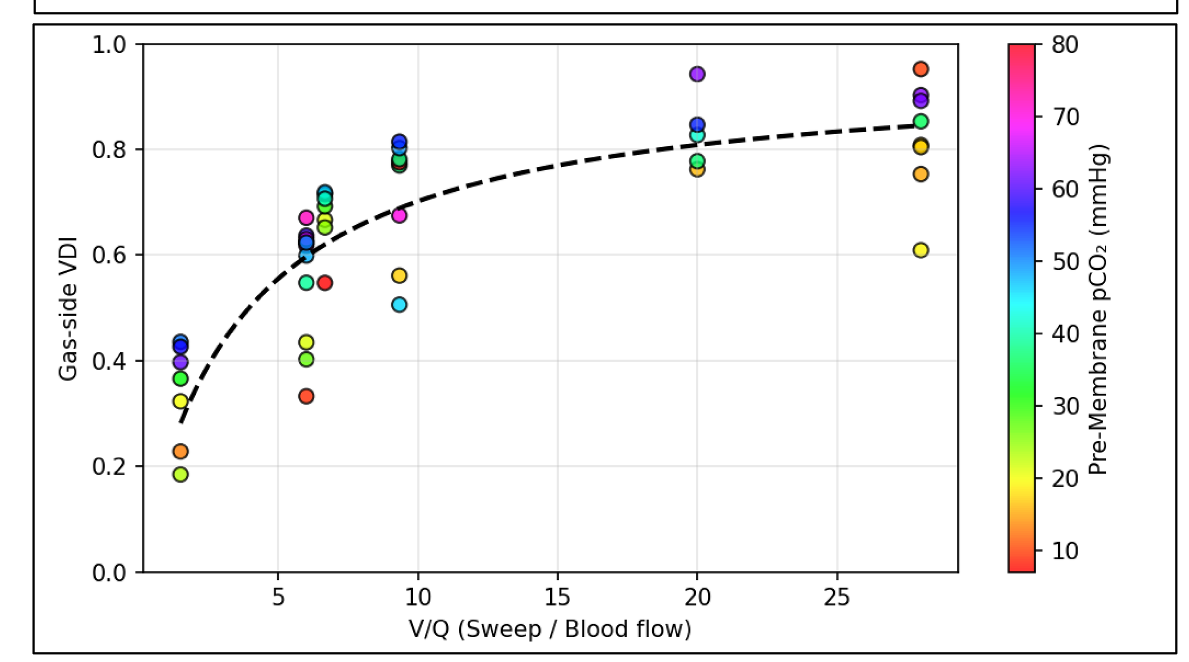

Figure 4: VDI vs V/Q
- VDI, as a function of V/Q, showed saturating behavior, with an asymptote approaching VDI~0.9
- Consistent with a mixed ventilation–dilution effect on the exhaust signal

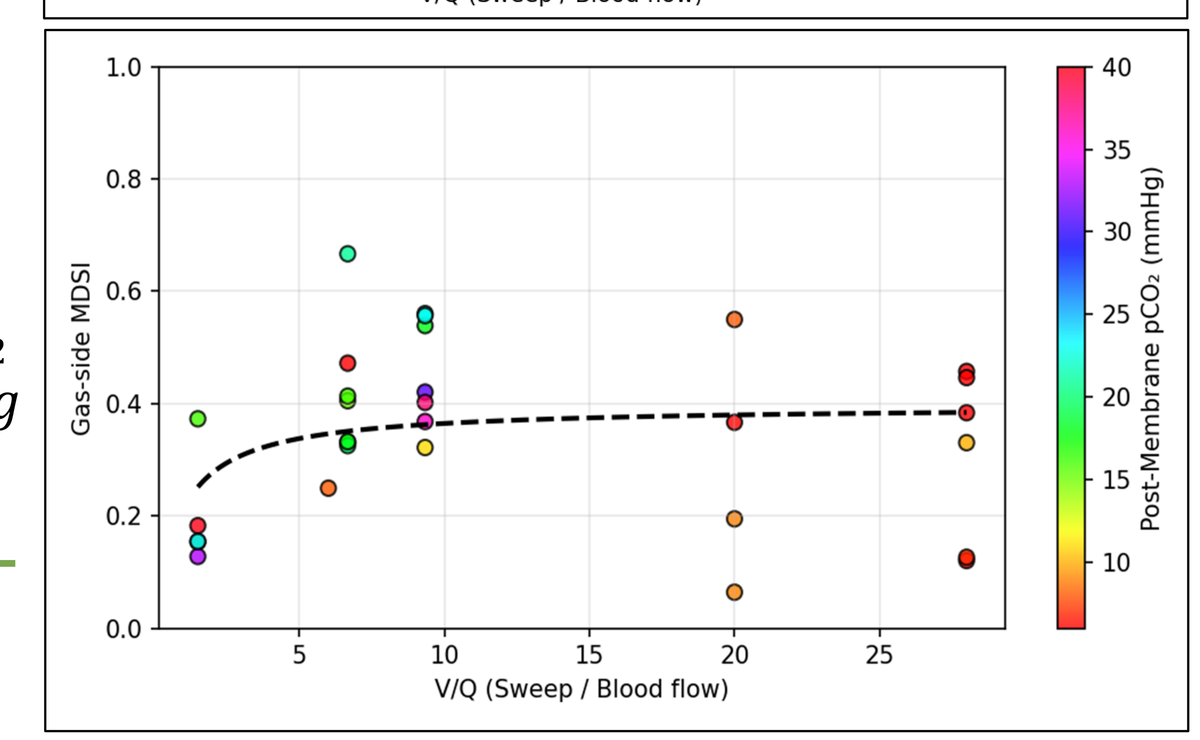

Figure 5: MDSI vs V/Q
- The MDSI showed no significant correlation with V/Q

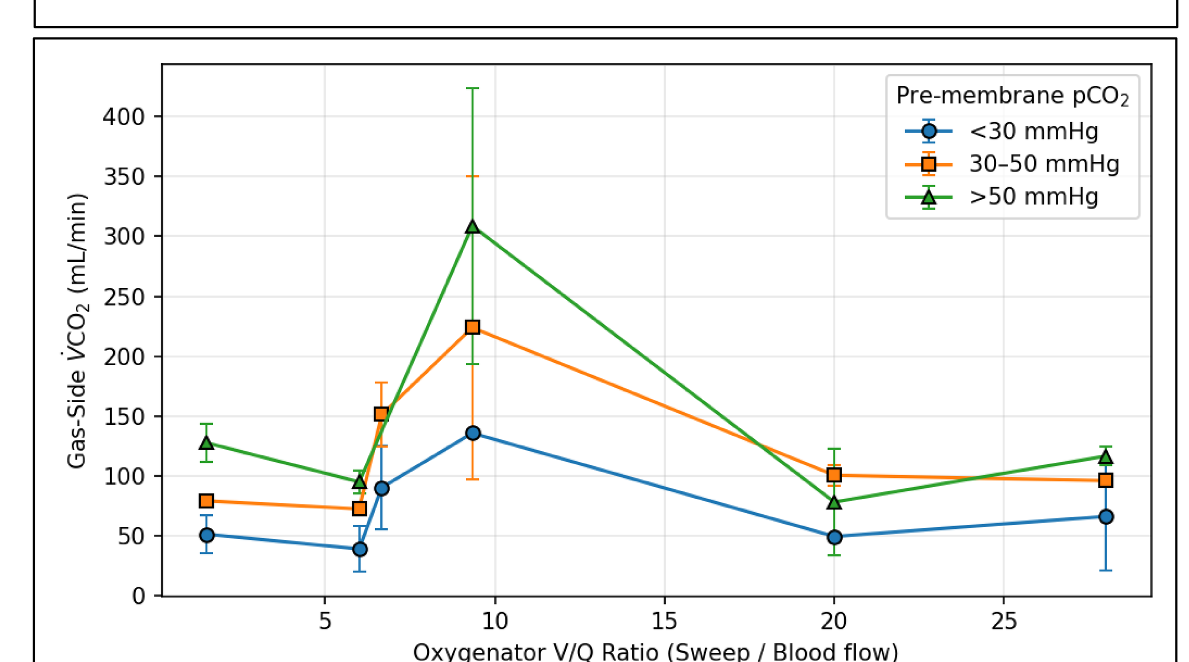

Figure 6: $\dot{V}CO_2$ vs V/Q
- Peak $\dot{V}CO_2$ occurred at V/Q=9.33 (V_g=14, Q_b=1.5, t=3.73, *p*=0.007)
- Decreasing or plateauing values at higher V/Q ratios

Conclusions

- Optimal V/Q ratio for CO_2 removal is 9.33; higher ratios provide limited benefit in this model
- CO_2 removal inefficiency is attributable to overventilation rather than inadequate perfusion

Acknowledgments

This research was supported, in part, by UIWSOM and sponsored by AREVA Research Institute.