Computational Simulation of Mechanically Ventilated Patients in ICU

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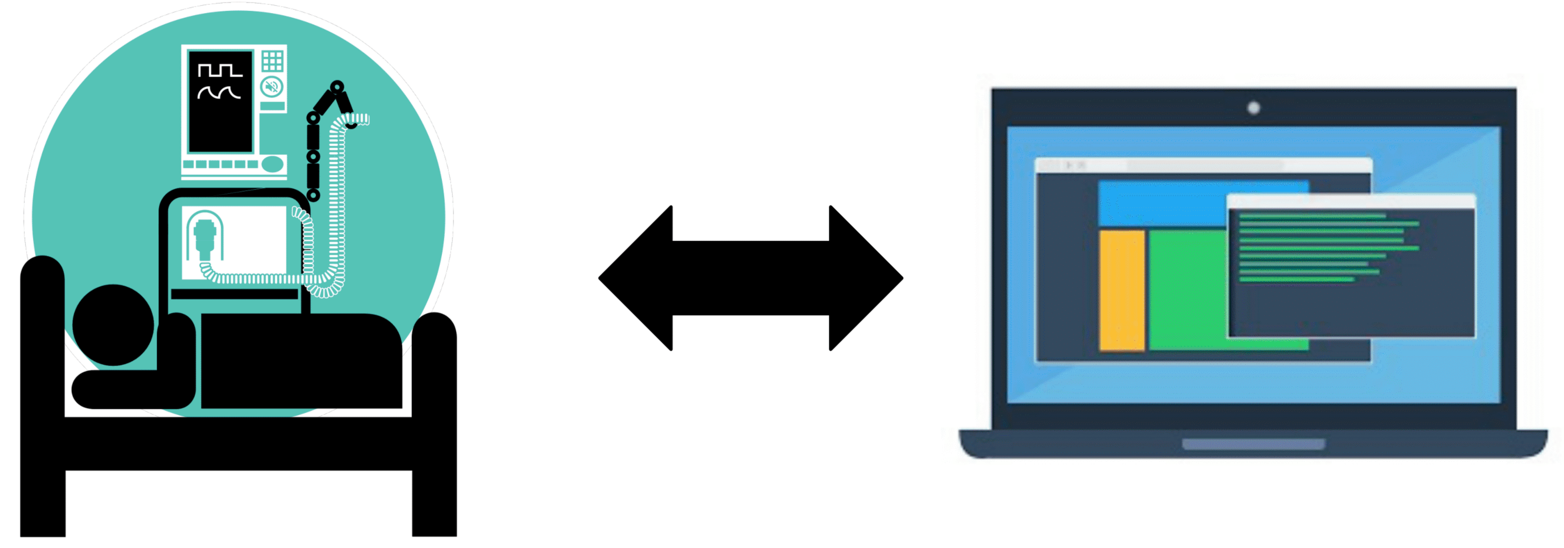
Why use simulations for research into respiratory illnesses?

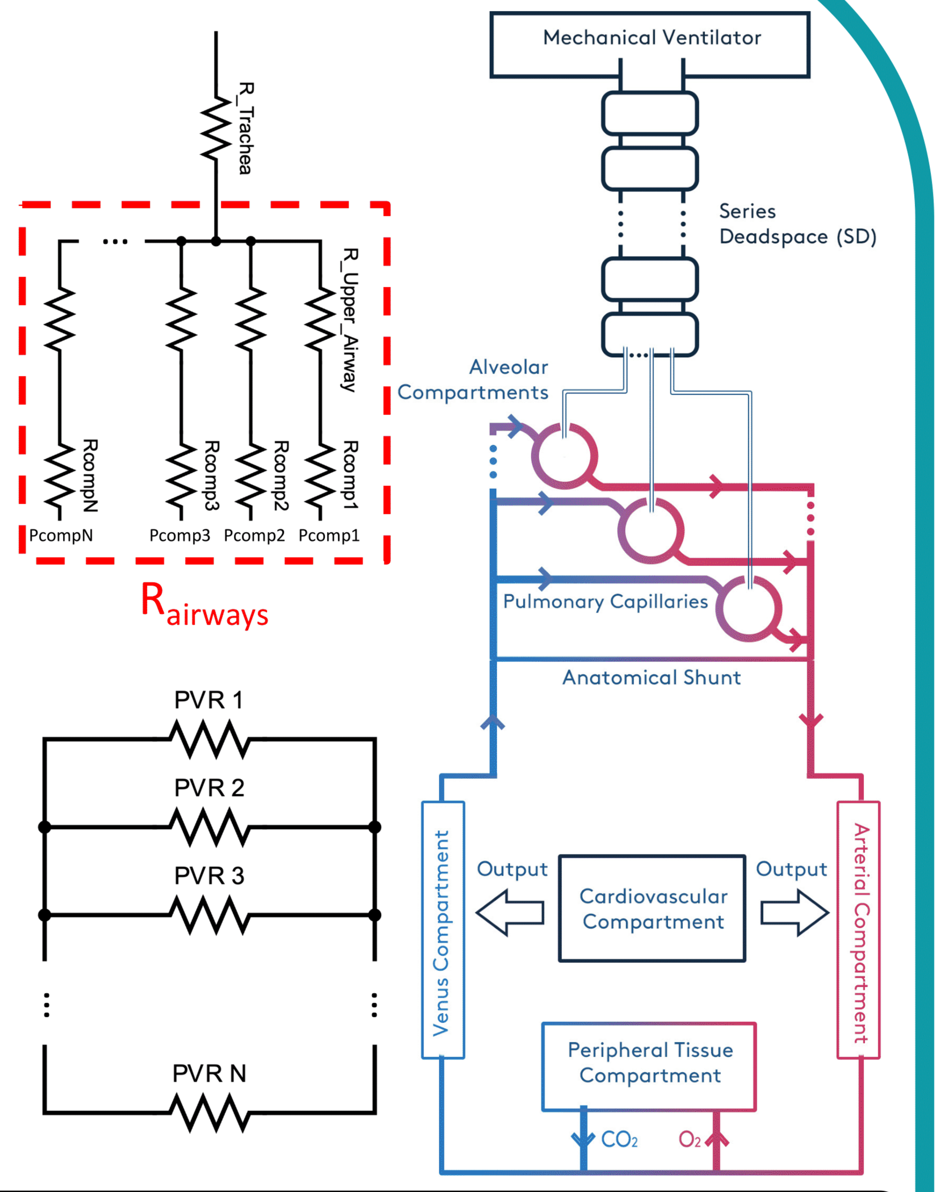


- ❖ Mechanical ventilation is the **most important therapeutic intervention** for patients with respiratory failure in ICU [1]. However, mechanical ventilation can **also cause injury** (VILI).
- ❖ A sizeable number of patients receive mechanical ventilation (69k patients in the UK in 2012, Case Mix Programme) with an average **daily cost of €1590** [2].
- ❖ Very difficult to conduct clinical research on critically ill patients
  Many practical / **ethical issues**, clinical trials massively **expensive**, difficult to design, with high failure rates.
- ❖ No single animal model typically replicates the **complex pathophysiology** of respiratory diseases.
- ❖ Clinician workload has been shown to be directly linked to patient outcomes, and a significant number of life-threatening human errors regularly occur (**1.7 human errors per ICU patient per day**) [3].
- ❖ Still difficult to "**look inside**" the lung.
- ❖ Demand for more **personalised** treatment strategies.
- ❖ Strong interest from Funding Agencies and Industry.

Pulmonary simulator

- ❖ Computational model where changes in compartmental constituents calculated iteratively over time [4]
- ❖ Includes representations of multiple interacting organ systems (e.g airways, multi-compartmental alveolar units, gas exchange, compliance) and key aspects of cardio-pulmonary dynamics (e.g. blood-gas solubility and haemoglobin behaviour)
- ❖ Represents various pathological phenomena:

1- Heterogeneous distributions of pulmonary ventilation & perfusion
2- Collapse and recruitment of airways and alveolar compartments



Transport of air from mouth to trachea, conducting airways (series dead space) and multiple alveolar compartments

$$R_{airways} = \frac{1}{\sum_1^N \left(\frac{1}{R_{UpperAirway} + R_{mult} \times Rcomp_i}\right)}$$

$$R_{total} = R_{Trachea} + R_{airways}$$

$$Flow_{comp_i}(t_K) = \frac{P_{Trachea} - P_{comp_i}}{R_{UpperAirway} + R_{comp_i}} \times Sampling\ Time$$

Calculate the corresponding pressure in each alveolar unit

$$P_{comp_i} = ST_{alv_i}(V_{comp_i} - Collapse\ Volume)^2 - P_{ext_i}$$

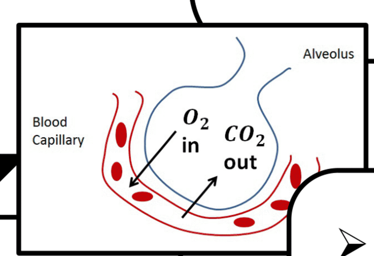
Calculation of blood flow in each capillary compartment

$$PVR = \frac{1}{\sum_1^N \left(\frac{1}{PVR_{mult} \times PVR_i}\right)}$$

$$CO(t_K) = CO \times Sampling\ Time$$

$$CO_{non-shunted}(t_K) = (1 - Anatomical\ Shunt) \times CO(t_K)$$

$$Q_{comp_i}(t_K) = \frac{CO_{non-shunted}(t_K) \times PVR_{total}}{PVR_i}$$



Equilibrate the gases between alveolar unit and its corresponding capillary

Update blood parameters

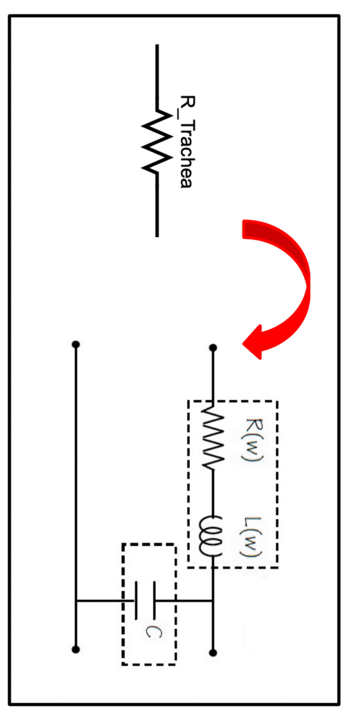
- ➢ McHardy version of Visser's equation (C_{CO_2})
- ➢ Henderson Hasselbach equation (pH)
- ➢ Van-Slyke Equation (HCO_3)
- ➢ Severinghaus equation (S_{O_2}, P_{O_2})

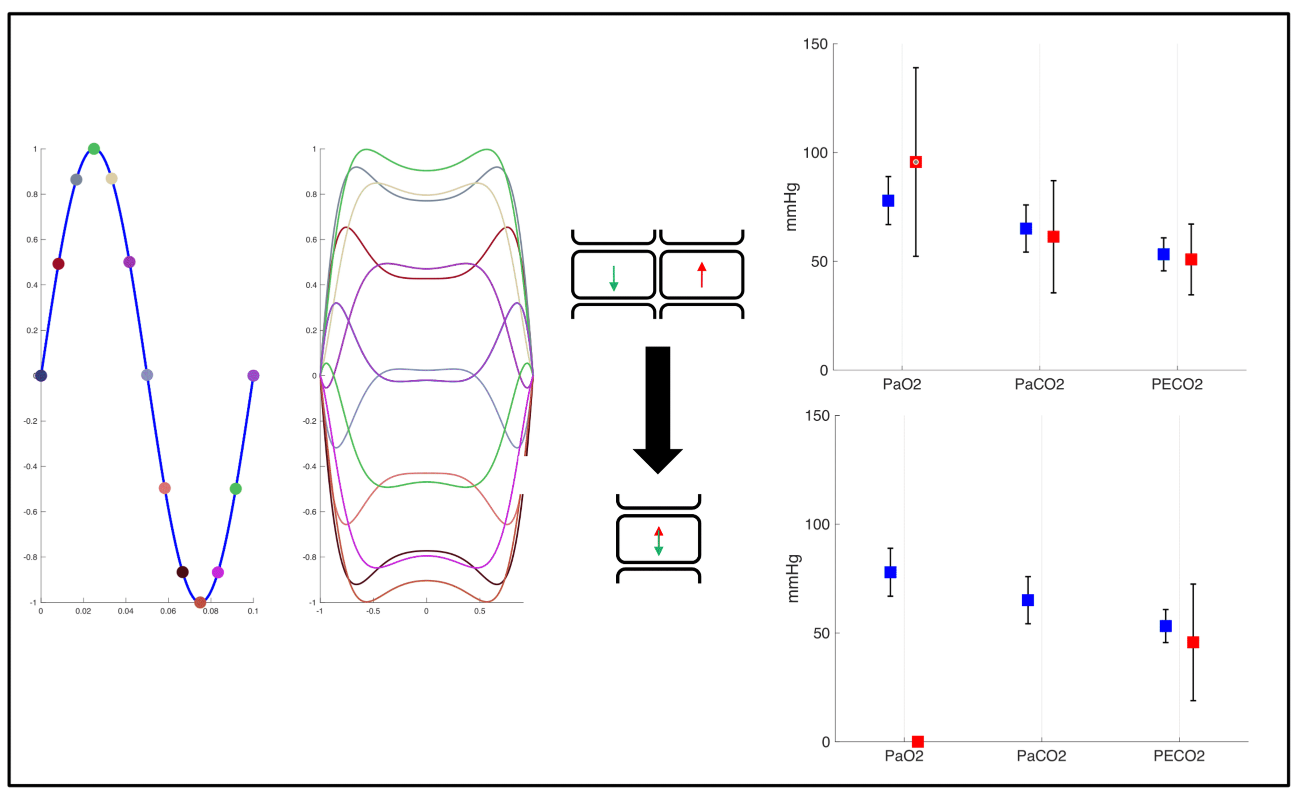
HFOV (High-Frequency Oscillatory Ventilation)

- ❖ Small tidal volumes delivered at high frequencies (3-15 Hz)
- ❖ Aims to prevent lung injury from overdistention and loss of recruitment
- ❖ Sinusoidal input:

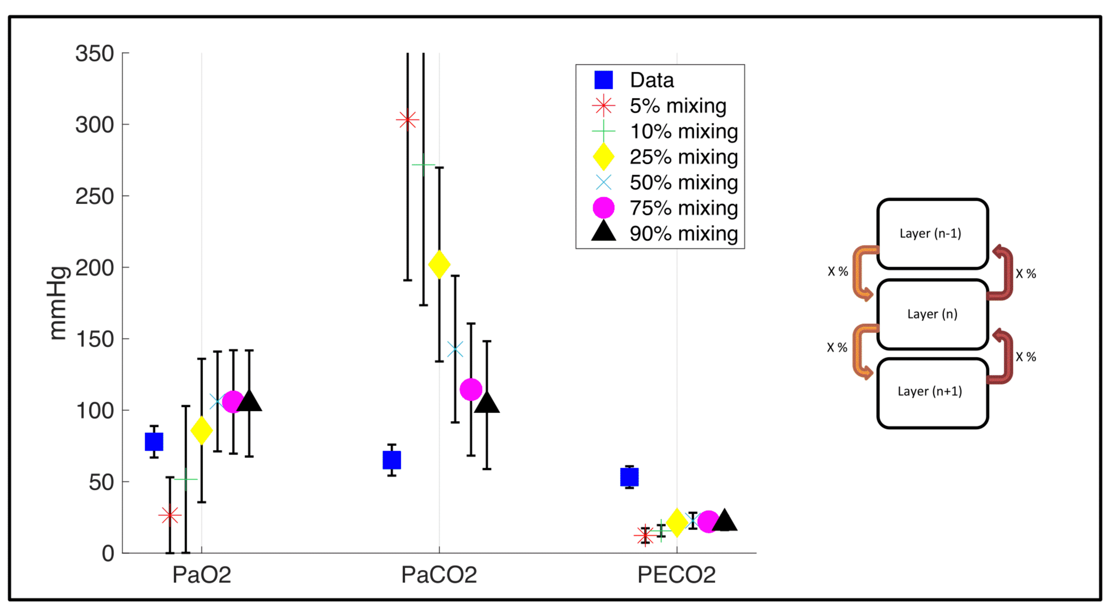
$$P_{ao}(t) = MAP + A\sin(2\pi f t)$$

- ❖ Adding airway compliance by re-modelling and adding a capacitance
- ❖ Study the profile of the flow





- ❖ Considering mixing of the gas in the series deadspace (compensating small V_T)
- ❖ Mix x% of each layer with the next layer once for every millisecond



Future work

Modelling:

- ❖ Modelling the amount of mixing

Clinical Studies:

- ❖ Comparing HFOV and conventional modes of ventilation
- ❖ Investigating the impact of different settings of HFOV on VILI

References

[1] Fenstermacher D., et al. Mechanical ventilation: what have we learned? Crit Care Nurs Q. 2004
[2]Kaier K., et al. Mechanical ventilation and the daily cost of ICU care, BMC Health Serv Res, 2020
[3] Lee A., et al. Are high nurse workload/staffing ratios associated with decreased survival in critically ill patients? A cohort study, Ann. Intensive Care, 2017
[4] Hardman J. G., et al. A physiology simulator, Br. J. Anaesth., 1998

Acknowledgment

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Selected publications from this model

Scan Me!