An extension to the first order model of pulmonary mechanics to capture a pressure dependent Elastance in the Human Lung

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Motivation

Finding a model that can capture patient pulmonary mechanics and predict the outcomes of changes in therapy has been proven to be a very difficult task.

There is a tension between simplistic and detailed models of pulmonary mechanics.

Simplistic modelling

- Easy to understand
- Easy to identify
- Limited ability to describe mechanics in different scenarios
- Lumped parameters may describe a number of disparate behaviours

VS

Detailed modelling

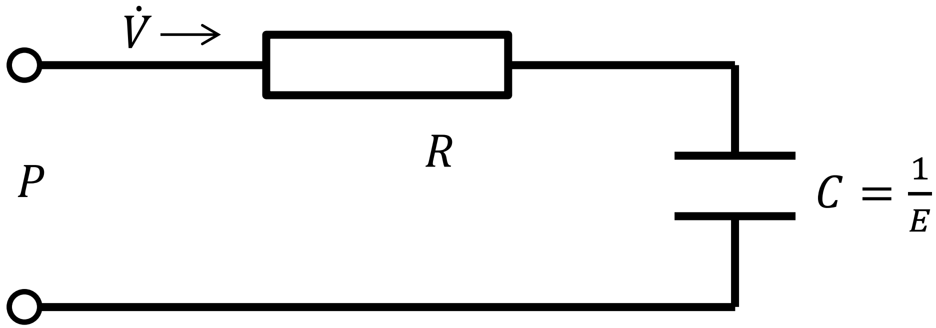
- Often difficult to understand
- Often difficult to identify robustly – susceptible to practical identifiability issues
- Better potential to describe behaviour in situations not found in training set.
- Direct parameters may yield more physiological information.

Ultimately, we need methods to get information from accessible data to aid treatment in pulmonary dysfunction and ARDS.

Existing Modelling Approach

The First Order Model (FOM) of pulmonary mechanics is a very simple model that determines pressure as simple functions of volume and flow.

$$P = EV + R\dot{V} + P_0$$



One potential way to interpret outcomes of the FOM is identify E and R, then rearrange the governing equation for E_{drs}.

$$E_{drs} = \frac{P - R\dot{V} - P_0}{V}$$

Then the shape of E_{drs} can be interpreted.

Adaptation

When interpreting E_{drs}, we must remember that the zeroth and 1st order characteristics of the curve are set by the identification system.

- Pressure responses in elastance and resistance may not be constant or evenly distributed across a breath.

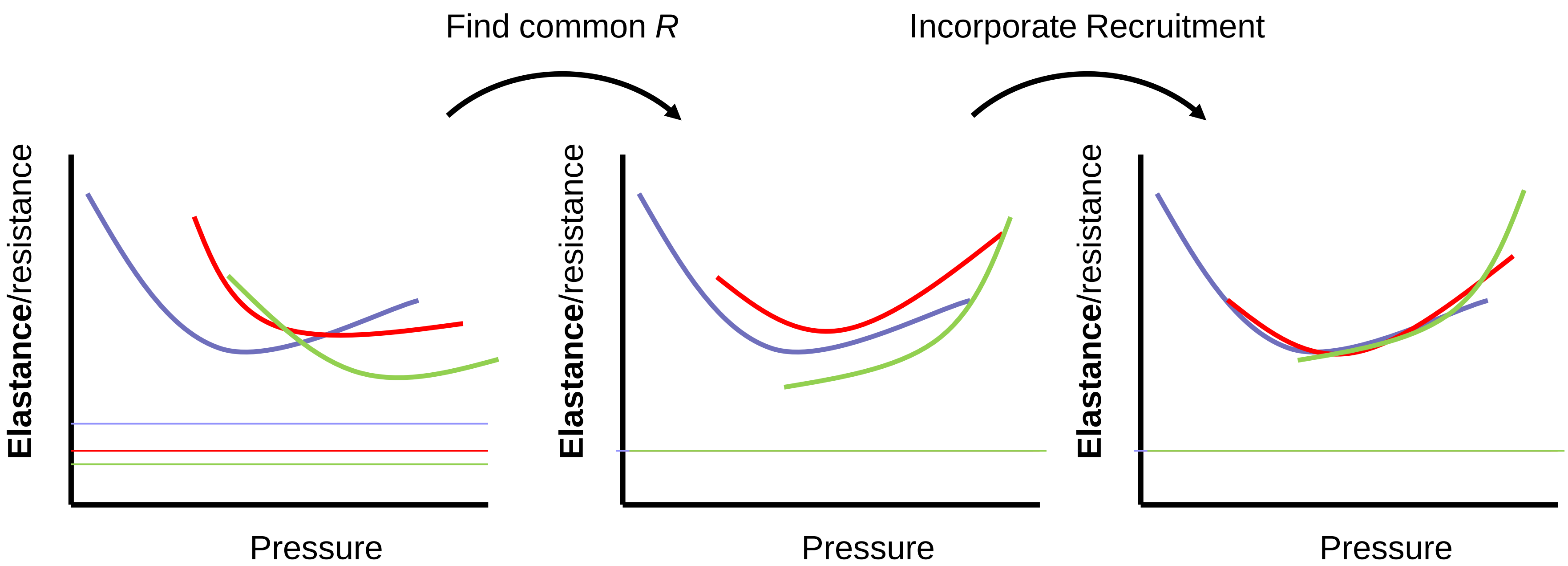
- Mechanical responses to bronchial pressure should be consistent across various PEEP levels

- Hence, we should adapt the FOM to capture the mechanics across PEEP levels.

Mathematical form of adaptation

The FOM is adapted with a pressure dependent elastance ($E_\alpha(P_{aw})$) and an alveoli recruitment term that is a function of the PEEP level ($\alpha_x(\mathrm{PEEP})$).

$$P_{aw} = R\dot{V} + \alpha_x E_\alpha(P_{aw})V + P_{0,x}$$



The inverse problem

The parameters of the model are found by minimising the discrepancy between elastance at equivalent pressures. This can be written mathematically as:

$$\mathbf{x} = argmin_{\mathbf{x}} \sum_{i=1}^{n} \sum_{j=i+1}^{n} \sum_{Paw}^{50} \left(E_{\alpha,i}(P_{aw}) - E_{\alpha,j}(P_{aw}) \right)^2$$

where: $\mathbf{x} = [R, \alpha_{[0,5,10,\dots]}]$

The following bounds are used: $\mathbf{x} = \begin{bmatrix} 0.25 < \mathrm{R}_\alpha < 30 \\ 0.5 < \alpha_1 < 1.5 \\ 0.25 < \alpha_2 < 2.5 \\ 0.25 < \alpha_3 < 2.5 \end{bmatrix}$

Since elastance is not a treated like a constant variable in this approach, the optimisation cannot be made in terms of pressure. The optimisation is done in terms of elastance equivalence.

Approach Interpretation

The proposed approach can be used to determine a minimum elastance level that might achieve a certain tidal pressure (*TP*) and thus minimise ventilator induced injury to the alveoli during mechanical ventilation.

$$PEEP_{OPT} = PEEP\colon E_{\alpha}(PEEP) = E_{\alpha}(PEEP + TP)$$

In some cases the elastance was not observed to be rectifiable across PEEP values. In these cases, rather than make an assessment of the optimal PEEP level, the approach will reject the findings. Ultimately, it does this by setting a threshold of discrepancy above which the model is deemed to have failed:

$$\sqrt{\sum_{i=1}^{n}\sum_{j=i+1}^{n}\sum_{Paw=5}^{50}\left(E_{\alpha,i}(P_{aw}) - E_{\alpha,j}(P_{aw})\right)^2} > 5000$$

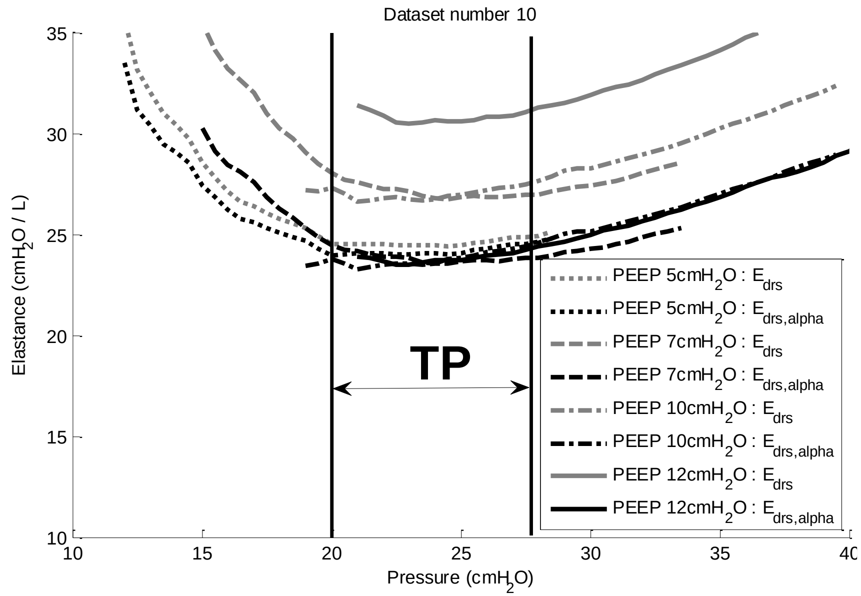
Patient Cohort

- 10 patients from Sundaresan *et al.* (2011) (*BioMed Eng Online*, 10:64)
- All patients had ARDS at time of testing
- Recruitment manoeuvre including three or four incremental PEEP changes
- 12 data sets
- Airway pressure and flow measured at airway using a pneumotachometer
- A single inspiration at each PEEP level will be analysed
- All analysis done on MATLAB using standard toolboxes

Outcomes

The approach worked well for Dataset 10.

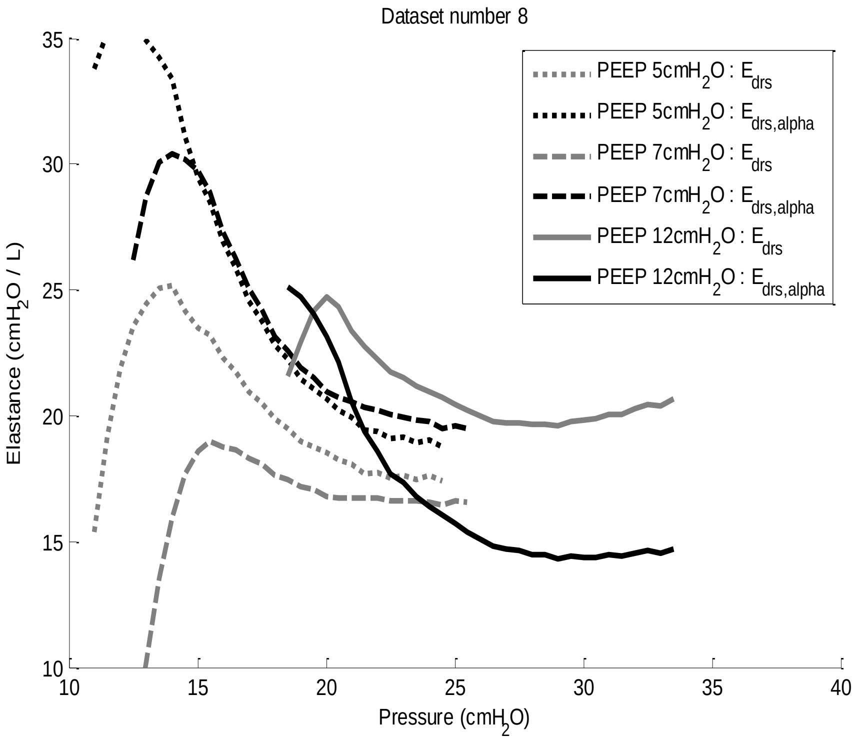
- There was good agreement in elastance across pressure at different PEEP levels
- A tidal pressure range that could operate at minimal elastance could be conclusively found.
- The original method yielded disparate elastances



Outcomes

Data set 8 had more problems…

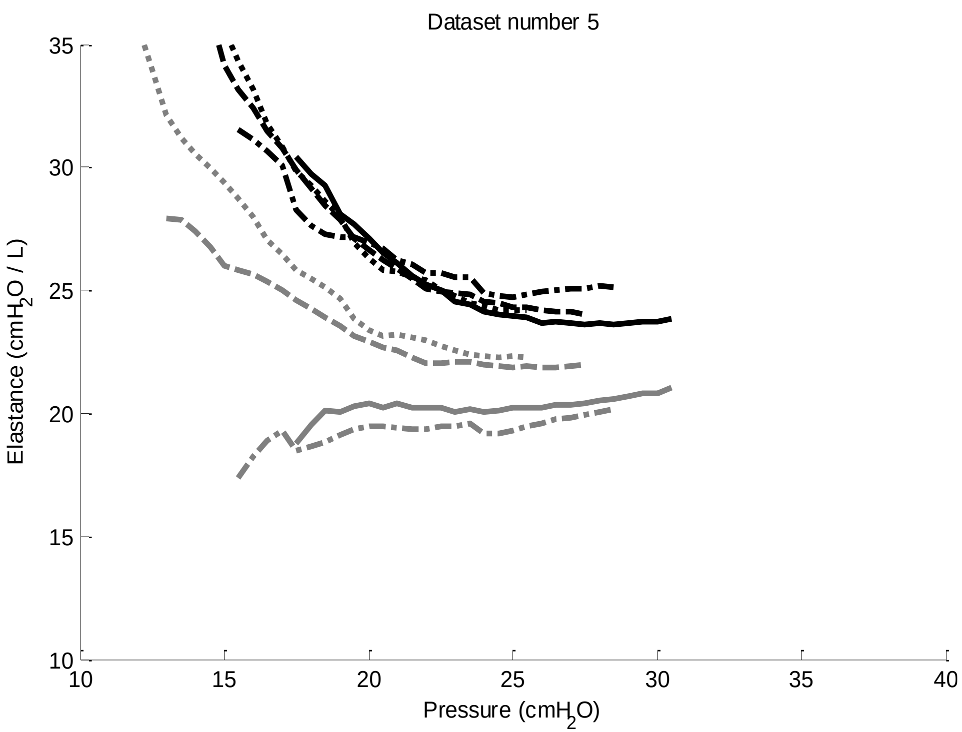
- There was only good agreement in elastance across two of the three different PEEP levels
- A tidal pressure range that could operate at minimal elastance could not be found.
- Better than typical FOM, but not a fair comparison



Outcomes

Data set 5 had different problems…

- There was only good agreement in elastance across all different PEEP levels
- A tidal pressure range that could operate at minimal elastance could not be found due to the still negative gradient at the end of the pressure range tested.
- PEEP levels in this range are not necessarily a good thing…



Outcomes

Dataset	R_{FOM}	R_{α}	α_1	α_2	α_3	Recommended PEEP
1	6.64	7.30	1.11	1.23	-	20
2	6.47	5.19	1.27	1.44	-	undefined
3	12.25	0.68	1.01	1.04	-	25
4	9.35	1.63	1.50	0.59	-	undefined
5	6.53	3.97	0.99	0.87	0.96	25
6	7.68	0.25	0.98	0.47	0.79	25
7	3.5	4.29	1.09	0.91	0.97	14
8	10.83	9.16	0.20	1.49	-	undefined
9	7.59	9.77	1.17	1.12	-	25
10	6.08	6.54	1.12	1.11	1.26	20
11	2.67	4.0	1.01	0.92	-	14
12	10.3	3.55	0.85	0.78	-	30

Interpretation

The approach was somewhat successful in determining consistent elastance across different PEEP levels

- Most cases worked in at least a few pressure levels meaning that elastance can be
- Some confounding recruitment values were determined
    - Unmodelled effects
    - Changing patient state
- Ambiguity regarding applicability since level of confounding was too high.
- Optimal PEEP levels were more or less in-line with recent findings that indicate a lower PEEP is beneficial.
- There are many factors contributing to a section of PEEP – Although minimum elastance should be considered, it should not be the only consideration in selecting PEEP.

Improvements

- The algorithm is computationally intense.

- The algorithm currently uses only one breath per *PEEP* level. Increasing the number of breaths would potentially reduce the discrepancy between E_{drs} curves, or elucidate un-modelled effects.

- Interpretation of optimum *PEEP* needs to be further considered in a clinical context.

- The strength of the effect of the recruitment terms (α) needs to be considered since there were a number of cases wherein α confounded the expected outcomes.

Conclusions

The FOM was modified in such a way as to be able to determine and evaluate elastance across different PEEP levels.

In doing so, it was able to determine pressure ranges over which there was minimum elastance. This means that maximum volume can be introduced to the lung at a minimum pressure difference – potentially reducing the incidence of VILI.

The algorithm was only successful in 9/12 cases and yielded confounding behaviour in ~50% of cases. We are currently considering methods to mitigate the confounding behaviour.

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Questions?

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