Respiratory Airway Resistance Monitoring In Mechanically Ventilated Patients

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Damaged
lung due to
over inflation

Collapsed lung

- Modelling respiratory mechanics enables patient-specific understanding of lung physiology for optimal Mechanical Ventilation (MV) of critically ill patients
- However, only few models have been designed with a specific therapeutic goal or outcome
- Higher pressure provided by MV allow increased recruitment but can also cause over-distension to the alveoli – ventilator induced lung injury (VILI)

Thus, the motivation of this research is to determine the pressure drop for each branch of the airway system by estimating the airway resistance, which can be used as a clinical guidelines to prevent the alveoli from over-distension

- What is Pressure drop? Why it is important?
 - The pressure drop is due to the resistive components in the airway branching system.
 - It is important as it can estimate the end alveoli pressure that could cause lung injury due to the over-distension
- 3 airway models are used in estimating the pressure drop due to airway resistance in MV patients with ARDS
 1. Airway Branching Model (ABM)
 2. Single Compartment Linear Lung Model (LLM)
 3. The Dynostatic Model (DSM)

- The pressure drop at each airway branch is estimated by Poiseuille equation:

$$\Delta P_n = R_n Q_n$$

- The respiratory airways are branched into generations starting from trachea (Generation 0) through to the alveoli (Generation 23)

- In this model, Q_n is the flow rate of each airway branch. Thus, flow rate at each branch is assumed to be half of the previous generation flow rate:

$$Q_{n+1} = \frac{1}{2} Q_n$$

Branch Generations	Diameter (cm)	Length (cm)
0 (Tracheal)	1.80	12.0
1	1.22	4.80
2	0.83	1.90
3	0.56	0.80
4	0.45	1.30
5 -16	0.35 - 0.06	1.07 - 0.17
17 - 22	0.05	0.10
23	0.04	0.05

- Based on measured airway dimensions measured by Pedley *et al.*
- The airway resistance is estimated by using Poiseulle flow:

$$R_n = \frac{1}{2^n} \left(\frac{128\mu L}{\pi d^4} \right)$$

- μ – dynamic viscosity of air (Pa.s)
 - n – airway branch generation
 - L – length of airway branch (m)
 - d – diameter of airway branch (m)
- Thus, the total pressure drop of the ABM model can be modelled:

$$\Delta P_{R_ABM} = \sum_{n=0}^{23} R_n Q_n$$

1. J. H. T. Bates, *Lung mechanics an inverse modelling approach* vol. 1. United States of America: Cambridge University Press, 2009.

2. T. J. Pedley, R. C. Schroter, and M. F. Sudlow, "The prediction of pressure drop and variation of resistance within the human bronchial airways," *Respir Physiol*, vol. 9, pp. 387-405, Jun 1970.

- This model is based on equation of motion:

$$P_{aw} = E_{rs} V + R_{rs} Q_{aw} + P_0$$

- P_{aw} – airway pressure
- $E_{rs} V$ - alveoli pressure
- $R_{rs} Q_{aw}$ - resistive pressure
- P_0 - offset pressure

- By using integral-based methods, the resistive pressure drop can be estimated:

$$\Delta P_{R_LLM} = R_{rs} Q_{aw}$$

- The dynostatic algorithm is used to estimates the dynostatic pressure, P_{dyn} , which could be used as a “gold standard” in estimating the alveolar pressure.
- The inspiration airway resistance, R_{insp} is assumed to be the same as the expiration airway resistance, R_{exp} at iso-volume:

$$R_{exp} = \frac{P_{exp} - P_{dyn}}{\dot{V}_{exp}}$$

$$R_{insp} = \frac{P_{insp} - P_{dyn}}{\dot{V}_{insp}}$$

At iso-volume, V_{iso}

$$R_{insp} = R_{exp}$$

- Thus, the P_{dyn} is calculated as below:

$$P_{dyn} = \frac{P_{insp} \times \dot{V}_{exp} - P_{exp} \times \dot{V}_{insp}}{\dot{V}_{exp} - \dot{V}_{insp}}$$

- Finally, the resistive pressure during inspiration is modelled as:

$$\Delta P_{R_Dyn} = \dot{V}_{insp} R_{insp} = P_{insp} - P_{dyn}$$

- The 3 airway models are used to determine the resistive pressure or pressure drop from the airway to the alveoli in 6 ARDS patients from 2 different cohorts with PEEP of 5cmH₂O.
- 3 patients (B1-3) have constant square wave input profiles while the other 3 patients (S1-3) are ventilated using a decreasing input flow profile.
- Each model is simulated using measured P_{aw} and Q_{aw} and flow rate at the airway.

Results and Discussion

- From the ABM model, the estimated resistance at each branch starting from Gen 0 to Gen 23.
- Resistance higher at the 5th generation branch due to the higher length at this branch. The total resistance for all branches is $5.13 \text{ cmH}_2\text{O}\cdot\text{s/l}$.
- The estimated pressure drop at each branch with highest pressure drop at Gen 0 (trachea) at $0.23 \text{ cmH}_2\text{O}$.

Results and Discussion

- The comparison of pressure drop for the three models.
- The maximum pressure drop for LLM and DSM models ranges from 8.2 to 8.8 cmH₂O.
- For ABM model, the maximum pressure drop is 0.43 cmH₂O and increases to 3.0 cmH₂O with ETT tube.

Results and Discussion

- The comparison of pressure drop for the three models.
- Patient S1 is ventilated at higher flow rate (0.61/s), resulting in higher pressure drop.
- For ABM model, the maximum pressure drop is 0.51 cmH₂O and increases to 3.6 cmH₂O with ETT tube.
- For LLM and DSM model, the maximum pressure drop ranges from 10.2 to 13.8 cmH₂O.

Results and Discussion

- The median [IQR] and maximum value of the pressure drop for the three models are:

ABM with ETT		LLM		DSM	
Median [IQR]	Max	Median [IQR]	Max	Median [IQR]	Max
2.1 [1.4 – 3.3]	3.6	9.1 [5.3 – 12.6]	17.8	4.0 [1.7 – 7.9]	10.2

- The pressure drop in LLM and DSM models are higher than the ABM model as expected.
 - because the LLM and DSM are consists of lumped bronchial airway resistance where as for ABM, the pressure drop are based on physiological information at every branch of the bronchial generations.
- The ABM model allows pressure drops at every branch generation to be estimated as alveoli begin to appear at branch 17.
- Thus, this study allows insight into the pressure flow mechanics of alveoli recruitment that is not possible with lumped parameter models.

Conclusion and Future Work

- By estimating the pressure drop due to resistive component is important to estimate the end alveoli pressure that could be used in clinical guidance in order to avoid further lung injury and reduce treatment cost.
- Model improvement and modification
 - To use a range of airway dimensions for each specific patients, which will result in different pressure values.
 - To consider the head losses due to the bifurcation at each of the branching bronchial
- The losses that occurs in the airway branching system due to the bifurcations in the respiratory tract is known as the minor head loss or pressure loss.
 - because every time it change to the next branch, there is a change in the velocity distribution

Current ABM model

ABM model with head loss

The minor head loss equation is :

$$H_L = K_L \frac{V^2}{2g}$$

- K_L – minor loss coefficient
- V – velocity (m/s)
- g – gravity (m/s²)

Thus, the total pressure drop is :

$$\Delta P_T = \sum_{n=0}^{23} (R_n + H_{Ln}) Q_n$$

• $H_{L0} = 0$

- For example, for patient B1 at the same PEEP 5cmH₂O, the pressure drop with head loss is higher compared to the ABM model

Patient	ABM with head loss		ABM	
	Median [IQR]	Max	Median [IQR]	Max
B1	5.02 [4.53 – 5.19]	5.69	2.1 [2.2 – 2.2]	2.3

QUESTIONS?