Automatic Mechanical Ventilation Control (AMVC)

Background Readings

Team 18

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Project Summary

1. Problems to address in ventilation:
    a. Accurate inputs are required from clinicians
    b. Manual adjustments are required constantly from clinicians
2. Steps:
    a. Building a mathematical model to obtain and understand the relation between various inputs and outputs.(Based on the introduced Paper)
    b. Use results of part 1 to compose a set of MDPs and devise the AI-GYM environment for the RL agent to train on.
3. Goal:
    a. Automated Inputs and Management for a Ventilator

Introduction of Paper

1. Published on ***Scientific Research Publishing, Journal of Biomedical Science and Engineering*** in 2015
2. Author：Noman Q. Al-Naggar

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Modelling and Simulation of Pressure Controlled Mechanical Ventilation System

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Relevance to Project

1. An important step in understanding the relation between inputs and the outputs of the Ventilator
2. Provides data for construction of MDP
3. A fallback/alternative option for the training dataset. If MIMIC III dataset access is not granted in time, this model would be able to produce needed data for training.

Paper Summary

1. Proposes a mathematical model that describes the behavior of the lung during artificial ventilation.
2. Constructed using Simulink in Matlab.
3. Represents respiratory activities under various input parameters
4. Important Inputs:
    a. PEEP(Positive-End-Expiratory-Pressure)
    b. PIP(Peak Inspiratory Pressure)
    c. I/E(Inhale/Exhale Ratio)
    d. RR(Respiratory Rate)
    e. Other parameters include compliance etc. These are linked to the lung conditions and will mostly remain the same throughout the tests
5. Outputs:
    a. Flow rate(Q)
    b. Volume(V)
    c. Pressure(P)
    d. Dynamic Compliance: PV-Loop

Methods and Tools

The following blocks represents different components of the ventilation.

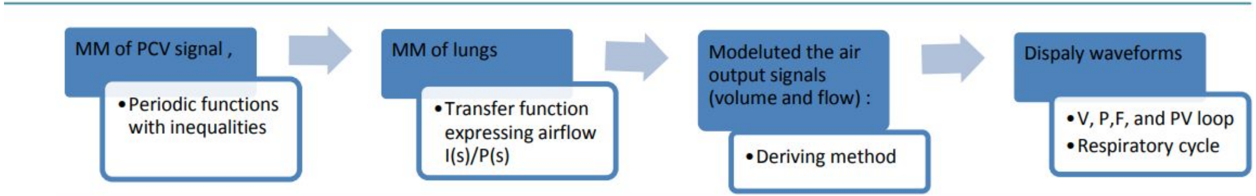

Figure 1. Block diagram of MMs combination.

Previous Work(PCV Signal)

Mathematical Model for PCV(Pressure Controlled Ventilation) signal

- Figure 1:
  - Simulates Expiration and Inspiration
  - IP = Inspiratory Pressure
  - PEEP=Positive End Expiratory Pressure
- The basis is the set of equations to the right
  - P_aw is the pressure in airways. During T_in(inspiratory period), it is calculated through equations 1 and 2
  - In equation 3, EP(Expiratory pressure) = PEEP
- Ideal Parameter Ranges:
  - T_in ∈ [0.7, 1]
  - T_in/T_ex = 1:2 or 1:3
  - TCT(total cycle time) = T_in + T_ex
  - RR(Respiratory Rate) = 60 / TCT = [10, 20] breaths/minute
  - $\mathcal{J}$(rise time of pressure) is set by clinicians
- The last three equations(4-6) depict when the inspiratory period and expiratory period begins.

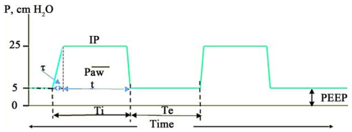

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Figure 2. Typical waveform of pressure signal for PCV.

$$P(t)=\begin{cases} P_{aw}\cdot\dfrac{t}{\tau}+\text{PEEP}, & 0\le t\le\tau \quad (1)\\ P_{aw}+\text{PEEP}, & \tau\le t\le T_{in} \quad (2)\\ \text{PEEP}, & T_{in}\le t\le T_{ex} \quad (3)\end{cases}$$

$$(3n-3)\le t\le(3n-3)T+\tau \quad (4)$$

$$(3n-3)T+\tau\le t\le(3n-2)T_{in} \quad (5)$$

$$(3n-2)T_{in}\le t\le 3nT_{ex} \quad (6)$$

Previous Work(Lung Model)

Multi-Compartment Model for Lungs

- The graph on the right is a representation of a multi-compartment model for lungs in Simscape
  - I represents the airflow
  - V represents the applied pressure produced by the Ventilator
- The values are represented as following:
  - RC = 1 cm H2O/L/s: the airflow resistance of the central airways
  - RP = 0.5 cm H2O/L/s: the resistance of the peripheral airways
  - CL = 200 ml/cm H2O: the capacity of the alveoli
  - CW = 200 ml/cm H2O: the chest wall capacity
  - CS = 5 ml/cm H2O: shunt capacitance(does not participate)
  - CT: the total compliance of airways
    - Calculated through equation 2

$$\frac{I(s)}{P(s)} = \left(\frac{s^2 + \left(\frac{s}{R_P \times C_T}\right)}{R_C \times s^2 + \left(\frac{1}{C_S} + \frac{R_C}{R_P \times C_T}\right) s + \left(\frac{1}{R_P \times C_S}\right)\left(\frac{1}{C_L} + \frac{1}{C_W}\right)} \right) \quad 1$$

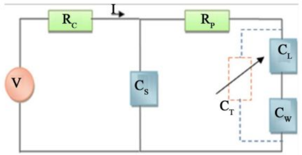

Figure 3. The equivalent electrical model of respiratory system—multi compartments.

$$C_T = \left(1/C_W + 1/C_L\right)^{(-1)} \quad 2$$

Simulator Construction

- Preset Parameters:

Table 1. The parameters values setting of PCV MM.

Parameters	IP, cm H_2O	PEEP, cm H_2O	Rise rate (time)	Inspiratory time (T_{in})	Respiratory rate in breaths/min
Normal case	25	5	1:2	1	20
Another case	27	8	1:2	1	20

- Block Diagram of Simulink Structure

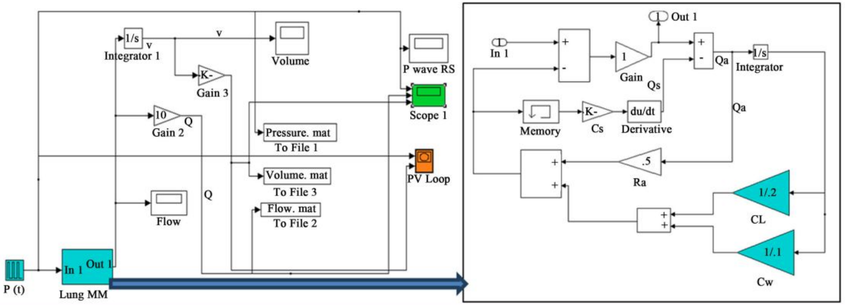

Figure 4. Block diagram of building simulator.

Deriving Output Signals and Displaying Curves

1. Direct Outputs:
    a. Pressure
    b. Volume
    c. Flow
2. Derived Output:
    a. Dynamic Compliance: Displays the dynamic effect of change in PV-LOOP.
        i. It is calculated from the ratio of the change in Volume over the change in Pressure.

$$C_{dyn} = \frac{\Delta V}{\Delta P}$$

Results

1. Figure one shows the corresponding graphs for the values Flow, Pressure and Volume under the parameters of "Another Case" listed in the table.
    a. Showed Similarities to real PCV wave signals
        i. correspondence and convergence in shapes and characteristics
    b. Time Periods in the waveforms are uniform among all outputs
    c. PIP and PEEP changes are reflected directly in the Pressure Curve
2. Figure 2 is the PV LOOP for the same case in one cycle.

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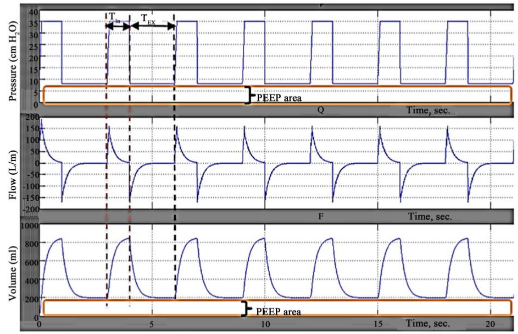
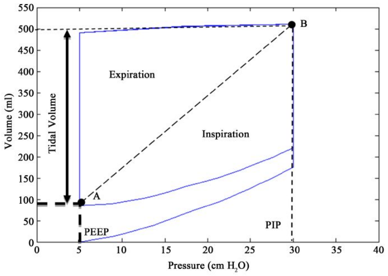


Figure 7. Waveforms of pressure, volume and flow at PEEP = 8 cm H_2O and IP = 27 cm H_2O.



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8. PV loop of PCV.

Results(Continued)

1. The different PV-LOOP graphs are variations caused by different input values of CT
    a. CT is the total compliance of the airway, dependent on both CL and CW
        i. CL: the capacity of the alveoli
        ii. CW: the chest wall capacity
2. The driving pressure remains the same
3. Concludes that the changes are reflected by the model

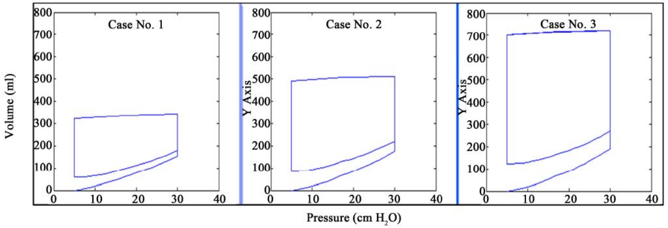

Figure 9. PV loop of PCV at different C_T.

Table 2. The parameters values changed in Lung simulator.

Parameters of PCV signal	Case number	C_T, ml/cm H_2O	C_T^{-1}, ml/cm H_2O	C_L, ml/cm H_2O	C_w, ml/cm H_2O	V_T, ml
IP = 25 cm H_2O,	1	15	0.07	0.2	0.1	320
PEEP = 5 cm H_2O,	2	10	0.1	0.2	0.2	500
T_{in} = 1 sec., τ = 0.1,	3	7	0.14	0.2	0.5	700

Discussion

1. Pros
   a. The model includes both the simulation of PCV signals and the lung responses.
   b. The model is implemented in Simulink, Matlab and the overall graph including the base equations used were all included. This allows us to have a clear reconstruction which we can compare and adjust.
2. Cons
   a. The corresponding version number of Matlab was not provided. This is not ideal for a software which is updated frequently(about twice a year in versions a and b) and could affect the recreation results.
   b. Despite the conclusion that the Data is reliable and realistic, no source or evidence could be provided or reasoned

Future Works

1. Add in noise
2. Implement features such as simulation of the lung condition under various circumstances
    a. ARDS: a lung condition which causes low blood oxygen
3. Provide either real world comparison data or reasoning as proof of simulation data validity to make the results more convincing
    a. During the early steps, we verified the results and information ourselves with Professors involved in the Project.

References

1. Al-Naggar, N. Q. (2015). Modelling and simulation of pressure controlled mechanical ventilation system. *Journal of Biomedical Science and Engineering*, *8*(10), 707.

Thank you!