NeT-Vent: Low-Cost, Rapidly Scalable, IoT-enabled Smart Invasive Mechanical Ventilator with adaptive control to reduce incidences of Pulmonary Barotrauma in SARS-CoV-2 patients

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Pulmonary Barotrauma (VILI)

- Pulmonary barotrauma, a form of Ventilator induced lung injury (VILI), occurs due to elevated transalveolar pressure causing alveolar rupture while patient is on Ventilator.
- Results in increased mortality, can lead to multi-organ failure & is life-threatening. Moreover, excess alveolar air could result in complications such as pneumothorax.
- The natural mechanism of breathing in humans depends on -ve intrathoracic pressures, whereas patients on mechanical ventilation ventilate with +ve pressures. Since +ve pressure ventilation is not physiological, it may lead to barotrauma.
- Adjacent CT Scan shows clinical course of an cerebral air embolism likely due to ruptured pulmonary bullae.

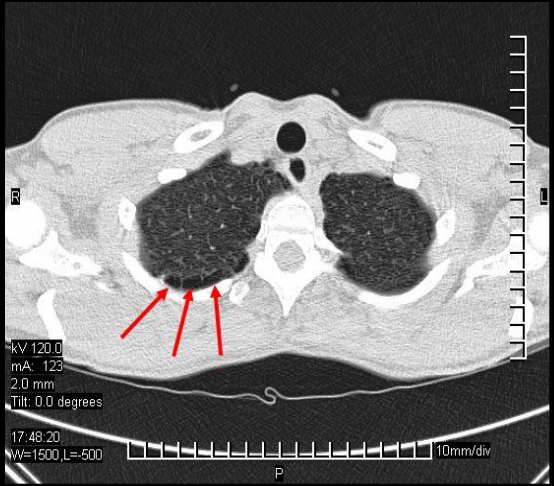

Fig 1. Ventilator Induced Lung Injury (Pulmonary Barotrauma) (CT Scan with *Bullae in Lung*) *(Courtesy: AquaMed)*

Prevention of Pulmonary Barotrauma

Approaches used to minimize pulmonary damage in patients with ARDS include-

- Delivering low V_T (to Minimize shear forces via smaller-volume inflation of aerated alveoli adjacent to flooded/atelectatic alveoli) & while maintaining a low plateau pressure to prevent overdistention. This is often referred to as "lung protective ventilation"
- High PEEP to reduce cyclical atelectasis (Decrease blood flow to attenuate capillary stress failure)
- Prone Positioning
- Airway pressure release ventilation (APRV)
- High-frequency oscillatory ventilation (HFOV) & Limit Inspiratory & Plateau Pressure

VILI Prevention can attenuate multiorgan failure & improve survival. Presently there is no well defined Strategy for prevention of VILI & no clinical data to suggest efficacy.

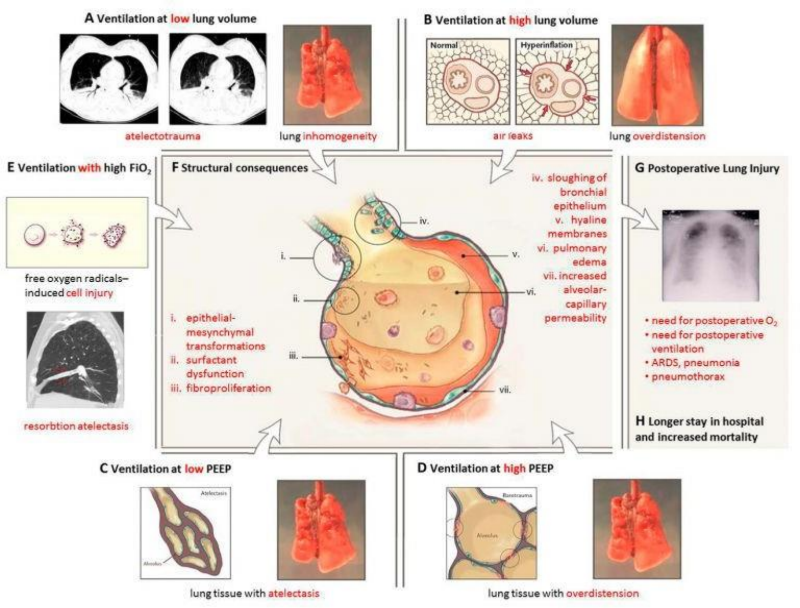

Fig 2. Postoperative pulmonary complications caused by forces generated by ventilation at low and high lung volumes, low and high PEEP and high FiO_2 *(Courtesy: Swiss Medical Weekly)*

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Our Research Problem

- Designing an Open-Source, Low-Cost, Easy-to-manufacture & use Ventilator system
- The Ventilator will control factors which induce pulmonary barotrauma in patients under ventilation system for long durations using novel and cheap methodology available at our disposal.
- To develop a system to drastically reduce PPE-Kit Requirement in COVID-19 Ward
- To prevent nearly complete contact of medical staff with COVID-19 Patients.

Assumptions pertaining to Research problem

The assumptions necessary to understand how the design concept solves the identified need-

- High pressure approach has been used.
- Uninterrupted Power Supply & Easy access to compressed oxygen in great supply
- Availability of trained medical staff
- Sufficient cooling for the ventilator system
- Normal breathing condition data used for validation
- Monitoring pressure & volume flow will be sufficient to generation correction signal
- Feedback in the control system is efficient to trigger solenoid valves
- Other factors (non-mechanical) influencing VILI is negligible

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NeT-Vent Design Model

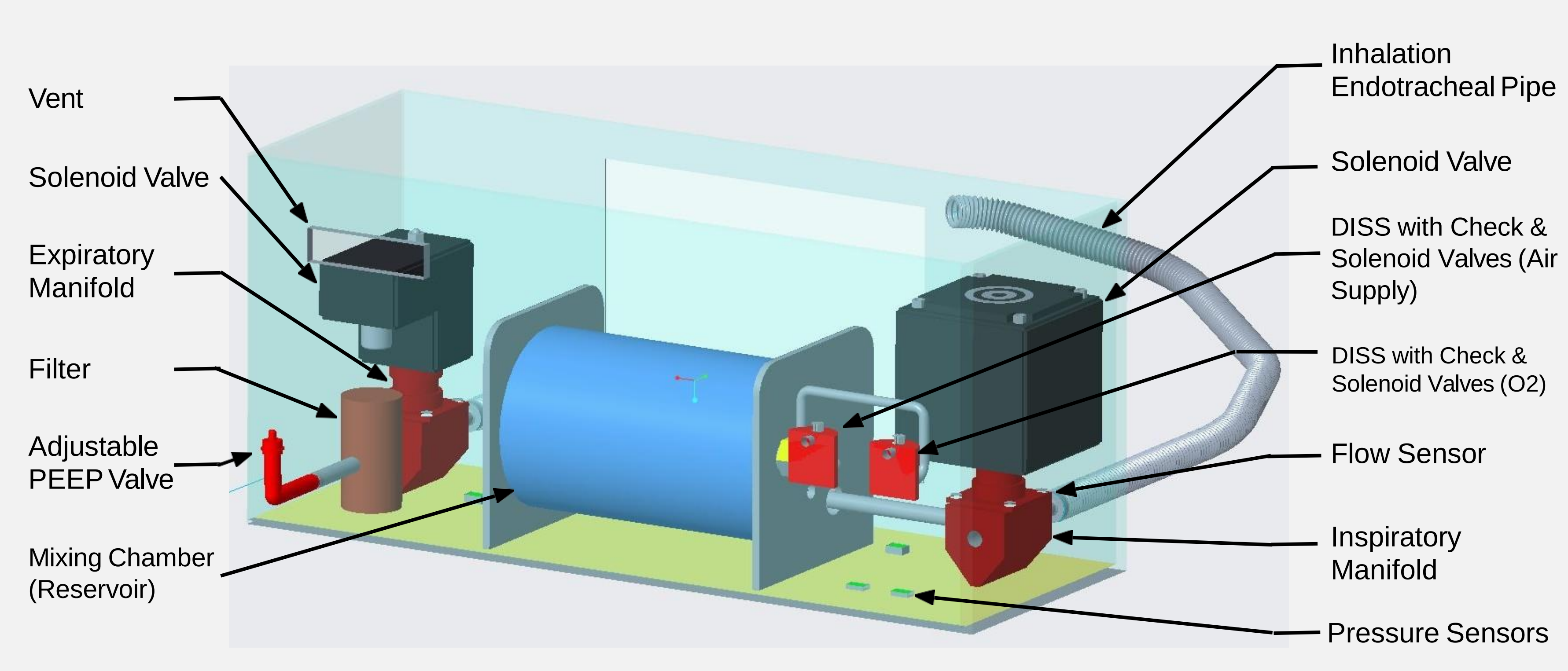

Fig 3. The Computer-Aided Design of Net-Vent modeled in PTC Creo

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Salient Features of CAD model

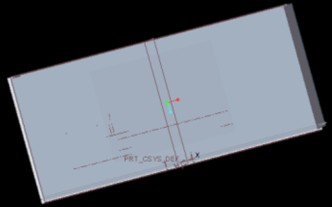
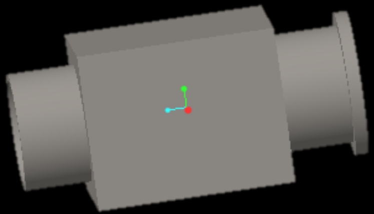
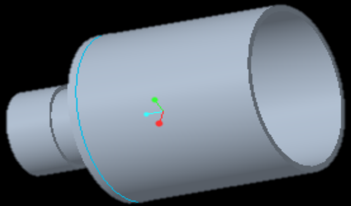
- Modeled on PTC CREO Parametric 6.1 CAD Software
- Includes detailed design of components satisfying industrial standards
- Easy to recreate and assemble
- Meets Australian safety requirements

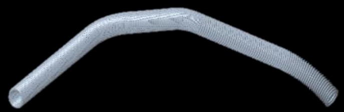
Inspiration system

- Inlet of compressed air from hospital delivering at a standard pressure of 3.5 bar
- Air and the oxygen lines both have air filters
- Passes through a set of one way check valves
- DISS made x (¼ fitting) to ensure no interchange
- Gas blender present for blending air with oxygen in correct proportions
- From blender it goes through the proportional solenoid valve
- Pressure relief valve has been provided near the inspiratory air exit
- Passes through HEPA filter and enters the patient through the breathing circuit

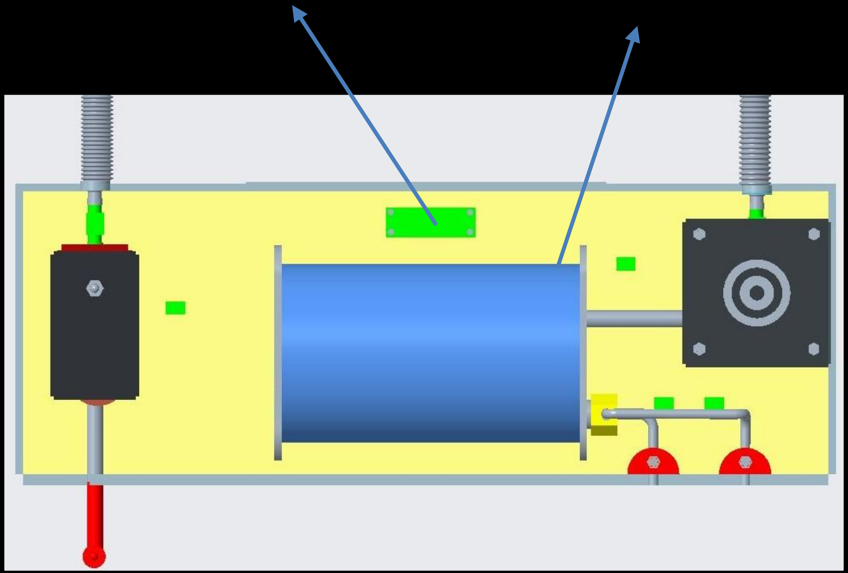
Expiration system

- Person breathes out, the air enters the expiratory line via a non return valve
- Additionally consists of a pressure sensor and a flow sensor
- Expired air meets the second one solenoid valve
- This solenoid valve is in natural ON state
- Air finally goes out of the HEPA filter and finally through the PEEP valve
- PEEP helps to maintain necessary pressure to prevent lung rupture

Part	CAD Model	Specifications	Function
Base		L= 410 mm B= 250 mm H = 250 mm Material = ABS or simulated ABS	It serves as housing for all the parts that go in a ventilator, increasing portability and reducing damage
Pressure relief valve		L= 27mm D= stepped (8,9,11,13 mm) material= ABS (depending upon type of manufacturing)	It serves as the airway channel to remove excess pressure going into the patient
Exhale & Inhale Manifold		D = stepped (9,10,18.5,20 mm) L = 45 mm complete Material = ABS or simulated ABS (for 3D printing)	-

Part	CAD Model	Specifications	Function
PEEP Valve		L = 65mm D = 45 mm Weight = 40g Material = Adjustable cap: Poly-amide(nylon),Transparent plastic part: Poly-sulphone	PEEP is used to maintain pressure on the lower airways at the end of the breathing cycle which prevents the alveoli from collapsing during expiration
Solenoid Valve		Operating Mode: Direct Acting Type: Normally closed Pipe size: 19.01mm Orifice: 22.6 mm Available Voltage: AC 230V Operating Pressure: 0-7Pa Material: Aluminium alloy	Solenoid valves were used to close, open, dose, distribute or mix the flow of gas or liquid in a pipe
Pipes		Length: As per requirement Diameter : Internal =15mm, External =22 mm Material : Corrugated plastic	Pipes are used to supply air in and out of breathing patients

Other Design Views



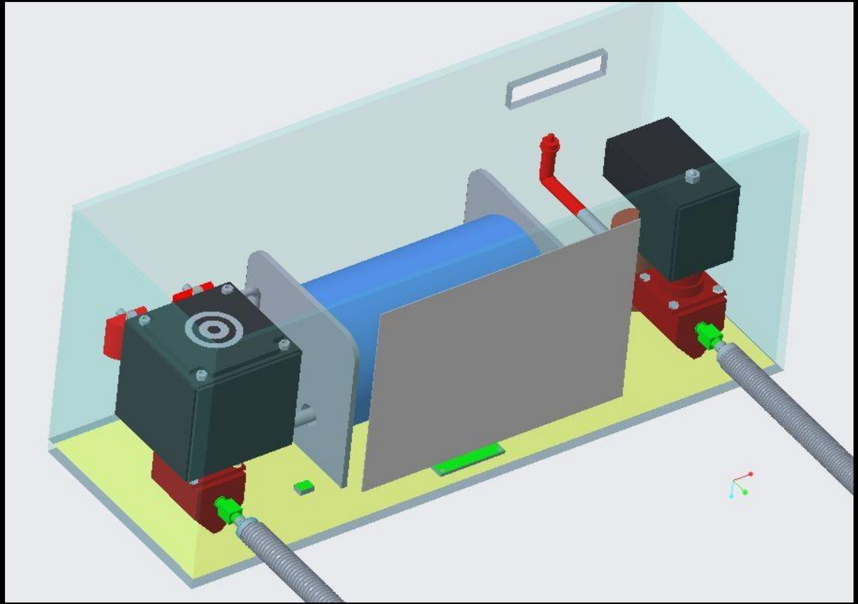


Fig 4. The Top & Isometric view of the CAD Model of Net-Vent designed in PTC Creo

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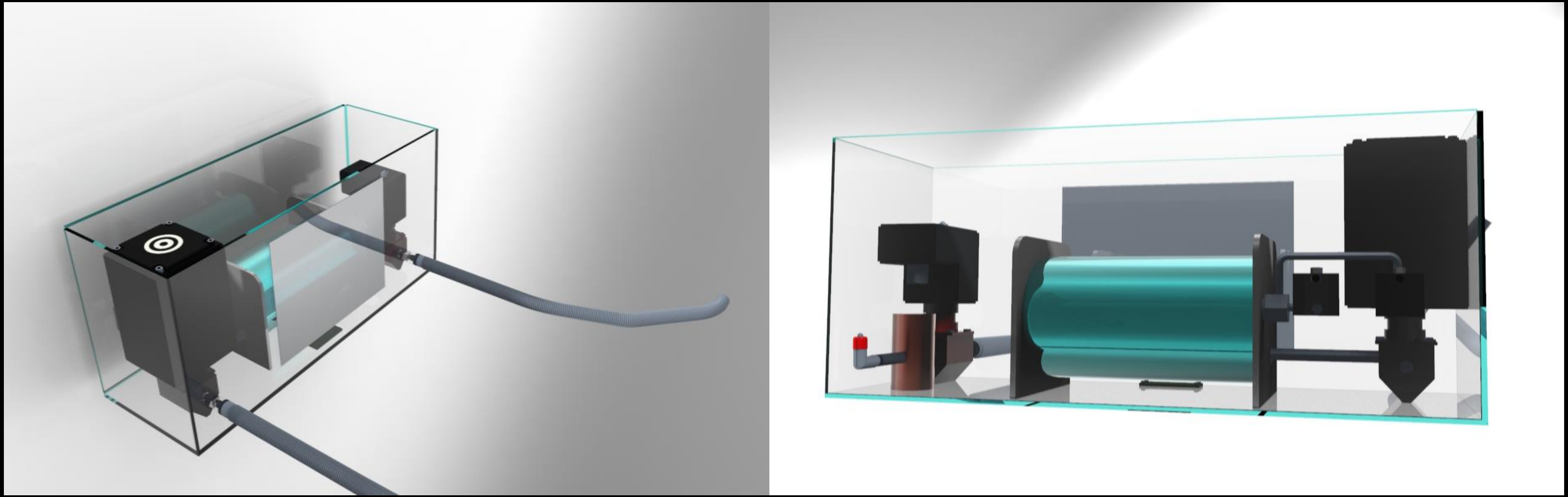
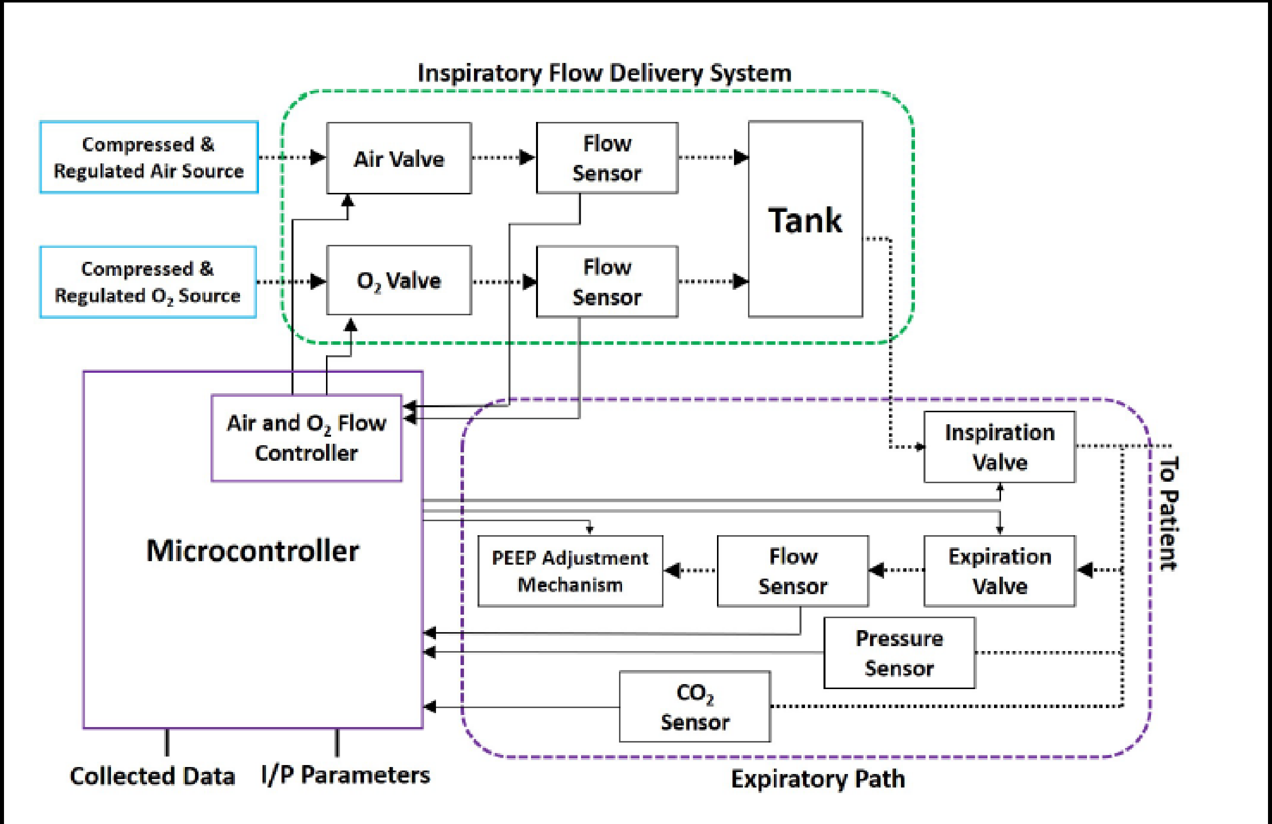
Rendered CAD Model of the Proposed Ventilator



Control Flow Chart



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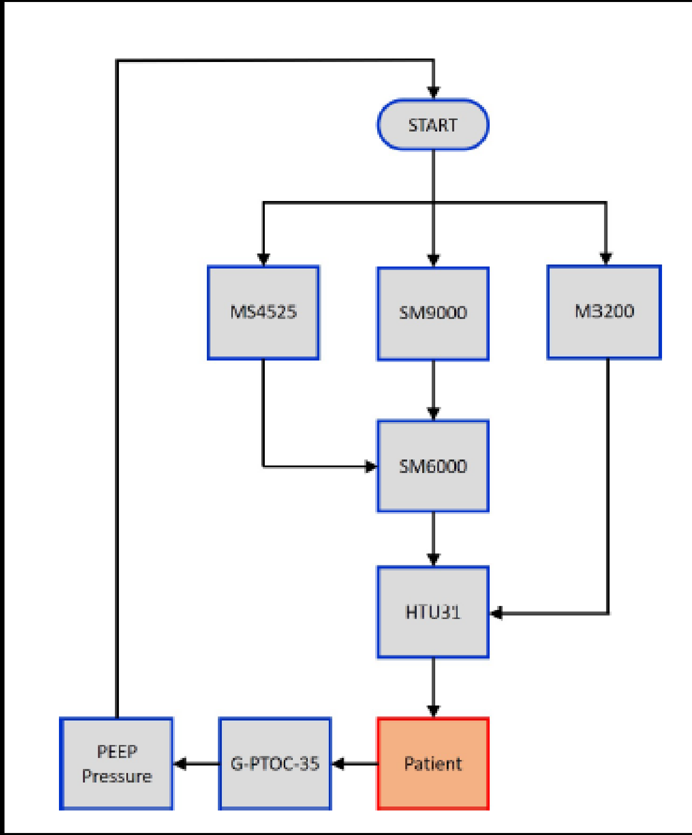
Sensor Flow chart (TE Connectivity)



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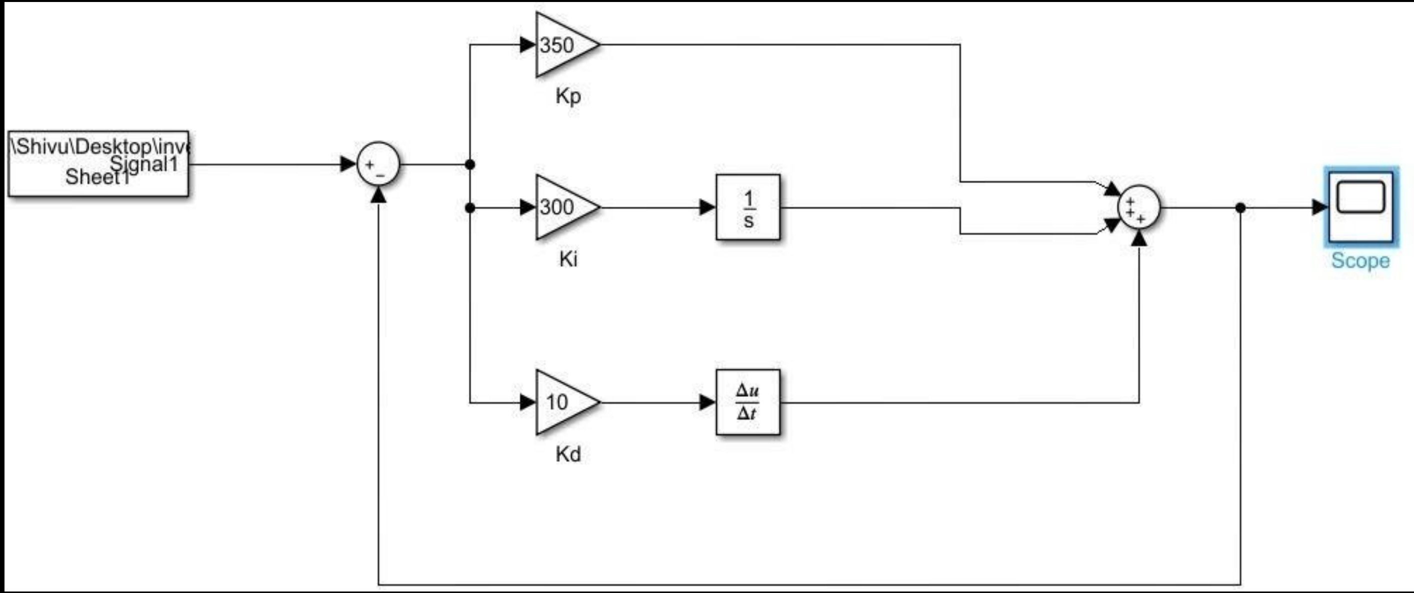
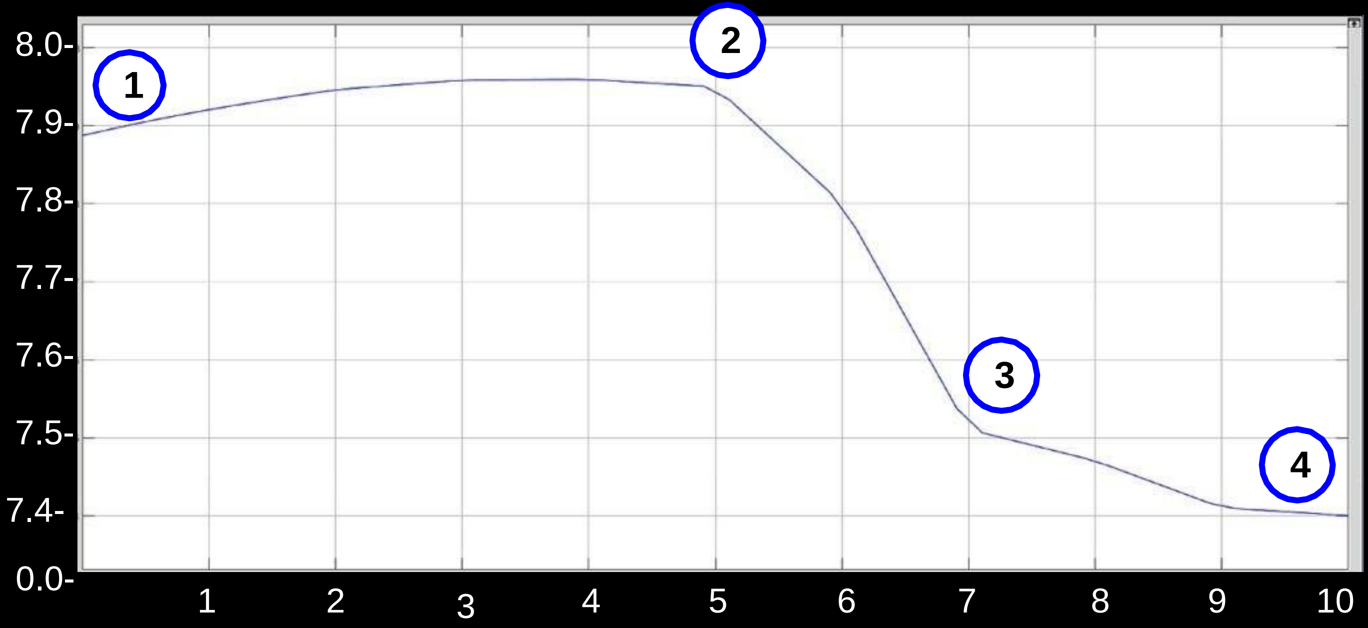
Control System Block Diagram in Simulink



Kp = 350, Ki = 300, Kd = 10

Simulation Results: Pressure vs Time Curve



1-2 is Plateau Pressure (Maintaining Low Plateau Pressure)

At pt., 2 termination of pressure support occurs

4. Baseline PEEP (High PEEP to Decrease blood flow to attenuate the capillary stress failure)

Fig 5: Pressure vs Time Curve obtained from our Control System

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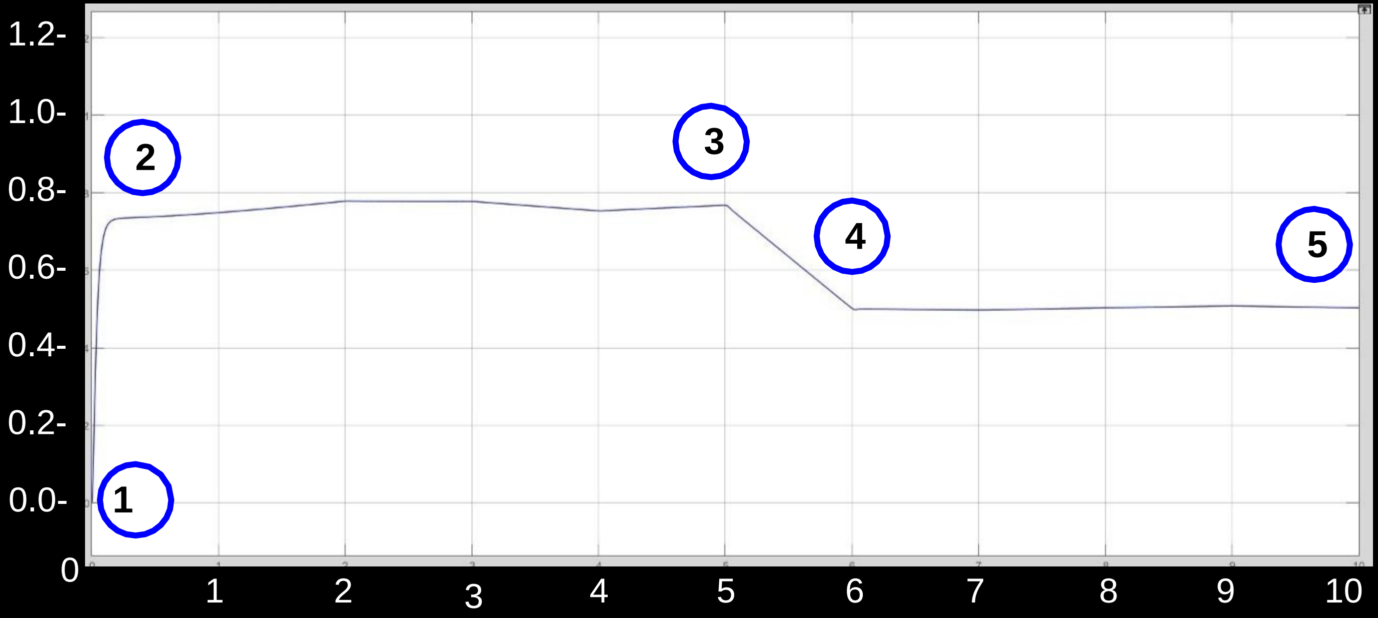
Simulation Results: Flow Rate vs Time Curve



1-5 Demonstrates the Curve obtained for the Flow Rate vs Time through our Simulink Simulink

Delivering low V_T (to Minimize shear forces via smaller-volume inflation of aerated alveoli adjacent to flooded alveoli)

Fig 6: Flow Rate vs Time Curve obtained from our Control System.

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IoT Enabling

By introduction of Internet of Things (IoT), doctors and medical staff will be able to monitor the state of patients remotely using an app/web-based interface & need not visit the COVID-19 ward in frequently.

This will indirectly reduced COVID-19 virus transmission from patients to the medical staff & is estimated to reduce the use of PPE Kits to a great extent.

ZigBee/ XBee Module

Bee modules are based on the IEEE 802.15. 4-2003 standard designed for point-to-point and star communications.

They will allow different Net-Vents to communicate with each other and allow data sharing. Important data could be shared with each other, as they get connected on a low-Wifi based network over the cloud.

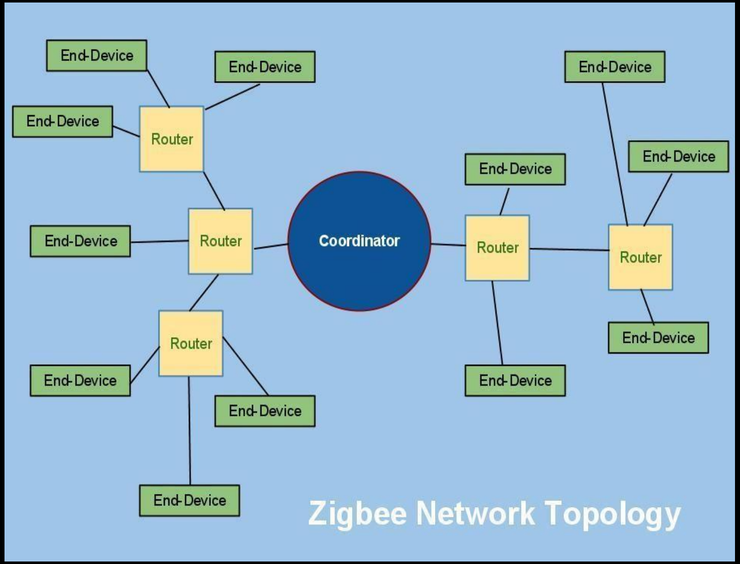

Fig 7. The Zigbee Network Topology

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Compliance with Australian Design Requirements

NeT-Vent's Compliance with the ventilator Design standards/ specifications laid down by the Australian Government

Australian Design Requirements	Standards	NeT-Vent's Range (Design and Simulation Based)
Positive end expiratory pressure (PEEP)	5 to 25 cm H_2O Adjustable	6 to 8 cm of H_2O
Respiratory Rate	5 to 30 breaths per minute	5 to 40 breaths per minute with adjustable increment
Tidal Volume V_t	200 to 800 mL adjustable	Adjustable; Controlled by system UI
Airway Pressure Safety	Have an operator adjustable limit upto 50 cm H_2O	Present
Inspired Oxygen Proportion (FiO_2)	Must have 22 mm outside diameter (OD), upto 100%	Present
O_2 and Air Supply to the Ventilator	All gas connectors and hoses must use standard non-interchangeable connectors with color coding according to AS 2902-2005	DISS with check valve present
Construction Material	Polyvinyl chloride (PVC) must be avoided in the patient gas pathway	Use of ABS or simulated ABS with glass reinforcing
Patient Safety	Expiratory tidal volume not achieved by 10%, Inspiratory tidal volume exceeded by 10%	Use of trigger alarm system
Passive mechanical blow-off valve	40 cm of H_2O	Added as a safety feature
Monitor Plateau pressure	Clinically controlled in person or remotely	Algorithm reprogrammed to achieve it

NeT-Vent’s Rapid Scalability and Ease of Manufacture

Ventilator Parts	Availability of parts	Method of Acquirement
Base	Easily Available	3D Printing or conventional manufacturing
Inhale Exhale Manifolds	Available	3D Printing or from market vendors
Solenoid Valves	Available	Manufacturers such as Burkert Fluid Control Systems, etc.
Flow, Pressure, Humidity Sensors	Standard catalogue parts from existing manufacturers easily available on Bulk orders; via e-commerce	Manufacturers like Manuflo, Mouser, TE Connectivity, etc.
Filters	Available	Manufacturers like AES International, Filtermakers, Camfil Australia, etc.
Pipes	Easily Available	Conventional Manufacturing/ Medical Vendors
PEEP Valve	Available	3D Printing or medical vendors

NeT-Vent's Ease of Use

- Has IoT Smart System (unlike any other commercially available high-end ventilators)
- Standard Power Requirements : 240V AC Mains Power

  Supply Portability of Ventilator: Highly Portable

- Part Malfunction: Highly reliable sensors but can be replaced easily on malfunction (includes Buzzer Alarm warning)
- Early Warning by IoT : Warning system by IoT to the cell phone of medical staff, also zigbee module transfers data between each other.

Comparison with other Open-Source Models

Model	Proposed	Major Challenges Addressed	Challenges Unaddressed	Cost (AUD)
Medtronic B560	Feb, 2010	Better Patient Management, Open-sourced	Easily serviceable parts in case of failure	14,000
MIT E-Vent [26]	April, 2010	Extremely Low Cost, Open-source	Adjusting to patient requirement, Safety features, Accuracy	500
Philips Respironics v680	Sep, 2015	Advanced ventilator with better patient management	Expensive sensors, negligent servicing, not open-source	25,000
Co-Ventor [29]	March, 2020	Volume based ventilation, Open-source	Functionality unknown, Bag-based	1,000
Respira-Works	April, 2020	Open source, Low cost patient monitoring	Use of less available, expensive micro-controllers	1,000
Team Armadilla	April, 2020	No specialized manufacturing dies or moulds required	Patient breathing cycle, proper lung orientation, VILI unaddressed	900
SmithVent	June, 2020	Easy manufacturing, Open-source	Airway correction pressure as per patients need, VILI unaddressed	3300
NeT-Vent	Nov, 2020	Open-source, Low-cost, Correction of airway pressure & volume flow as per patient's requirement, Reduction in risk of Pulmonary Barotrauma (VILI), reducing medical staff exposure to SARS-CoV-2 & reduction in PPE-kit requirements	Efficient Flow dynamics and patient orientation for effective ventilation	650-700

Novelty & Contribution

- Design based on low-cost (Approx. 650-700 ASD) & easily available parts (thus easily replaceable & serviceable)
- Accurate diagnosis of parameters & addressing the pressure and volume flow characteristic problems i.e., ventilation induced lung injuries (VILI) specifically Pulmonary Barotrauma to a great extent.
- IoT enabled, easy and remote monitoring of real time data on app/web based interface. IoT enabling to drastically reduce PPE-Kit Requirement & exposure of medical staff to COVID-19.
- Easy monitoring of data as per patient requirements.
- Complies with the regulatory design standards as per Australian Government.

Limitations & Future Study

- Fabrication with Medical Testing to get concrete results before actual use.
- Gyroscope, Accelerometer and Magnetometer sensors could also be used for proper mapping of the chest and diaphragm.
- A CFD Simulation analysis could also be useful in analysing various parameters.