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

Aviral Chharia[1,2,*], Shivu Chauhan[1], Shankhaneel Basak[1,2], Bikramjit Sharma[1]

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***Abstract*— The recent outbreak of the SARS-CoV-2 pandemic has disrupted healthcare systems all over the world. With the spread of multiple variants, the progress of the pandemic is unpredictable. In critical cases, viral respiratory illness causes fluid build-up in the lungs, requiring the patient to be on ventilation to have sufficient oxygen. With an enormous shortage of ventilators worldwide, the creation of an emergency ventilator has become a compelling international engineering challenge. This paper demonstrates a distinct proof-of-concept design and working of NeT-Vent: a low cost, rapidly scalable, easy to manufacture and IoT-enabled smart invasive mechanical ventilator which addresses Pulmonary Barotrauma, a Ventilator Induced Lung Injury, whose incidences are being increasingly reported during ventilation of COVID-19 patients and remains unaddressed in most open-source ventilators. Prevention of Pulmonary Barotrauma can attenuate multi-organ failure, thus improving survival in high-risk patients. The proposed control system addresses this problem through adaptive control with real-time pressure correction. Further, using Internet-of-Things for remote monitoring of real-time patient vitals through app/ web-based cloud interface drastically reduces the chances of exposure of medical staff to COVID-19 also reducing the requirement of PPE-Kits. The proposed ventilator is extensively evaluated on various parameters and compared with other open-source ventilators. Project NeT-Vent won the Best Project Award at the University of Queensland Engineering Design hackathon, India 2020 on Ventilator Design.**

***Index Terms*— COVID-19, Biomedical Engineering, Invasive Mechanical Ventilation, Ventilator induced lung injury, Computer Aided Design, Internet-of-Things**

I. Introduction

Throughout history, the world has seen many pandemics, with the most recent and ongoing being the COVID-19 caused by the novel coronavirus. The first case of COVID-19 was reported in late December 2019 at Wuhan, China [1]. The most common symptoms of COVID-19 are fever, dyspnea, cough, myalgia and headache [2]. In severe cases, CT-scans show diffuse heterogeneous consolidation with ground-glass opacities, air bronchograms, and bronchiectasis, presenting as "white lung" when most lung lobes are affected [3]. In critical cases, the viral respiratory illness causes fluid build-up in the lungs, in which the patient requires an invasive mechanical ventilator to have sufficient oxygen. The shortage of ventilators has fuelled the dire situation and led to increased mortality. The development of low-cost, easy-to-manufacture and rapidly scalable ventilators for under-resourced regions may be able to save many lives.

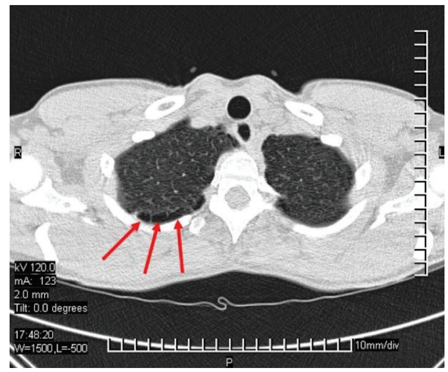


Fig. 1. CT-Scan with Bullae in Lung (Pulmonary Barotrauma) *Courtesy: AquaMed*

Over several decades, mechanical ventilation has been used as a basic form of life-support with patients facing breathing distraught in emergency situations [4]. It is required to provide sustainable life-support with reduced levels of side-effects. There has been significant progress in identifying various ventilator induced lung injuries (VILI) [5] that have proven to increase fatality amongst patients. Barotrauma, Volutrauma, Atelectrauma, and Biotrauma are the four main VILI pathways. [6]. Various other variables, such as heterogeneity in lung mechanics, frequency of stress including pulmonary capillary stress, have recently found to contribute significantly to VILI. [7].

Pulmonary barotrauma, a form of VILI, occurs due to elevated trans alveolar pressure causing alveolar rupture while the patient is on ventilator and is a recognized complication of mechanical ventilation [8]. In other words, it is a tissue-related injury which is caused by sudden and continuous pressure changes in the lungs. Damage happens because of hydro-statically transferred pressure through the tissues either due to shear forces or through tension from the gas expansion within [9]. Complications involve local gas penetration into the affected tissue or local circulation that interferes with the functionality of the organ contributing to circulatory compromise. Pulmonary Barotrauma has adverse effects on the health of patients on mechanical ventilation leading to an increase in morbidity and mortality rate. Reducing VILI can help to substantially minimize multi-organ failure, thus

All authors claim equal contribution
[1]Mechanical Engineering Department, Thapar Institute of Engineering and Technology, Patiala, Punjab, India
[2]Department of Computer Science and Engineering, Thapar Institute of Engineering and Technology, Patiala, Punjab, India
[*]Corresponding author: achharia_be18@thapar.edu

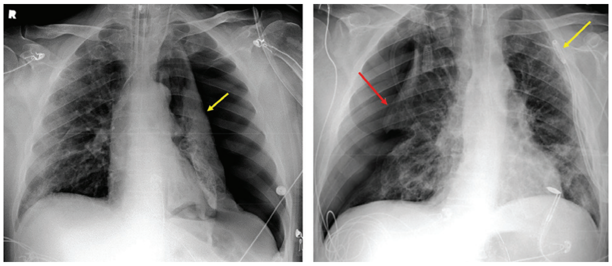


Fig. 2. Frontal chest X-Ray scan confirming Barotrauma in 64-year-old male suffering from diabetes and hypertension, intubated for four days (a) Large left pneumothorax in lungs (yellow) 6 days after intubation. (b) A large right pneumothorax (red) developed 14 days later i.e., 20 days after intubation. The Radiograph highlights left pleural pigtail catheter (yellow) and re-expansion of left lung [21].

improving survival in patients at high-risk. [7].

Computed Tomography Scan shown in Fig. 1 depicts the clinical course of an cerebral air embolism likely due to ruptured pulmonary 'Bullae' in Lung of a patient. The natural mechanism of breathing in humans depends on $-$ve intrathoracic pressures, whereas patients on mechanical ventilation ventilate on $+$ve pressures [10]. Since $+$ve pressure ventilation is not physiological, it may lead to barotrauma in many patients [11]. The incidences of pneumothorax (barotrauma leading to bronchial or alveolar rupture evident by air leak detected on chest X-ray radiographs) in patients ventilated with acute respiratory distress syndrome [12] was as high as 40% prior to protective mechanical ventilation [13], [14]. Incidences of pneumothorax reduce by 5 to 10% when the VT and plateau pressures are reduced [15]–[19]. Rates of pneumothorax and barotrauma increase markedly when plateau pressures above exceed 35 cm H_2O [11], [20].

Recent studies on 601 COVID-19 patients by [21] proved that Pulmonary Barotrauma is an independent risk factor for death in SARS-CoV-2 patients (odds ratio = 2.2; P = 0.03) and is associated with a longer hospital stay (odds ratio = 0.92; P $<$ .001) i.e., the patients on invasive mechanical ventilation with SARS-CoV-2, had a higher rate of barotrauma than patients with acute respiratory distress syndrome (ARDS) and patients without COVID-19 infection as shown in Fig. 2. Research by [21], which reported 15% rate of barotrauma in invasive ventilated COVID-19 patients were mainly focused on radiological findings and methods, but did not investigate a possible association between ventilator settings and barotrauma. Studies by [22], detected severe barotrauma in 40% of patients with COVID-19, considerably higher than reported from larger registries of non-COVID-19 patients and suggested that under reporting cases of barotrauma in large registries is occurring. In-depth studies by [23], [24] further elaborate upon increasing cases of Barotrauma in SARS-CoV-2 patients. Research by [25] suggests that Barotrauma may be specially relevant concern in COVID-19 ventilated patients.

The key contributions of the present work can be summarized as follows-

1) Development of NeT-Vent- an open-source, low-cost, easy-to-manufacture, use and serviceable invasive mechanical ventilator designed using easily manufactured components available from the market in abundant supply, for patients suffering from COVID-19, especially in under-resourced regions where sophisticated ventilators and adequate trained healthcare staff aren't available. The proposed design complies with regulatory design standards of the Australian Government. Proof-of-concept by generated simulation results close to those available in the literature.
2) Accurate diagnosis of parameters along with addressing the pressure and volume-flow characteristic problems including Pulmonary Barotrauma (VILI) using the developed control system with real time pressure correction, unaddressed by most open-source ventilator designs at present.
3) Our ventilator design is primarily based on safe operation, easy and reliable production while addressing specific needs of patients suffering from ARDS due to COVID-19. The proposed design is also driven towards minimising production cost, part count and complexity, reducing assembly time and creating a smooth user interface for operation of personnel with limited experience.
4) Introduction of real time remote monitoring of patient vitals on app/ web-based cloud-interface using Internet-of-things (IoT). This novel approach drastically reduces the requirement of PPE-Kits and ensures minimal patient-doctor contact thus reducing exposure of medical staff to COVID-19

II. Related Works

The creation of a low-cost, easy to manufacture, service, and rapidly scalable invasive mechanical ventilator, is a compelling international engineering challenge today. Locally sourced, these rapidly manufactured machines may be able to save many lives. An adequate ventilator design is still lacking in many fronts especially in underprivileged countries which has led the research community to focus in this direction. Most low-cost and portable ventilators are based on Bag Valve Mask-type (BVM) ventilation systems including ventilators such as VORTRAN Automatic Resuscitator (VAR™) which is essentially a single patient disposable ventilator and Lifesaving Systems Inc.'s Oxylator, Otwo CAREvent® Handheld Resuscitators and Ambu® Matic which is reusable in nature costing somewhere between $900-1000. One of the most important open source ventilator projects is the MIT E-Vent [26].

There have been several innovative designs developed by various teams at different institutes including Rice University's Apollo BVM [27] which is based on Bag Valve Mask (BVM) type of non-invasive mechanical ventilation. It is customized with end-to-end clinician-informed architecture including all essential engineering touch points, control systems designed to handle ARDS environments with positive pressure, entirely made from DIY and components readily accessible at a cost of less than $300. MADVent [28] developed by University of California San Diego's Acute Ventilation Rapid

Response Taskforce (AVERT) is another open-source non-invasive ventilator based on BVM. MADVent significantly focuses on minimising part count with their robust albeit minimal design stacking all the essential components which are required in one single stock, reducing or eliminating dependency on scarce components and services to ensure its feasible operation in multiple healthcare facilities around the world. Coventor [29], developed by University of Minnesota Medical Devices Center is another open-source ventilator based on BVM. Their key emphasis was on the proposed device consisting of a frame (which can be made of metal/ 3D printing or modified consumer products) and a mechanical actuator to stabilize and compress a commercially available ambulatory ventilation bag attached to the endotracheal tube of the patient and external compressed O_2, or ambient air if O_2 is not available.

The main drawback with BVMs is their manual operation which requires continuous operator engagement to hold the mask on the patient and squeeze the bag. This approach in itself has its own demerits. It introduces several restrictions on the type of personnel needed for operating it. If handled by an untrained operator, he/ she may damage the lungs of the patient who is under BVM ventilation just due to over compression of the bag [30]. The other major problem being the cost of operation. Many studies have shown that utilizing BVMs in low cost ventilators increases the risk of Ventilator Induced Lung Injuries [31], [32].

The University of Illinois Urbana Champaign's Rapid-Vent [33] is powered by pressurized gas and controlled by a mechanical modulator, thus not requiring any form of electronic sensor. However, it lack sensors which are used to provide closed loop control, particularly found in expensive open-source ventilators. Most of the medical staff are heavily dependent on these electronic generated data for the monitoring of patient's vitals and emergencies.

High cost of ventilators pose serious technological problems in resource stricken countries [34]. Also, most of these ventilators require high power for their compressors which limits battery life. Many components are not readily available in poor countries limiting their operation [34]. This may lead to sharing of ventilators among patients which has often led to harmful effects than any good [35]. It was also noticed that in certain low cost ventilators, the exhaled air was cycled back and forth into the patient causing breathing problems.

Another major issue that rose to prominence during the COVID-19 pandemic is the deaths of frontline healthcare workers taking care of patients/ ventilator settings, etc., in COVID-19 wards [36]. Most open-source ventilators do not address this critical issue. This leads to healthcare workers monitoring ventilators, in person near the patient which increases chances of contracting SARS-CoV-2 virus. Further, no open-source ventilator papers at present addresses the problem of rising Pulmonary Barotrauma in COVID-19 patients. The most definitive reason for this is cost of procurement and manufacturing.

The pressure and alarm system is used to detect pressure spikes due to mechanical failure, sudden pressure loss due

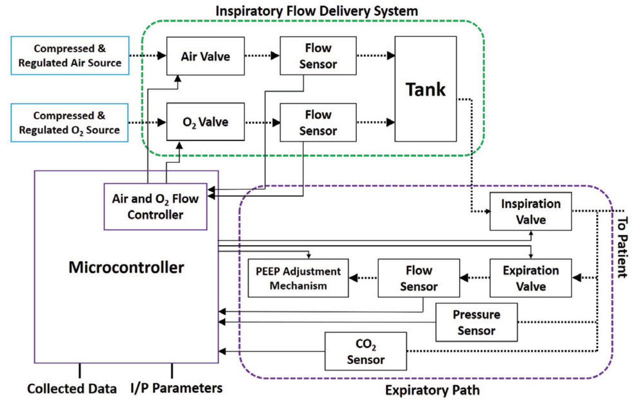


Fig. 3. Block diagram representing ventilator operation

to disconnection and to estimate clinically useful parameters such as the peak inspiratory pressure (PIP), measuring the rate of respiration and $PEEP$. Most high-end ventilators come with advanced electronics that not only monitor the above aforementioned parameters but also monitor secondary parameters like temperature of breath, moisture content of breath and O_2 dissolved level in the air supplied. Majority of these functionalities aren't met by open-source ventilators. Many open-source ventilators are manufactured to just provide patients with a constant air delivery system without adjusting to patient requirements.

Net-Vent has taken these challenges into consideration and designed an optimum solution to remedy most of them.

III. Proposed Design and Methodology

The following section introduces the proposed model and the methodology used.

A. Design Components

Table I gives a detailed description of the mechanical design components used in the proposed ventilator model, along with the quantity, the CAD model (designed in PTC-Creo), its specifications, functions and total cost in Australian Dollar (AUD). Table II expands upon the sensors and the various alarms used in the ventilator's control system.

B. Ventilator Design and Operation

Fig. 4 illustrates the CAD model of NeT-Vent, designed on PTC-Creo Parametric 6.1. The model includes detailed design of components satisfying industrial standards. The main components include gas mixing chamber for blending of compressed air and oxygen, two solenoid valves as per their design drawings, multiple pipes for flow into various parts in sequence, a model HEPA filter box, PEEP valve, various flow sensors, DISS and check valves, bidirectional valves, inhalation manifold, exhalation manifold and the corrugated plastic pipes that goes to the patient on mechanical ventilation.

The ventilator takes compressed air and compressed oxygen, pressurised to 3.5 bar as per regulatory ventilator standards. Both the air and the oxygen lines have air filters from which the air and oxygen passes, preciously through a

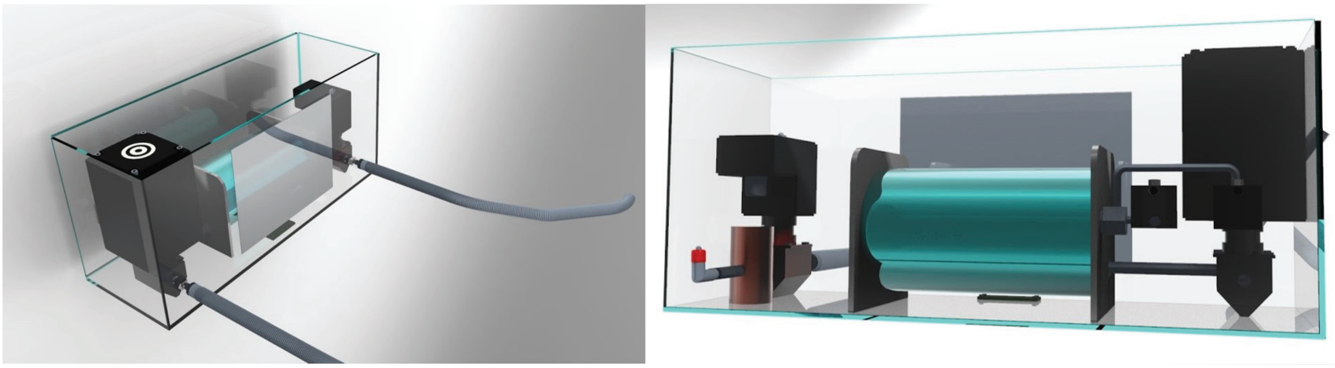


Fig. 4. Computer Aided Design Model developed in PTC-Creo (a) Back view (b) Isometric View showing all the components of the proposed ventilator model

set of one way check valves which ensures that no intermixing of the input contents occurs before reaching the blender. The rear wall has a special DISS fitting which ensures that the ports of supply cannot be interchanged. The air and the oxygen are then further combined in the mixing gas chamber (shaded in blue).

Although the mixing chamber is present for blending air with oxygen in correct proportions, it might contain to an extent up to 100% oxygen depending on system settings. The pressure in the mixing chamber is continuously monitored using a pressure sensor to be in the operating range of $0.689-1.723$ bar. The mixed air then flows into the inspiratory part of the ventilator, where it finds the first component of the inspiratory part which is the proportional solenoid valve. Solenoid valves here regulate fine control of the flow of air in the inspiratory line. The inspiratory line also has a pressure sensor and a flow sensor through which the proportional solenoid valve is controlled. The airflow then exits the ventilator through an inhalation manifold and enters the patient through the breathing circuit which is essentially a connection of pipe running down into the patient trachea.

After the patient breathes out, the air enters the expiratory line through a one way valve which ensures that the patient does not accidentally inspire the exhaled air. The expiratory line has a pressure sensor and a flow sensor for data collection and ensuring proper flow control. From there, the expired air meets the second solenoid valve which is normally in always ON state compared to the inhalation one which is in an always OFF state. Also the solenoid valves are alternate in operation which ensures only one process is working at a time. After that the air passes through a HEPA/ HME filter to ensure the exhaled air is devoid of virus. It helps reduce the inter patient contamination when kept in ventilator wards. After that the air finally goes out of the PEEP valve and out of the expiratory line. What the PEEP valve essentially does is that it induces a specific amount of back-pressure that ensures that alveolar lining in the lung does not rupture. Fig. 3 shows the block diagram representing the ventilator operation.

C. Control System Design

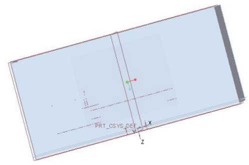
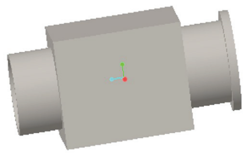
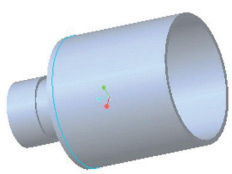
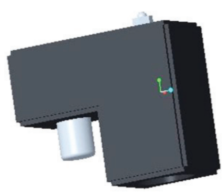
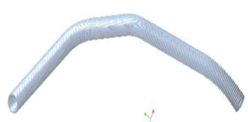
The control system is designed to regulate the supplied oxygen to the patient depending upon the requirements of the patient. Real time data acquisition of patients vitals from sensors aids the process as shown in the control system sensor chart in Fig. 7. TE connectivity's sensors are used since they are highly reliable and have low latency. SM9000 is a low pressure sensor that controls the airflow within the device to the patient. The M3200 pressure transducer checks the oxygen pressure in the tank and supplies the required oxygen at a specific pressure with the help of MS4525 and SM9000 sensors. The air passes through a filter before going to the patient whose cleanliness is detected by the SM6000 sensor. The humidifier contains a mixture of air/gas to be supplied and this is confirmed by the HTU31 sensor. The exhaled breath is passed through a G-PTOC-35 sensor which measures the CO_2 levels and sends the data to the microcontroller to determine the subsequent pressure and amount required. The generated data is in form of rows and columns as well as line charts. All sensors are controlled by a single microcontroller, an Arduino MEGA board as shown in Fig. 6. Values of pressure and volume flow are measured in real time at the ventilator outlet and fed into the microcontroller. The microcontroller is programmed with a custom-made control algorithm based on the Proportional-integral-derivative control [37]. Real time data acquisition of the parameters like pressure and flow rate from the sensors occurs and these are maintained at optimal levels with help of the algorithm.

D. Proportional-Integral-Derivative Control

A proportional-integral-derivative controller [37] is a control loop mechanism that is widely used in many industrial applications. It uses feedback and continuously calculates an error value $e(t)$ as the difference between a desired setpoint (SP) and a measured process variable (PV) and applied a correction based on proportional, integral and derivative terms (denoted P, I, and D). Open-source breathing simulator data available in $.csv$ file format was used to validate the developed control system in Simulink (MATLAB Tool). The control parameters were tuned and the gains were set accordingly for the P, I, and D controllers as depicted in Fig. 5. The overall

TABLE I

DETAILED DESCRIPTION OF MECHANICAL DESIGN COMPONENTS USED IN THE PROPOSED MODEL ALONG WITH THEIR QUANTITY, CAD MODEL, SPECIFICATIONS, FUNCTIONS AND COST IN AUD

Part	Qty.	Cost (AUD)	CAD Model of the component	Specifications	Functions
Base	1	9.5-10		L = 410 mm, B = 250 mm, H = 250 mm, Material = ABS or simulated ABS (acrylonitrile-butadiene-styrene)	The Base serves as the housing for all the parts that go in a ventilator, increasing portability and reducing damage
Pressure Relief Valve	1	10		L = 27mm, D = stepped (8, 9, 11, 13 mm), Material = ABS (depending upon type of manufacturing)	The Pressure Relief Valves serve as the airway channel to remove excess pressure going into the patient
Exhale and Inhale Manifold	1	10		D = stepped (9, 10, 18.5, 20 mm) L = 45 mm, Material = ABS or simulated ABS (for 3D printing)	They serve as the pathway for air to flow in and out of breathing pipes
PEEP Valve	1	25		L = 65 mm, D = 45 mm, Weight = 40 g, Material = Adjustable cap: Poly-amide (nylon), Transparent plastic part: Poly-sulphone	To maintain lower airways pressure, at the end of the breathing cycle, thus preventing alveoli from collapsing during expiration
Solenoid Valve	4	12		Operating Mode: Direct Acting; Type: Normally closed; Pipe Size: 19.01 mm, Orifice: 22.6 mm, Available Voltage: AC 230V, Operating Pressure: 0-7 Pa, Material: Brass	Mainly used for opening, closing, distributing or mixing the flow of gas in a pipe
Pipes	5	10		L = As per requirement, Diameter (Internal) = 15 mm, (External) = 22 mm, Material = Corrugated Plastic	Pipes are used to supply air in and out of breathing patients

control function is,

$$u(t) = K_p e(t) + K_i \int_0^t e(t^{'})dt^{'} + K_d \frac{de(t)}{dt} \qquad (1)$$

where K_p, K_i and K_d, represent the proportional, integral and derivative term coefficients respectively.

E. Internet-of-Things Module

Most open-source ventilators do not provide remote-monitoring of patient vitals and ventilator parameters, which necessitates medical workers to individually monitor them by going towards the patient and manually altering them. This leads to many healthcare workers contracting the virus themselves [36]. To address this issue, Internet-of-things (IoT) is introduced for remote-monitoring of ventilators. The IoT

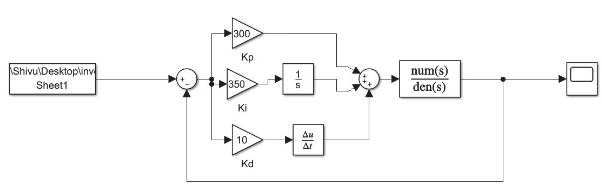


Fig. 5. Simulink Diagram of the PID Control System

TABLE II

DETAILED DESCRIPTION OF THE SENSORS AND ALARMS USED IN THE PROPOSED VENTILATOR'S CONTROL SYSTEM, ALONG WITH THEIR QUANTITY, SPECIFICATIONS, FUNCTION AND COST IN AUD

Component	Qty.	Cost (AUD)	Specifications	Functions
Filter monitoring sensor	1	-	TE Connectivity SM6000 Pressure range : 0.07 - 2.5 PSI Total error: -1% to 1% FS (digital) Temperature range: -20 to 85 °C	Ultra low pressure sensor to detect filter cleanliness
Micro-controller	1	-	Arduino MEGA 2560 Operating Voltage: 5V, Input Voltage: 6-20 V Digital I/O pins : 54 (of which 15 provide PWM output) Analog Input pins: 16, DC current per I/O pin: 20 mA Length: 80.53 mm, Width: 53.3 mm, Weight: 37 g	Main controlling part
Air flow control sensor	2	3.95	TE Connectivity SM9000 Pressure (psi): 0.018, 0.036, 0.044, 0.087, (mbar): 1.25-6 Board Level Pressure Sensor Type : Digital Pressure and Altimeter Sensor Modules Board Level Pressure Sensor Style : Differential, Gage	Low pressure sensor that control the airflow within the device and to the patient
O_2 source pressure sensor	1	4.22	TE Connectivity M3200 Pressure Transducer Sensor Type: Industrial Pressure Transducers, Pressure (bar): 7, 17, 35, 70, 170, 350, 500 Pressure (psi): 100, 250, 500, 1000, 2500, 5000 Output Span: 0.5 - 4.5 V, 0 - 10 V, 0 - 100 mV, 4 - 20 mA, I to C Pressure Transducer Type : Compound, Gage	Stainless steel high pressure transducers to monitor the oxygen tank pressure
O_2 flow control sensor	1	3.30	TE Connectivity MS4525 Pressure (psi): 1, 2, 5, 15, 30, 50, 100, 150 Board Level Pressure Sensor Type: Digital Pressure and Altimeter Sensor Modules; Board Level Pressure Sensor Style : Absolute, Compound, Differential, Gage, Vacuum; Output/Span: 14 bit ADC	Pressure sensors control oxygen flow within the device
Humidity Sensor	1	5.9	TE Connectivity HTU31 Humidity Sensor Component Product Type: RHT Supply Voltage (Peak): 6V; Current consumption (mA): 0.76 Humidity Operating Range (%RH): 0-100 Operating Temp. Range (°C): -40 – 125	Consists of temperature and humidity sensors to confirm the adequate state of the air/gas mixture
CO_2 level sensor	1	3.30	TE Connectivity G-PTOC-35 Operating Ambient Temperature: -20 to 80 °C Absorber Area: 1.4 x 1.4 sq mm Thermopile Resistance: 180 ± 60 k ohm	Thermophile sensors monitor the CO_2 level of the exhaled air
Power Alarms	1	2.5	3.3 to 5 V Active Buzzer Alarm Module Sensor Transistor drive module uses 8550 PCB Dimensions: 34.28 mm (L) x 13.29 mm (W) x 11.5 mm (H)	Electrical supply failure (Visual Cue Alarm)
Output Alarms	1	2.5	-	High/ Low conditions (e.g. volume, pressure, sound alarm, respiratory rate)
Inspired gas properties alarm	1	2.5	-	Failure to deliver prescribed FiO_2 (Both visual and sound cue alarm)

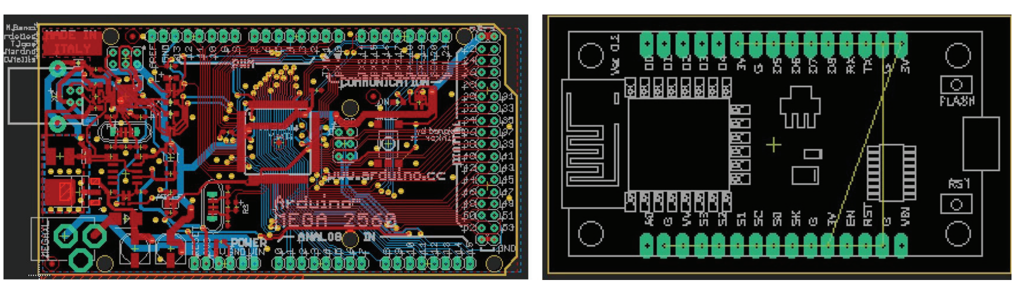


Fig. 6. (a) Arduino Mega Eagle PCB board Model (b) NodeMCU 8266 IoT Module

module is integrated with the control system block using the NodeMCU-8266 module, which is a low-cost, open-source, Lua-based firmware and IoT development platform and uses local WiFi to connect to the internet, as shown in Fig. 6. This module will transfer data of patient vitals on a website/ app-based application securely in real time and will

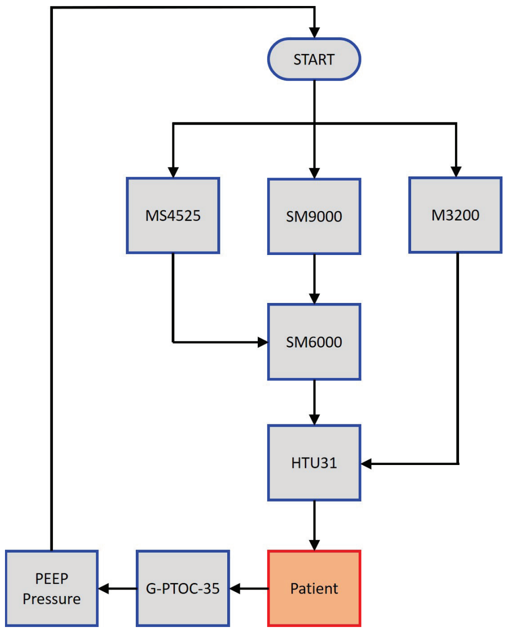


Fig. 7. Control system sensor chart

be monitored by the healthcare staff remotely. For emergency situations, healthcare staff will be able to change any ventilator parameters immediately through the IoT-enabled platform.

IV. EXPERIMENTS AND RESULTS

The control parameters were tuned and the values of gains i.e., K_p, K_i and K_d were adjusted to be 300, 350 and 10 respectively as shown in Fig. 5. The PID generated the output graph on the breathing simulator dataset collected on active patient simulator. The dataset consists of PEEP pressure with time [28] in $.csv$ format. From the generated output graphs as shown in Fig. 8, it can be inferred that unlike other ventilators, using PID control with adaptive parameters, Net-Vent maintains a continuous low plateau pressure of nearly 7.9 cm H_2O (at pt 1). The obtained smooth plateau indicates the appropriate flow responsiveness to patient demand. At the peak where pressure is nearly 7.95 cm H_2O, termination of pressure support occurs (at pt 2) and coincides with the end of neural inspiration. At pt (4) i.e., the end of the graph, the PEEP pressure decreases to baseline PEEP of 7.4 cm H_2O to decrease the blood flow thus attenuating capillary stress failure. The PID control thus decreases the error and reduces the chances of barotrauma.

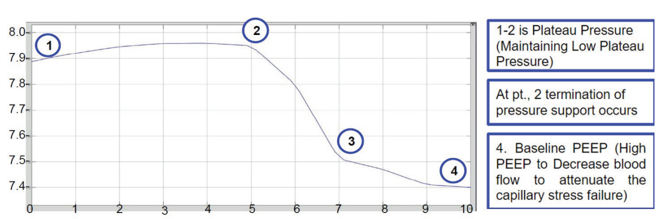


Fig. 8. The generated Pressure (cm H_2O) vs Time (sec) Curve

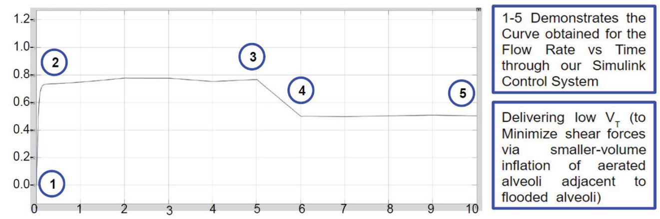


Fig. 9. The generated Flow (mm^3/sec) vs Time Curve (sec)

Analysis on flow rate vs time, gives the inference that Net-Vent maintains low flow rate depending on the data acquisition of the patient's vitals to minimize the shear forces through smaller-volume inflation of aerated alveoli adjacent to flooded alveoli. This further minimizes chances of pulmonary barotrauma in the patient as shown in the generated graph in Fig. 9. Care has been taken to adjust ventilation power which is directly proportional to volume of air pumped into a patient per tidal volume (V_t) adjusted as per patient's lung capacity. NeT-Vent adjusts to the patient's breathing frequency rather than giving a fixed number of breaths per minute by sensing the pressure and volume of exhaled air. Fig. 10 depicts the ventilator Pressure (cm H_2O) vs time curve (sec).

NeT-Vent is equipped with a robust alarm system that is essential when any of the parameters goes beyond a desired range. A high volume alarm would be triggered if ΔP (see Eq. 2) is $>$ set threshold or there is an accidental leak/ disconnect, while a low volume alarm will be triggered by blockage in the inspiratory circuit or if ΔP is $<$ a set threshold. In such cases, the control system will maintain the Pressure and Volume Flow rate as shown in Fig. 8 and Fig. 9.

$$\Delta P = PIP - PEEP \quad (2)$$

where, PIP is the Peak Inspiratory pressure and $PEEP$ is the Positive end expiratory pressure.

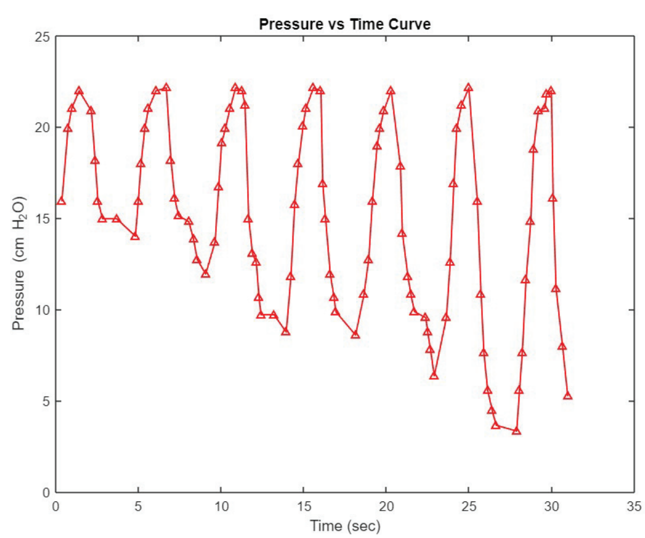


Fig. 10. Pressure (cm H_2O) vs Time (sec)

TABLE III

NeT-Vent's rapid scalability and ease-of-manufacture (with respect to Australia)

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

TABLE IV

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

TABLE V

Comparison of NeT-Vent with other open-source models/ those in Literature

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

V. Discussion and Relevance to COVID-19

NeT-Vent is one of the most affordable open-source ventilators especially in regions where resources are scarce. Most of the mechanical parts can be easily manufactured in house using conventional manufacturing techniques if dealing with metal or 3D printing if dealing with polymeric plastics such as ABS. The supply of these parts is abundant and parts are easy to acquire as shown in Table III. Most parts don't require extensive services. Bundled up, the entire package dimensions are not more than $500 \times 300 \times 300$ mm cube making it easily transportable. The approximate weight of the entire structure is not more than $1 - 1.5$ kg making it easy to transport to distant locations. The results produced by simulation studies provide the ventilator proof-of-concept and it is demonstrated how pulmonary barotrauma can be minimized using the developed control system and is inline with the necessary requirements as per Australian government regulatory standards as shown in Table IV.

The retail cost of the ventilator is around 650-700 AUD, including all required parts, sensors and electronic circuits and can be manufactured at a rapid pace with substantial help from organisations and government organisations. It is easy to operate even by a partially trained healthcare personnel and is equipped with all the necessary display of parameters which are required by doctors for monitoring the health of patients suffering from severe ARDS syndrome. With abundant air and oxygen supply, Net-vent can surely help reduce stress in critical ARDS patients who may be left out of treatment due to lack of ventilators for a considerable period of time. With the rise of open-source ventilators in the current situation of pandemic most of these ventilators are primarily based in few agencies or universities and are not currently within reach of most developing regions such as South Asia.

The developed ventilator has IoT smart system (unlike other commercial high-end ventilators), standard power requirements- 240V AC mains power supply, portability of ventilator- Highly Portable, in case of part malfunction, highly reliable sensors but can be replaced easily on malfunction (includes buzzer Alarm Warning). Early warning by IoT to the cell phone of medical staff enables high reliability and ease of use. The proposed Ventilator design is more useful in the present times and addresses the major challenges faced in nearly all open-source ventilator systems. Table V presents an in-depth comparison of NeT-Vent with other open-source ventilator models based on the major challenges addressed, the challenges unaddressed and their respective costs in AUD.

VI. Conclusion and Future Work

This article demonstrates a proof-of-concept study of a proposed method to reduce incidences of pulmonary barotrauma, a medical condition encountered in mechanical ventilation of COVID-19 patients. The study also proposes NeT-Vent- An open-source, low-cost, easy-to-manufacture, use, and rapidly serviceable invasive mechanical ventilator which addresses many challenges faced by its other open-source counterparts. Unlike many open-source ventilators, Net-Vent does not rely on BVMs due to their reported disadvantages and adverse effects on patient's health in case of prolonged ventilation. Net-Vent is specifically designed to offer under-resourced regions access to high-quality, robust, and powerful ventilators at a significantly reduced cost. The proposed design is evaluated on many parameters, including its rapid scalability, easy-of-manufacture, cost, compliance with the Ventilator design standards/ specifications of the Australian Government, and compared with other open-source ventilator models. Most of the components can be manufactured in-house using conventional manufacturing or 3D printing. The sensors used are of industrial-grade, having good operating accuracy for the specified ranges, and can be easily acquired from suppliers in abundant quantities. The parts are relatively inexpensive and can be re-serviced with a minimal cost, even in remote areas. Moreover, the novel concept of the introduction of Internet-of-things (IoT) for remote sensing in ventilators drastically reduces the number of trips a healthcare worker needs to take into a COVID-19 ward for ventilator monitoring, reducing his/ her risk of possible virus exposure.

Fabrication of the proposed ventilator design based on the proof-of-concept is planned by the authors. Extensive and rigorous testing of the ventilator in severe environments to estimate the model's robustness under various operating conditions is further planned. Various non-mechanical factors can be optimized for better resistance to VILI, including high inspired oxygen fraction, raised body temperature, and increased trans-alveolar gradients of pulmonary vascular pressure. Future work will also incorporate a longer-term supply of power in case of a power outage and study the effects of Wifi on a patient's health. Other areas of improvement involve working on features like various support systems, the design of a robust humidifier, and a blow-off valve. Other research directions include reducing the ventilator's space, dimensions, and overall weight to improve its portability. Increasing the battery life of the ventilator within the stipulated cost range is another challenge.

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