A Project on

The Life Saving Ventilator

Submitted for partial fulfillment of award of
BACHELOR OF TECHNOLOGY

Degree

In

ELECTRONICS AND COMMUNICATION ENGINEERING

By

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DR. APJ ABDUL KALAM TECHNICAL UNIVERSITY, LUCKNOW, INDIA
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CERTIFICATE

Certified that **Ambikesh Prajapati (1852531013)** has carried out the research work presented in this project entitled **"The Life Saving Ventilator"** for the award of **Bachelor of Technology** from Buddha Institute of Technology affiliated to Abdul Kalam Technical University, Lucknow under my supervision. The project embodies result of original work and studies carried out by Student himself and the contents of the project do not form the basis for the award of any other degree to thecandidate or to anybody else.

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Assistant Professor & Project Guide

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DEPARTMENT OF ELECTRONICS AND COMMUNICATON ENGINEERING

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Dr. A.P.J. ABDUL KALAM TECHNICAL UNIVERSITY, LUCKNOW, U.P.

DECLARATION

We hereby declare that this submission is our own work and that, to the best of our knowledge and belief, it contains no material previously published or written by another person nor material which to a substantial extent has been accepted for the award of any other degree or diploma of the university or other institute of higher learning, except where due acknowledgment has been made in the text.

Ambikesh Prajapati (1852531013)

ACKNOWLEDGEMENT

It gives us an excellent sense of delight to present the report of the B.Tech Project undertaken during B. Tech Final Year. We place on record and warmly acknowledge the continual encouragement, invaluable supervision, timely suggestions and inspired guidance offered by our guide we owe special debt of gratitude to our Guide **Mr. Ghanshyam Mishra**, **(Assistant Professor)** of ECE Department, Buddha Institute of Technology, GIDA, Gorakhpur for his constant support and guidance throughout the course of our work.

We also take the chance to acknowledge the contribution of **Dr. Arvind Kumar Panday (DIRECTOR)**, **Mr. Anil Kumar Chaudhary (HOD)** & **Dr. Saiyeed Salim Sayeed** (**ASSISTANT PROFESSOR**), Department of Electronics and Communication Engineering, Buddha Institute of Technology, GIDA, Gorakhpur for his full support and assistance during the development of the project.

Signature: - Date: -

Ambikesh Prajapati (1852531013)

ABSTRACT

As we all know the fact 'Health is Wealth' so everyone gives the primary priority to health. Patients are now increasingly informed about their health. As a result, there's a necessity for a brand new relationship of shared deciding between patients and health care providers. Providers also must be more tuned in to patient values, preferences, and cultural backgrounds. In today, social insurance structure where patients reside home after operations they are monitored by a medical caretaker or a friend. Many of us nowadays who work full time faces a controversy of monitoring their health. The COVID-19 crisis has placed enormous strain on global healthcare due to the sudden and exorbitant caseload burdens, compounded by insufficient access to the requisite supplies and equipment necessary to treat patients. In this article, we will discuss about how we developed an easily-reproducible mechanical ventilator out of core components that can be sourced locally, inexpensively.

Keywords—COVID-19, Global Healthcare, Mechanical Ventilator

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Chapter 1
The Life Saving Ventilator

1.1 INTRODUCTION

A ventilator is a machine that provides mechanical ventilation by moving breathable air into and out of the lungs, to deliver breaths to a patient who is physically unable to breathe, or breathing insufficiently [1]. Ventilators are computerized microprocessor-controlled machines, but patients can also be ventilated with a simple, hand-operated bag valve mask. Ventilators are chiefly used in intensive-care medicine [2].Ventilators are sometimes called "respirators", a term commonly used for them in the 1950s. Mechanical ventilation is termed invasive if it involves an instrument to create an airway that is placed inside the trachea [1]. This can be achieved with many instruments, most commonly through an endotracheal tube.

“Open source hardware is hardware whose design is made publicly available so that anyone can study, modify, distribute, make, and sell the design or hardware based on that design. The hardware’s source, the design from which it is made, is available in the preferred format for making modifications to it [2]. Ideally, open source hardware uses readily-available components and materials, standard processes, open infrastructure, unrestricted content, and open-source design tools to maximize the ability of individuals to make and use hardware [3].Open source hardware gives people the freedom to control their technology while sharing knowledge and encouraging commerce through the open exchange of designs.”

Blood is supplied to the diaphragm by a complex arterial network arising from anastomoses between the phrenic artery and internal mammary arteries and between branches of the phrenic artery and the intercostal arteries [3]. The venous anatomy parallels the arterial circulation. This rich and redundant arterial supply helps to ensure that blood flow is sufficient to meet the occasionally strenuous energetic demands placed upon the muscle [4]. Blood flow is heterogeneous throughout the muscle and directed toward regions where energetic demand is highest.

The structural arrangement of the costal and crural diaphragm and its relations to the various components of the chest wall is summarized in Figure 1-1. The diaphragm receives its entire innervation from the phrenic nerve, originating from cervical nerve roots .

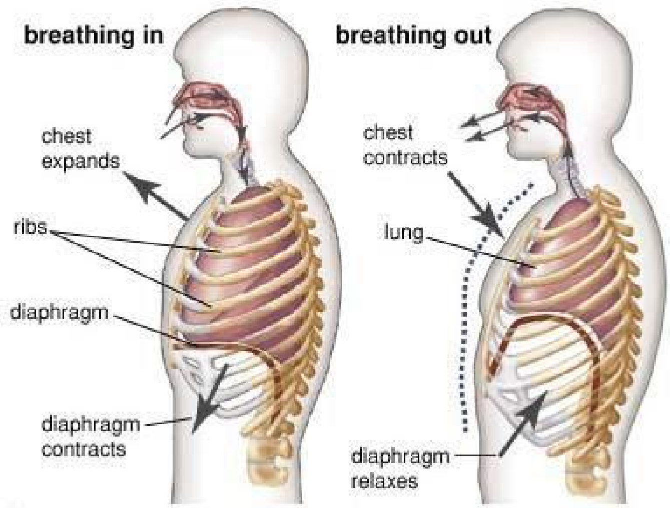


Figure 1-1. Schematic of costal and crural diaphragm action.

1.2 IMPORTANCE OF VENTILATORS

Mechanical ventilation is a life-support system used to maintain adequate lung function in patients who are critically ill or undergoing general anesthesia (1,2); however, it may cause lung damage. The benefits and harms of mechanical ventilation depend not only on the adjustment of ventilator parameters, but also on the interpretation of ventilator-derived parameters, which should be used to guide ventilatory strategies. Regardless of ventilator mode, the following ventilator-derived parameters should be measured in order to mitigate harmful effects (2,4): intrinsic PEEP (PEEPi), peak (Ppeak) and plateau (Pplat) pressures, driving pressure (ΔP), and transpulmonary pressure (P_L) [4].

Furthermore, additional clinical studies are required to ascertain the safe thresholds of each of these parameter in injured and uninjured lungs [3].

1.3 COASTAL AND CRURAL DIAPHRAGM

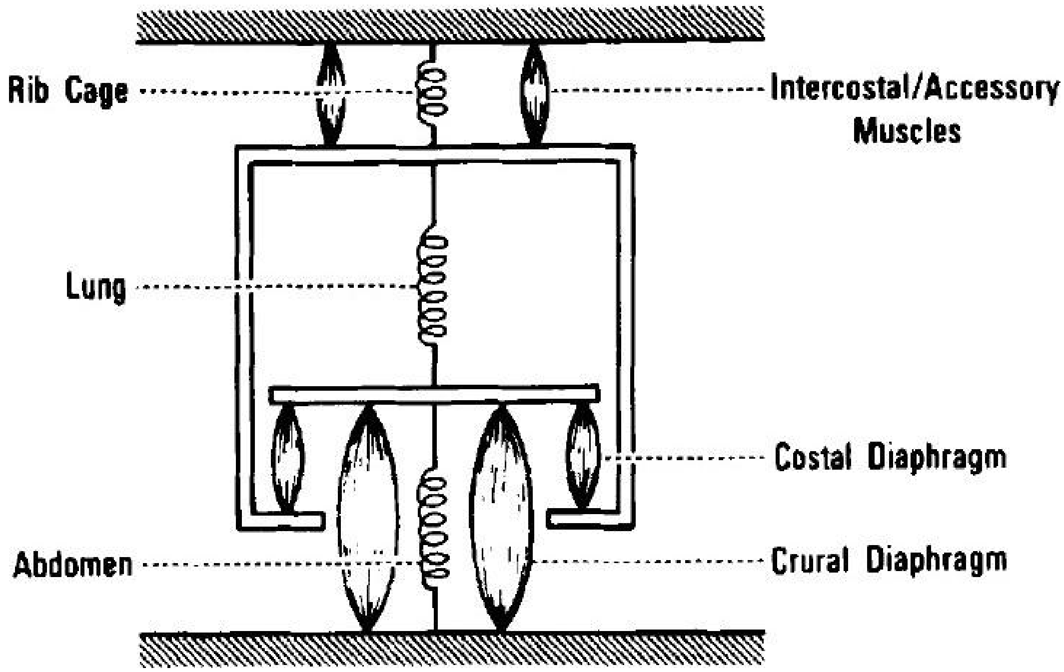


Figure 1-2. Costal and Crural Diaphragrm Working Model.

The parasternal intercostal is an obligatory inspiratory muscle working in coordination with the diaphragm, apparently sharing a common pathway of neural response. This similarity has attracted clinical interest, promoting the parasternal as a noninvasive alternative to the diaphragm, to monitor central neural respiratory output [5]. However, this role may be confounded by the distinct and different functions of the costal and crural diaphragm. Either mechanical function of the parasternal may also impact differential function of the costal and crural. The objectives of the present study were, during eupnea and hypercapnia, [1] to compare the intensity of neural activation of the parasternal with the costal and crural diaphragm and [2] to examine parasternal recruitment and changes in mechanical action during progressive hypercapnia, including muscle baseline length and shortening.

We directly measured the electrical activity of the parasternal, costal, and crural diaphragm, and the corresponding mechanical shortening of the parasternal, during eupnea and hypercapnia [5].

During eupnea and hypercapnia, the parasternal and costal diaphragm share a similar intensity of neural activation, whereas both differ significantly from crural diaphragm activity [6]. In conclusion, the parasternal shares an equivalent intensity of neural activation with the costal, but not crural, diaphragm.

Carbon dioxide, gas exchange monitoring, transcutaneous monitoring, near-infrared spectroscopy, pulse oximetry, and electrical impedance tomography are examined. Although some of these technologies have been utilized for decades, incorporation into mechanical ventilators and recently developed methods may provide important clinical insights in a broader patient range. Less mature technologies (electrical impedance tomography and near-infrared spectroscopy) have been of particular interest, since they offer easy bedside application and potential for improved care of children with respiratory failure and other disorders [3]. This article provides an overview of the principles of operation, a survey of recent and relevant literature, and important technological limitations and future research directions.

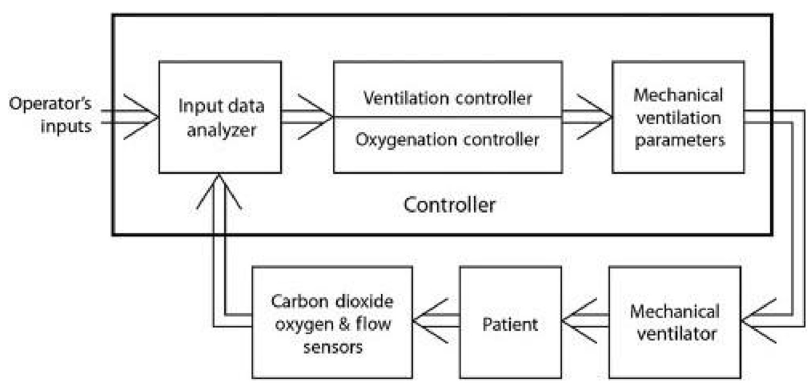


Figure 1-3. Oxygenation and Ventilation Cycle.

Chapter 2

Design of The Life Saving Ventilator

2.1 INTRODUCTION

The COVID-19 crisis has placedenormous strain on global healthcare due to the sudden and exorbitant caseload burdens,compounded by insufficient access to the requisite supplies and equipment necessary to treat patients [7]. Most notably, critical shortages of mechanical ventilators, which are essential for oxygenating patients who cannot breathe on their own, have forced physicians to make difficult decisions between who will and will not receive treatment, especially in resource-limited communities.In this article, we will discuss about how we developed an easily-reproducible mechanical ventilator out of core components that can be sourced locally, inexpensively [8]. Overall, the goal of mechanical ventilation is to support gas exchange and sustain life until the cause of respiratory failure is resolved. As Hippocrates stated, an important goal of medical practice is to “do no harm”, and this is a crucial aspect to consider when setting the goals during mechanical ventilation.

2.2 THE MAJOR HARDWARE PARTS OF PROJECT

1. Arduino UNO
2. Blood Oxygen Sensor
3. Pressure Sensor
4. Servo Motor
5. Breather Mask
6. Air Breather Bag
7. Atmega Processor
8. LCD Display IC (16*4)
9. Jumper Wires
10. Adapter

a). Arduino UNO:

The **Arduino UNO** is an open-source microcontroller board based on the Microchip ATmega328p microcontroller and developed by Arduino.cc.The board is equipped with sets of digital and analog input/output(I/O) pins that may be interfaced to various expansion board (shields) and other circuits. The board has 14 digital I/O pins (six capable of PWM output), 6 analog I/O pins, and is programmable with the Arduino IDE (Integrated Development Environment), via a type B USB cable. It can be powered by the USB cable or by an exit 9-volt battery, though it accepts voltages between 7 and 20 volts. It is similar to the Arduino nano and Leonardo. The hardware reference design is distributed under a creative common Attribution Share-Alike 2.5 license and is available on the Arduino website. Layout and production files for some versions of the hardware are also available.

Figure 2.1 Arduino UNO

b). Blood Oxygen Sensor:

A pulse oximeter (pulse ox) is a noninvasive device that estimates the amount of oxygen in your blood. It does so by sending infrared light into capillaries in your finger, toe, or earlobe. Then it measures how much light is reflected off the gases.A reading indicates what percentage of your blood is saturated, known as the SpO2 level. This test has a 2 percent error window. That means the reading may be as much as 2 percent higher or lower than your actual blood oxygen level. This test may be slightly less accurate, but it’s very easy for doctors to perform. So doctors rely on it for fast readings.

Things like dark nail polish or cold extremities can cause the pulse ox to read lower than normal. Your doctor may remove any polish from your nails before using the machine or if your reading seems abnormally low. It is because a pulse ox is noninvasive, you can perform this test yourself.

Figure 2.2 Blood Oxygen Sensor

c). Pressure Sensor:

A pressure sensor is a device or instrument which is able to measure the pressure in gases or liquids [3]. A pressure sensor consists of a pressure-sensitive element which can determine the pressure being applied and components to convert the information into an output signal.

Pressure sensors are critical components in the ventilators that provide necessary breathing assistance to patients battling COVID-19. Depending on the role of a pressure sensor in a ventilator, several sensor solutions are available for different applications. These include filter monitoring, airflow control, O2 flow control, O2 source pressure, CO2 level.

Figure 2.3 Pressure Sensor

d). Servo Motor:

A servo motor is a rotary actuator that allows for precise control of angular position. It consists of a motor coupled to a sensor for position feedback. It also requires a servo drive to complete the system. The drive uses the feedback sensor to precisely control the rotary position of the motor.
Servo motors or “servos”, as they are known, are electronic devices and rotary or linear actuators that rotate and push parts of a machine with precision. Servos are mainly used on angular or linear position and for specific velocity, and acceleration.

Figure 2.4 Servo Motor

e). Breather Mask:

A respirator is a masklike device, usually of gauze, worn over the mouth, or nose and mouth, to prevent the inhalation of noxious substances or the like. Health professionals wear respirators to filter out virus particles as they breathe in so they don't get infected with COVID-19 while helping people and patients.

Figure 2.5 Breather Mask

f). Air Breather Bag or Ambu Bag:

A bag valve mask (BVM), sometimes referred to as an Ambu bag, is a handheld tool that is used to deliver positive pressure ventilation to any subject with insufficient or ineffective breaths. It consists of a self-inflating bag, one-way valve, mask, and an oxygen reservoir [10].

The Ambu device can provide 100% oxygen from its rear part even at low flow rates and 100% oxygen during active ventilation provided at least 10 L/min oxygen is used.

Figure 2.6 Air Breather Bag or Ambu Bag

g). Atmega Processor:

The ATmega328 is a single-chip microcontroller created by Atmel in the megaAVR family It has a modified Harvard architecture 8-bit RISC processor core [8].

An Arduino Uno is a defined product made to a certain specification and workmanship. An AVR ATMega328 board is a clone, and may or may not function the same. Many folks use clones successfully.

Figure 2.7 Atmega Processor

h). LCD Display IC (16*4):

A 16x2 LCD means it can display 16 characters per line and there are 2 such lines. In this LCD each character is displayed in 5x7 pixel matrix [3]. The 16 x 2 intelligent alphanumeric dot matrix display is capable of displaying 224 different characters and symbols. This LCD has two registers, namely, Command and Data.

A liquid-crystal display (LCD) is a flat-panel display or other electronically modulated optical device that uses the light-modulating properties of liquid crystals combined with polarizers. Liquid crystals do not emit light directly, instead using a backlight or reflector to produce images in color or monochrome.

The principle behind the LCDs is that when an electrical current is applied to the liquid crystal molecule, the molecule tends to untwist [4]. This causes the angle of light which is passing through the molecule of the polarized glass and also causes a change in the angle of the top polarizing filter.

The LCD (Liquid Crystal Display) is a type of display that uses the liquid crystals for its operation. Here, we will accept the serial input from the computer and upload the sketch to the Arduino.

LCDs are commonly used for portable electronic games, as viewfinders for digital cameras and camcorders, in video projection systems, for electronic billboards, as monitors for computers, and in flat-panel televisions.

Figure 2.8 LCD Display IC (16*4)

i). Jumper Wires:

Jumper wires are used for making connections between items on your breadboard and your Arduino's header pins.There are different types of jumper wires [5]. Some have the same type of electrical connector at both ends, while others have different connectors.A jumper wire's purpose is to temporarily close an electrical circuit without needing the wire to be soldered in place permanently.

Figure 2.9 Jumper Wires

j). Adapter:

An adapter or adaptor is a device that converts attributes of one electrical device or system to those of an otherwise incompatible device or system [6]. Some modify power or signal attributes, while others merely adapt the physical form of one connector to another.When it comes to some electronic devices such as laptops, your charging cord and your adapter are pretty much the same thing.

Figure 2.10 Adapter

Chapter 3
Experimental Setup

3.1 INTRODUCTION

Mechanical ventilation works by applying a positive pressure breath and is dependent on the compliance and resistance of the airway system, which is affected by how much pressure must be generated by the ventilator to provide a given tidal volume .The tidal volume is the volume of air entering the lung during inhalation [10]. These are machines that act as bellows to move air in and out of your lungs. In our respiratory therapist and doctor set the ventilator to control how often it pushes air into your lungs and how much air you get.

In our project, we have used Ambu Bag which generates oxygen according to the requirement of the patient with help of oxygen mask patient inhales the oxygen generated, this process is carried out using Arduino UNO programming.

The aims of mechanical ventilation according to the initiating indications include:

Achieve adequate ventilation - CO_2 elimination

Improve oxygenation

Relieve respiratory distress – off-load respiratory muscles

The patient can breathe easily till their respiratory muscles rest.

The patient's allowed time to recover makes breathing normal again.

Helps the patient get adequate oxygen and clears carbon dioxide.

Preserves a stable airway and preventing injury from aspiration .

3.2 BLOCK DIAGRAM

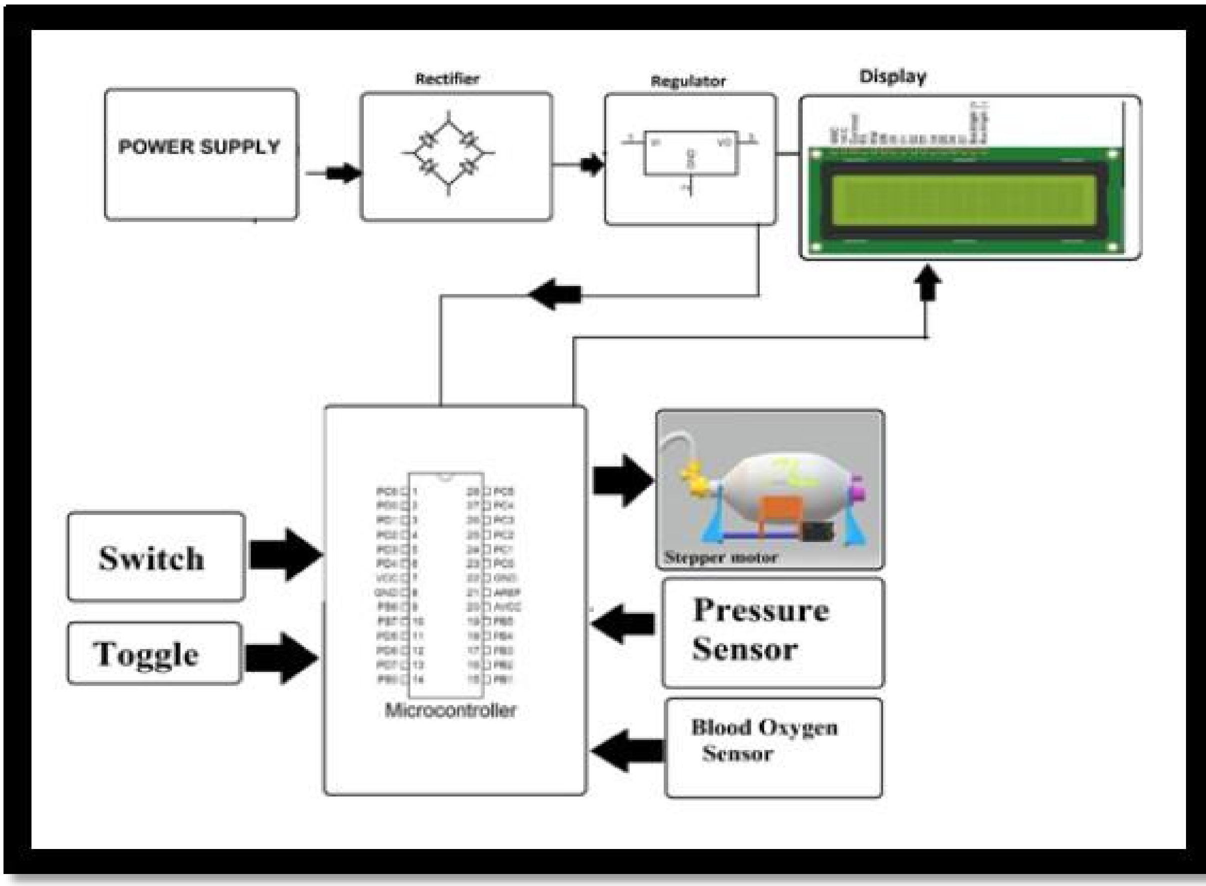
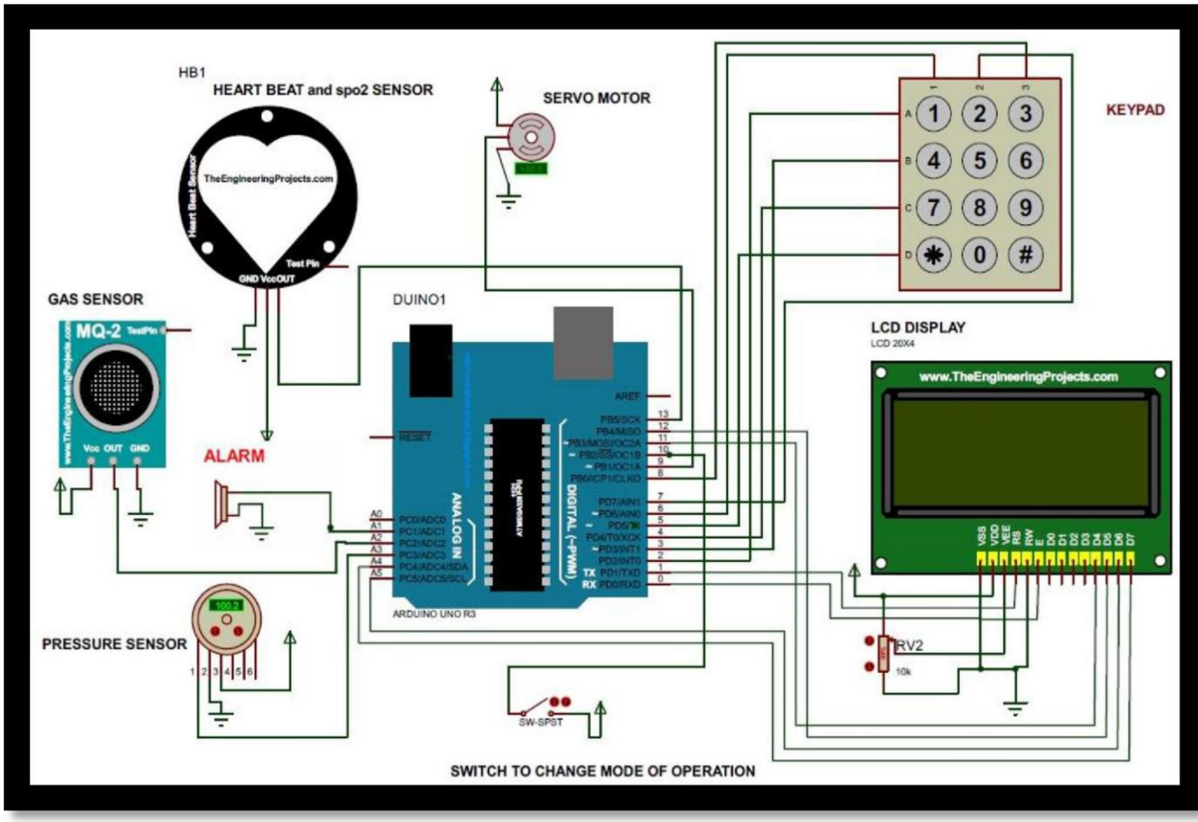


Figure 3.1 Block diagram of The Life Saving Ventilator

Mechanical ventilation is essentially a process that replaces all or part of the action of the inspiratory muscles as well as the neural control of breathing [9]. Two basic types of respiratory cycles can be defined. In the first type, the ventilator "controls" the entire inspiratory phase, or totally replaces the respiratory muscle effort and neural control of the patient. This cycle is referred to as a “controlled” cycle [7]. In the second type, the venitlator only assists the inspiratory muscles that are active and is referred to as an “assisted” cycle. Some authors use the term "spontaneous cycle" to refer to that which occurs during supply of pressure support (PS). Instead, the term “assisted” is used here to designate the second type of cycle in order to be consistent.

3.3 CIRUIT DIAGRAM



The ventilator circuit refers to the tubing that connects the ventilator to a patient, as well as any device that is connected to the circuit tubing [8]. The most common devices include heaters and humidifiers, filters, suction catheters, and therapeutic aerosol generators. For the mechanical ventilator that was designed in this work, it was chosen to use the ST due to it was very practical to find components to design it [5]. This is a good advantage under pandemic time owing to markets tend to be in emergency social restrictions, moreover the ST had to be calibrated, because of using in the designed mechanic ventilator. It was not chosen the sensor based on nanostructures due to it is under researching tasks to enhance controllability and stability of mechanical systems. Nevertheless, it is proposed as an outlook of this kind of ventilator, when it could need control task.

Chapter 4
Results and Discussion

4.1 RESULT

The low-cost, easy-to-build non-invasive ventilator performs similarly to a high-quality commercial device, with its open-source hardware description, which will allow for free replication, facilitating application of this life-saving therapy to patients who otherwise could not be treated.

Thus, the functionality of the entire system has been tested thoroughly and it is said to function successfully. In the near future, more advanced function and compact sizes of the modern ventilators. It will enable them to effectively ventilate all patients in all settings, invasively or non-invasively. To ensure optimum respiratory care, smart ventilators will better adapt to each different individual’s situation and a patient’s changing condition. This will not only reduce complications and sedation but also greatly increase patient comfort and wean patients earlier.

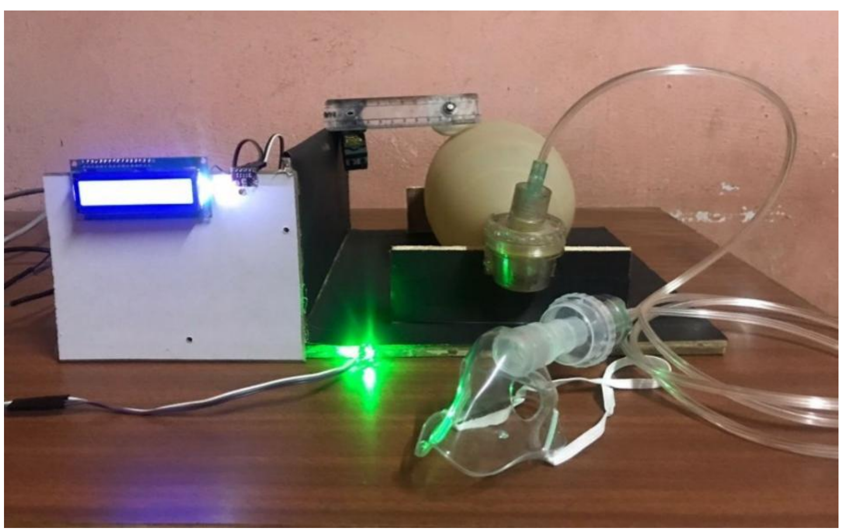


Figure 4.1 Working Model of The Life Saving Ventilator

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APPENDICES A

```
#include <PulseSensorPlayground.h>

#include <Servo.h>

#include <Wire.h>

#include <LiquidCrystal_I2C.h>

// Set the LCD address to 0x27 for a 16 chars and 2 line display

LiquidCrystal_I2C lcd(0x27, 16, 2);

Servo myservo; // create servo object to control a servo

const int PulseWire = 0; // PulseSensor PURPLE WIRE connected to ANALOG PIN 0

const int LED13 = 13; // The on-board Arduino LED, close to PIN 13.

int Threshold = 550;

float pos = 0;

PulseSensorPlayground pulseSensor; // Creates an instance of the PulseSensorPlayground object called
"pulseSensor"


void setup()

{

//lcd.begin();

// Turn on the blacklight and print a message.


lcd.backlight();

myservo.attach(9);// attaches the servo on pin 9 to the servo object

Serial.begin(9600);

lcd.setCursor(0,0); //sets the cursor at row 0 column 0

lcd.print(" Life Saving "); // prints 16x2 LCD MODULE
```

```
lcd.setCursor(2,1); //sets the cursor at row 1 column 2
lcd.print(" Ventilator ");
delay(4000);
}

void loop() {
int myBPM = pulseSensor.getBeatsPerMinute();
// scale it to use it with the servo (myBPMue between 0 and 180)
myservo.write(0); // sets the servo position according to the scaled myBPMue
delay(15); // waits for the servo to get there
if (pulseSensor.sawStartOfBeat()) { // Constantly test to see if "a beat happened".
Serial.println("♥ A HeartBeat Happened ! "); // If test is "true", print a message "a heartbeat happened".
Serial.print("BPM: "); // Print phrase "BPM: "
Serial.println(myBPM); // Print the myBPMue inside of myBPM.
}

if (myBPM >=120 ) {
lcd.setCursor(0,0); //sets the cursor at row 0 column 0
lcd.print("Spd:Fast Ang:100 "); // prints 16x2 LCD MODULE
lcd.setCursor(0,1); //sets the cursor at row 1 column 2
lcd.print("Breath cycle 4 sec ");
for (pos = 0; pos <= 180; pos += 1) { // goes from 0 degrees to 180 degrees
// in steps of 1 degree
myservo.write(pos); // tell servo to go to position in variable 'pos'
delay(15);
}
```

```
for (pos = 180; pos >= 0; pos -= 1) { // goes from 180 degrees to 0 degrees
myservo.write(pos); // tell servo to go to position in variable 'pos'
delay(15);// waits 15ms for the servo to reach the position

}
}

else if (myBPM >=110 && myBPM<=119 )
{ lcd.setCursor(0,0); //sets the cursor at row 0 column 0
lcd.print("Spd:Fast Ang:110 "); // prints 16x2 LCD MODULE
lcd.setCursor(0,1); //sets the cursor at row 1 column 2
lcd.print("Breath cycle 4.43 sec ");
for (pos = 0; pos <= 110; pos += 1) { // goes from 0 degrees to 180 degrees
// in steps of 1 degree
myservo.write(pos); // tell servo to go to position in variable 'pos'
delay(15);
}
for (pos = 110; pos >= 0; pos -= 1) { // goes from 180 degrees to 0 degrees
myservo.write(pos); // tell servo to go to position in variable 'pos'
delay(15);// waits 15ms for the servo to reach the position
}
}
else if (myBPM >=100 && myBPM<=109 )
{ lcd.setCursor(0,0); //sets the cursor at row 0 column 0
lcd.print("Spd:Fast Ang:120 "); // prints 16x2 LCD MODULE
```

```
lcd.setCursor(0,1); //sets the cursor at row 1 column 2
lcd.print("Breath cycle 3.53 sec ");
for (pos = 0; pos <= 120; pos += 1) { // goes from 0 degrees to 180 degrees
// in steps of 1 degree
myservo.write(pos); // tell servo to go to position in variable 'pos'
delay(15);
}
for (pos = 120; pos >= 0; pos -= 1) { // goes from 180 degrees to 0 degrees
myservo.write(pos); // tell servo to go to position in variable 'pos'
delay(15);
}
}
else if (myBPM >=90 && myBPM<=99 ) { lcd.setCursor(0,0);
//sets the cursor at row 0 column 0 lcd.print("Spd:Slow
Ang:100 "); // prints 16x2 LCD MODULElcd.setCursor(0,1);
//sets the cursor at row 1 column 2 lcd.print("Breath cycle 5
sec ");
for (pos = 0; pos <= 100; pos += 0.6) { // goes from 0 degrees to 180 degrees
// in steps of 1 degree
myservo.write(pos); // tell servo to go to position in variable 'pos'
delay(15);
}
for (pos = 100; pos >= 0; pos -= 0.6) { // goes from 180 degrees to 0 degrees
myservo.write(pos); // tell servo to go to position in variable 'pos'
delay(15);
```

```
// waits 15ms for the servo to reach the position
}
}
else if (myBPM >=80 && myBPM<=89 ) { lcd.setCursor(0,0);
//sets the cursor at row 0 column 0 lcd.print("Spd:Slow
Ang:110 "); // prints 16x2 LCD MODULElcd.setCursor(0,1);
//sets the cursor at row 1 column 2 lcd.print("Breath cycle 5.5
sec ");
for (pos = 0; pos <= 110; pos += 0.6) { // goes from 0 degrees to 180 degrees
// in steps of 1 degree
myservo.write(pos); // tell servo to go to position in variable 'pos'
delay(15);
}
for (pos = 110; pos >= 0; pos -= 0.6) { // goes from 180 degrees to 0 degrees
myservo.write(pos); // tell servo to go to position in variable 'pos'
delay(15);
// waits 15ms for the servo to reach the position
}
}
else if (myBPM >=70 && myBPM<=79 ) { lcd.setCursor(0,0);
//sets the cursor at row 0 column 0 lcd.print("Spd:Slow
Ang:120 "); // prints 16x2 LCD MODULElcd.setCursor(0,1);
//sets the cursor at row 1 column 2 lcd.print("Breath cycle 6
sec ");
```

```
for (pos = 0; pos <= 120; pos += 0.6) { // goes from 0 degrees to 180 degrees
// in steps of 1 degree
myservo.write(pos); // tell servo to go to position in variable 'pos'
delay(15);
}
for (pos = 120; pos >= 0; pos -= 0.6) { // goes from 180 degrees to 0 degrees
myservo.write(pos); // tell servo to go to position in variable 'pos'
delay(15);
// waits 15ms for the servo to reach the position
}
}
}
```

APPENDICES B

The Life Saving Ventilator

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Abstract—The COVID-19 crisis has placed enormous strain on global healthcare due to the sudden and exorbitant caseload burdens, compounded by insufficient access to the requisite supplies and equipment necessary to treat patients. Most notably, critical shortages of mechanical ventilators, which are essential for oxygenating patients who cannot breathe on their own, have forced physicians to make difficult decisions between who will and will not receive treatment, especially in resource-limited communities. In this article, we describe the efforts undertaken by a consortium of engineers, roboticists, and clinicians from Vanderbilt University to develop an easily-reproducible mechanical ventilator out of core components that can be sourced locally, inexpensively.
Keywords—COVID-19, Mechanical Ventilator, Volume-Controlled Ventilation

INTRODUCTION

COVID-19, caused by the novel human coronavirus, is a severe acute respiratory disease that has wreaked havoc on global public health with more than 14.7 million confirmed cases and 611,000 deaths worldwide as of the summer of 2020 [1] , with 3.9 million cases [1]and over 141,000 lives lost in the USA as of this writing.

Patients presenting with COVID-19 can develop severe acute respiratory distress syndrome (ARDS), [2],[3]which is characterized by low respiratory compliance and life threatening impairment of pulmonary gas exchange[4], [5]. Approximately 20% of admitted COVID-19 patients require respiratory assistance from a mechanical ventilator to achieve adequate oxygenation[6]. The resource-intensive therapeutic requirements posed by COVID-19, coupled with the sudden and exorbitant caseload onset, have overburdened healthcare infrastructures across the globe due to dwindling supplies of the personal protective equipment (PPE) and devices (e.g. mechanical ventilators) necessary to protect frontline workers and treat patients with the disease[7].

Insufficient access to clinically-approved ventilation systems has forced physicians to make particularly difficult triage decisions, including modification or even discontinuation of care for patients for whom the outcome is bleak, in an effort to free up ventilators for those with more favorable prognoses[8].

Ventilator Shortages Galvanize Grassroots Innovation

Recognizing these critical supply shortfalls, many communities across the globe have banded together to bootstrap ad hoc solutions in an effort to bridge the supply gap. These efforts range from breweries and alcohol distilleries bottling hand sanitizer instead of beer and whiskey, to large automotive (General Motors[10], Tesla[11]) and aerospace (Virgin Orbit[12], SpaceX, NASA) companies retrofitting and re-tooling entire factories to mass manufacture mechanical ventilators and requisite components at scale. A particularly inspiring example of grassroots ingenuity in the fight against COVID-19 comes from the engineering and 'maker' communities who have mobilized to develop custom, open-source designs for mechanical ventilators that can be rapidly manufactured with fairly simple processes and easily sourced components. These concepts range from mechatronic systems designed to compress clinically-approved bag-valve masks (Ambu bags) at digitally-programmable rates, to pneumatic systems that deliver ventilation directly through digitally-controlled valves, to hybrid systems which use a pressurized chamber to compress an Ambu-bag.

To list all of the open-source designs would require a separate article by itself, so we encourage the reader to consult for a more complete picture of the open-source ventilator landscape.

In this article, we describe the work done by a team of engineers, roboticists, and clinicians from Vanderbilt University, beginning in late March 2020, to develop an easily reproducible mechanical ventilator out of core components that can be sourced locally, inexpensively. This process resulted in an open-source design that is set apart from other solutions by its manufacturing simplicity and reliance on components that are either readily available locally or ubiquitous enough that they could be sourced quickly even in the face of pandemic-induced shortages and supply chain disruptions.

The Vanderbilt Open-Source Ventilator

The Vanderbilt Open-Source Ventilator is a volume controlled, intubation-style ventilator. We took this device from napkin sketch to a prototype in three weeks which, after a successful animal study, doctors deemed able to save a life. Over the following three weeks, we manufactured 100 units and submitted documentation to the FDA for Emergency Use Authorization clearance. Throughout this whirlwind process, we undertook multiple design iterations, informed by continuous clinical input, literature review, and experimental testing, enabling us to converge on a design that is low-cost, easily manufactured, and potentially lifesaving.

Our device implements a simple, inexpensive design; it is largely constructed from plywood, and we did away with expensive, specialized DC/stepper motors and optical encoders, instead relying on widely available windshield wiper motors and a simple reciprocating transmission design based around a scotch-yoke mechanism and drawer glides. The purpose of the device is to mechanically compress an Ambu bag, a widely available medical device that is normally squeezed by hand to transport patients to the hospital or within the hospital when they are having difficulty breathing on their own.

By leveraging medical Ambu bags and requisite ventilator/endotracheal (ET) tubing, the VOV is directly compatible with many standard oxygenation and humidification sources, and the only components that come into contact with the patient's airway are clinically-approved and disposable or otherwise subject to rigorous reprocessing protocols.

We added Arduino-based control electronics which, when combined with mechanical inputs, enables physicians to set the volume of air delivered each breath (called the tidal volume (TV)), the respiratory rate in breaths-per-minute (BPM), the amount of the breathing duty cycle devoted to inspiration vs. expiration (i.e. the I/E ratio), and the pressure thresholds at which alarms will sound during operation (designed in accordance with ISO 60601).Experimental validation in both calibrated mechanical test lungs and live animals has demonstrated that the VOV is capable of delivering consistent, repeatable, and reliable respiratory therapy under variable loading conditions.

DEVELOPMENT PROCESS

Rallying Cry and Rapid Prototype Iteration

The project began in earnest on March 21, 2020, when physicians at Vanderbilt University Medical Center deemed the risk of severe local ventilator shortages high enough that all efforts that could be brought to bear on the problem should be made. Sensing the urgency in their clinical colleagues, the engineering team quickly came together, consisting of faculty and graduate students with all of the skillsets required to quickly build a mechanical ventilator prototype. Within a matter of hours after this clinical call-to-action, a napkin sketch made by one of the engineers was converted into a first prototype that demonstrated the concept of using a motor-driven mechanism to compress an Ambu bag at a consistent rate to deliver mechanical ventilation. The need for accurate, continuous TV adjustment led to the development of Version 2.0 on March 24th, which implemented the scotch-yoke mechanism (SYM) that would become the preferred transmission mechanism of the design (described in more detail in the "Mechanical Design" section). In v2.0, the TV is adjusted by physically sliding the SYM to increase or reduce the compression of the Ambu bag on a single stroke. This TV adjustment mechanism was further improved in v3.0 (with a manually-actuated leadscrew.

At the time, the system was powered by an off-board adjustable lab power supply, meaning that only the BPM could be crudely adjusted by changing the voltage setting of the supply.

Realizing the need for more accurate control, sensors, and safety features, an embedded system (centered around an Arduino Uno) and an associated user interface (UI) was developed in parallel that would enable digital configuration and control of the ventilation profile, as well as the ability to report anomalous events to the caregiver through an ISO 60601-standardized alarm profile.

As the design progressed, extensive manufacturing and assembly instructions were created that would enable others to manufacture the VOV, which would be continually updated throughout the remainder of the project to reflect all design modifications. A complete Institutional Animal Care and Use Committee (IACUC) protocol was drafted and approved by Vanderbilt in 2 days, enabling us to move forward with animal experiments.

Concept Refinement and Testing

The integration of the UI/embedded controller with v3.0 led to the creation of v3.1 on April 2nd, which would be the first unit tested in an in vivo setting on the next day. At our first live swine experiment on April 3rd, we observed insufficient gas exchange from our device resulting in the animal breathing out of synchronization with our ventilator.

This was found to be due to the existence of substantial dead space in the ventilation circuit (specifics of which are provided in the "In Vivo and In Vitro Testing" section). To rectify this, we integrated a pressure-sensing single-limb circuit into the design which places the valves at the patient's mouth rather than remotely at the outlet of the Ambu bag. A second 4-hour live swine experiment was conducted five days later, in which the device worked flawlessly.

Design Lock-In and Manufacturing Scale-Up

Immediately following approval from our clinical collaborators, we began working with several local Nashville companies to ramp up production. Part kits and assembly instructions were distributed to a volunteer workforce consisting of Vanderbilt graduate students, faculty, and staff, as well as local unaffiliated 'makers' and tech enthusiasts in the greater Nashville area. One hundred windshield wiper motor assemblies were generously donated by Nissan Smyrna, a local automobile assembly plant. A local marketing agency (Abel+McCallister+Abel, Nashville, TN) volunteered their facilities and personnel to CNC-route all of the plywood components, which were subsequently assembled by a group of volunteers from two local makerspaces, Fort Houston and Make Nashville. Electronic control boxes were wired and assembled by a group of Vanderbilt University graduate students. All manufacturing and assembly instructions were communicated to volunteers using the documents made available in the Supplementary Information.

Over the course of the next two weeks, we assembled the mechanical frames for 100 units (Fig. 2(j)). By April 17, twenty of these mechanical units were outfitted with fully-wired control boxes for immediate use, with parts-on-hand for 80 more if needed.

Summary of the VOV Design Process

As the previous sections highlight, VOV hardware development, refinement, and manufacture took place rapidly, and was made possible through continuous daily collaboration between engineers, clinicians, and volunteers throughout. Now that we have described the design process, the following sections of this article will address engineering specifications, as well as details regarding the mechanical and electronic design. We also provide VOV testing data in in vitro and in vivo analogous to show that the VOV can provide reliable ventilation over a range of use cases and parameter settings.

VENTILATOR REQUIREMENTS AND SPECIFICATIONS

Clinical ventilators are very complex systems with many sophisticated ventilation modes and closed-loop control abilities, much more than we sought to replicate in the VOV, and we consciously made the decision to prioritize a minimum viable ventilator with the necessary functionality to meet the immediate emergent potential needs during the pandemic. Through many conversations between clinicians and engineers, we arrived at the following understanding of what it is required to ventilate COVID-19 patients.

Dynamics of Mechanical Ventilation

Under VCV, since the ventilator is configured to deliver a fixed TV, the airway pressure profile develops passively as a function of airway mechanics and dynamics. Typical VCV waveforms generated by the VOV. The peak inspiratory pressure (P_{PIP}) is the maximum pressure delivered during inspiration at peak airflow, and is affected by airway resistance and the lung's dynamic compliance, C_{dyn}. P_{PIP} should be monitored closely as high P_{PIP} has been linked with barotrauma (above 40hPa).

The plateau pressure (P_{plat}) is the pressure that develops within the lung when there is no airflow, and is largely dictated by the lung's static compliance, C_{stat}. Monitoring P_{plat} offers the physician a surrogate estimate of pulmonary health, and the relationship of P_{plat} with P_{PIP} can alert the physician to underlying and potentially deadly pulmonary conditions (e.g., if P_{plat} is well above 30hPa and is very close to P_{PIP}, The positive-end expiratory pressure (P_{PEEP}) is the amount of pressure held within the lungs between cycles, and is typically a therapeutic parameter set by the ventilator. Especially in COVID-19 patients who present with ARDS-like pneumonia, lung compliance can deteriorate over time, leading to an increase in airway pressure for a fixed tidal volume.

Therefore, when mechanically ventilating a patient using VCV, it is of paramount importance to be able to accurately monitor airway pressure at various points in the respiratory cycle and report anomalous or excessive pressure events to the physician, and automatically adjust tidal volume to limit P_{PIP} to within acceptable levels.

Understanding the dynamics of volume-controlled ventilation, reviewing current literature, and consulting with our clinical collaborators at Vanderbilt University Medical Center (VUMC), to guide our electromechanical design decisions with the general goal of generating a design that is low-cost, largely insensitive to supply chain disruptions and material accessibility limitations, and easy to manufacture. The range of adjustable TV, BPM, and I/E reported in Table I ensures that our design will be able to accommodate a wide range of patients suffering from compromised respiratory function. COVID-19 patients are typically ventilated at a rate of 2035BPM, and an I/E ratio of 1:1-1:2, where some outlying pathologies may require rates as high as 50 BPM and I/E ratios as low as 1:4. For TV, clinical wisdom dictates that TV should be initially selected based on patient weight (6mL/kg), and finely tuned ad hoc according to P_{late}, P_{PEEP}, and lung compliance.

Parameter	Value
Tidal Volume (TV)	0-800[mL] (Adjustable)
Max TV Deviation (long-term)	35%
Respiratory Rate	5-55 [BPM] (Adjustable)
BPM Repeatability (over 1 minute)	±1 [BPM]
I:E Ratio	1:1-1:4 (Adjustable)
Continuous Operation	>14 [days]
Maximum Deliverable P_{PIP}	>40 [hope]
PPEEP	0-25 [hope] (Adjustable)
Barotrauma Pressure Limiting?	Yes
Over/Under-Pressure Reporting?	Yes (Adjustable)

TABLE I: List of VOV Functional Requirements

MECHANICAL DESIGN

We approached the VCV design challenge by first identifying the actuator and structural materials given the general constraints of availability, cost, and manufacturability.

We selected the windshield wiper motor for its low cost, global availability, and ease of sourcing from auto manufacturers to junk yards. Furthermore, the worm gear mechanism inside the motor is designed to generate large forces at a range of speeds under extreme conditions from sub-freezing to extremely hot (>37C°) environments.

These features make windshield wiper motors excellent candidates for applications that require reciprocating, low-to-medium speed actuation for millions of cycles.

For the structural material, plywood was selected also for its availability and the relatively simple and inexpensive tools required to manufacture components. Cabinet makers, wood workers, and many hobbyists have the tools and know-how to make all the mechanical parts.

Scotch Yoke Mechanism

Given these materials and constraints, the scotch yoke mechanism offers a simple, relatively low component-count and low fabrication-precision-threshold solution to replicate the squeezing motion of the human hand. The SYM is a reciprocating motion mechanism that converts rotary motion into linear motion the pin. The linear travel of the sliding yoke in this design is constrained by ball bearing drawer glides, which can be sourced from office supplies stores, hardware stores, and offices. A dynamic analysis of the SYM, detailed in the Supplementary File, reveals that a maximum motor torque of 4.1 N·m is required to ventilate a worst-case lung (C_{stat} = 10mL/hope and airway resistance of R_{dyn} = 50hPa/(L/s)) at the highest ventilator settings (BPM = 55, TV = 800 mL). Representative displacement and torque curves at these settings. This requirement is well within the torque capabilities of standard windshield wiper motors, which typically have nominal working.

ELECTRONICS AND CONTROL

The VOV features an embedded controller and UI, mounted to the rear of the device, that enable the physician to digitally configure and monitor critical ventilator and patient parameters.

Integrated Electronics

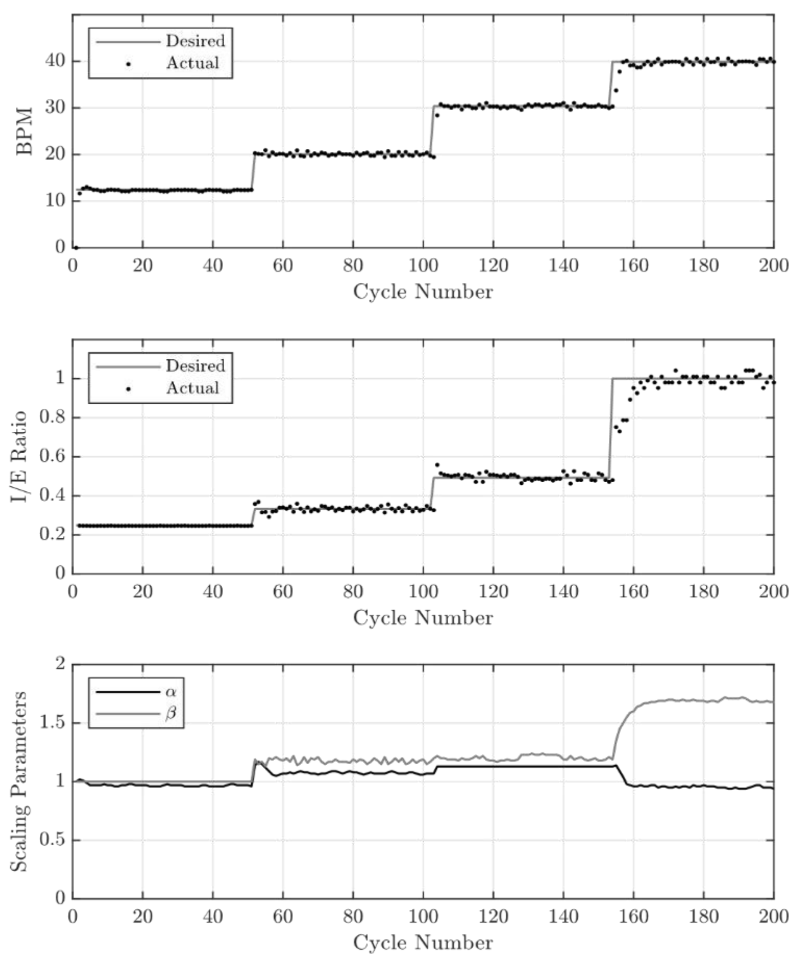
A block diagram of the electronics that comprise the embedded controller. The entire ventilator system (motor, sensors, and on-board controller) is powered by a 12VDC, 5A, ISO60601-compliant power supply. The Arduino Uno MCU (or equivalent) is responsible for executing the integrated controller, processing sensor/user interface data, and issuing motor commands. Various UI features (potentiometers, buttons, switches, and an LCD screen) allow the physician to interact with the ventilator and monitor the status of both the ventilator and the patient.

Control Architecture

The controller is implemented in the form of a finite state machine (FSM). An Alarm Manager object keeps track of various alarm conditions outside of the loop and reports them to the user through a combination of flashing LED, ringing buzzer, and a message displayed on the UI LCD.

End-Cycle Proportional Timing Control Methodology

Windshield wiper motors run in open loop, so to achieve accurate respiratory rate timing, we have implemented an endcycle proportional timing controller.



We sense the position of the motor at the two most important points in the respiratory cycle (full inspiration and full expiration) with a pair of limit switches, dead-reckon between these two points, and adjust speeds on the next cycle as necessary to meet these respiratory timing requirements based on the error between the desired and actual inspiration/expiration times.

The specific hardware implementation of the end-cycle proportional timing methodology is available in the Supplementary File. This proportional timing update capability is demonstrated experimentally in Fig. 7, where the BPM and I/E ratio were increased every 50 cycles (12BPM at 1:4I/E, 20 BPM at 1:3I/E, 30 BPM at 1:2I/E, and 40BPM at 1:1I/E) while the VOV was actively ventilating a test lung apparatus with a built-in compliance of 20mL/hope. As can be observed, the VOV is quick to converge to the new settings (within 30% of the desired setting after a single breath cycle), and with negligible steady-state error.

RESULTS

In preparation for the FDA EUA submission, the VOV has been experimentally validated using a combination of in vitro validation in a calibrated mechanical test lung, as well as live animal testing using an anesthetized swine model.

In Vivo Swine Study

Two live animal studies were performed where the VOV provided continuous ventilation to an anesthetized swine for four hours. In the first study, as mentioned in the “VOV Development Process” section, there was insufficient gas exchange due to the length of the ET tubing.

For a more detailed discussion of this please see “Insights from First In Vitro Swine Study” in the Supplementary File. In the second swine study, we corrected the problem with a pressure-sensing single-limb circuit.

The swine was ventilated continuously for four hours (with average settings of 20 BPM and an I/E ratio of 1:2) as per our approved IACUC protocol.

Throughout the course of the second experiment, the swine remained hemodynamically normal, with adequate oxygenation, ventilation, and a normal pH. Subsequent histology results revealed well preserved alveolar structural integrity with no evidence of barotrauma or atelectasis.

In Vitro Parameter Variation/Durability Study

In addition to live animal tests, we also performed a series of performance characterization and durability experiments on a mechanical test lung, pursuant to testing standards set forth in ISO.

The tests were performed using a calibrated test lung (Model 1601, Michigan Instruments) with adjustable compliance and linear resistance, which was generously loaned to the project by Volunteer State Community College, Gallatin, TN.

A Siargo FS6122 pressure/flow sensor was used to capture pressure, flow rate and tidal volume waveform data at a sampling rate of 200 samples/sec. The TV was calculated by numerically integrating the flow rate data. Data were post-processed and statistically analyzed in MATLAB.

CONCLUSION

The COVID-19 pandemic has crippled healthcare infrastructures across the globe due to insufficient supplies of protective, diagnostic, and therapeutic equipment. Most notably, clinically-approved ventilator shortages have led to many preventable deaths. This shortage has motivated engineering communities to quickly mobilize and develop alternative solutions that could provide a last resort for patients who face triage. As part of this effort, the Vanderbilt Open-Source Ventilator was developed by a team of engineers, roboticists and clinicians to provide an alternative to patients who otherwise may not have access to traditional clinical mechanical ventilators. Manufactured from inexpensive and easy-to-source components, the VOV and its open-source design could serve after the 24 hour period.

ACKNOWLEDGEMENT

We would like to formally thank our partners for making this project possible including the Provost's Office at Vanderbilt University, Vanderbilt's Office of General Counsel, the Wond'ry, the Vanderbilt Institute for Surgery and Engineering (VISE), the Vanderbilt University Medical Center and the Institutional Animal Care and Use Committee (IACUC), the MED Lab at Vanderbilt, the DCES Lab at Vanderbilt, the NERD Lab at Vanderbilt, Volunteer State Community College, Abel Mc Callister, Nissan Smyrna, George P. Johnson Experience Marketing, Fort Houston, Make Nashville and Virtuoso Surgical.

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Curriculum-Vitae

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Career Objective:

As per fresher, my priority is to learn new skills, in a globally competitive environment and getting an opportunity to prove my technical skills and utilize my knowledge in growth of organization.

Educational Qualifications

Course	Board/ University	School/ College	Year of Passing	(%)
B. Tech (ECE)	AKTU	Buddha Institute of Technology	2022	77.12
Intermediate	CBSE	Laxmi Prasad Memorial Public School	2018	60.4
High School	CBSE	St. Joseph's Convent High School	2016	77.9

Technical Skills
C LANGUAGE
CSS
ARDUINO PROGRAMMING
PCB DESINING

Project Done

1. Title: Air Pollution Monitoring System
Project Outline: This project measures the amount of pollution present in air.
Technology: Arduino UNO
Platform: BIT Tech Yuva
Duration: 4 weeks
Team Size: 4
Role & Responsibility: Leader, Making connections

2. Title: **Smart Waste Collector**
Project Outline:Gives reward to person who put waste in smart wastecollector.
Technology: Arduino UNO
Platform: BIT Tech Yuva
Duration: 4 weeks
Team Size: 6
Role & Responsibility: Providing connections and arduino programming

3. Title: TLSV (The Life Saving Ventilator)
Project Outline: This project helps in providing oxygen to the patient as per the requirement.
Technology: Oxygen generation by Ambu Bag with the help of Ardunio UNO.

Platform: BIT Tech Yuva
Duration: 4 weeks
Team Size: 4
Role & Responsibility: Arduino Programming.

Trainings, Seminar / Workshops

Training on PCB Designing in Buddha Institute of Technology for 1 Month
Training on CCNA organized by LTBP Software Solutions Pvt. Ltd. In BIT Gorakhpur for 15 Days
Workshop on IoT from LTBP Software Solutions Pvt. Ltd. For 3 days
Workshop on AI&ML from Wisdomware Technology For 2 days

Awards & Achievements

Gold medal in ‘Developing Soft Skills and Personality’ course organized by IIT Kanpur through NPTEL
Runner up in Chess Competition organized by Sports Department BIT Gorakhpur

Personal Information

Father’s Name: Krishna Mohan Prajapati
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Hobbies: Playing chess, Cardistry, Bodybuilding
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Declaration

I hereby declare that the above information is true and correct to the best of my knowledge. I bear the responsibility for the correctness of the mentioned particulars.

Date: June 2022
Place: Gorakhpur