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Research paper

Breathe Safely with Low-Cost Portable Ventilator

Abhilash Krishnan A[1*], Analram V S[1], Abhinav P[1], Archana S[1] and S Swapna Kumar[2]

[1] *B.Tech IV-Year, Department of Electronics and Communication Engineering*
[2] *Professor & HoD, Department of Electronics and Communication Engineering*
[1,2] *Vidya Academy of Science and Technology Thrissur, Kerala*
[*] *Corresponding author E-mail: abhilasharapanatt@gmail.com*

Abstract

The global healthcare landscape has been profoundly impacted by the COVID-19 pandemic, highlighting the urgent need for a robust and adaptable healthcare infrastructure to navigate public health crises effectively. In response to this imperative, a project was initiated to develop a low-cost portable ventilator system that embodies key attributes of affordability, rapid deployability, and scalability. This paper provides a comprehensive exploration of the design principles, challenges, and ethical considerations associated with the development of low-cost ventilators, emphasizing the critical importance of clear documentation, rigorous testing, and regulatory compliance in the realm of open-source ventilator design. Through a meticulous process of research and testing, the ventilator system has been meticulously evaluated and validated for clinical applications across diverse healthcare settings. The findings of this project not only validate the feasibility and efficacy of the ventilator system but also underscore its potential to address critical gaps in emergency respiratory support. This innovative solution represents a significant technological milestone in reshaping the landscape of emergency respiratory care, offering a scalable and affordable alternative to traditional ventilator systems. The development of this low-cost portable ventilator system stands as a testament to the power of innovation and collaboration in addressing pressing healthcare challenges. By enhancing global health preparedness and resilience through the creation of accessible and efficient medical technologies, this project paves the way for a more secure and adaptable healthcare infrastructure capable of meeting the demands of future public health crises.

Keywords: *COVID-19; Mechanical Ventilators; Healthcare; Respiratory Support*

1. Introduction

The COVID-19 pandemic underscored the pressing necessity for ventilators amid a rise in severe respiratory distress instances. The crucial significance of ventilators in the treatment of respiratory complications became apparent as healthcare infrastructures encountered unparalleled obstacles[1]. A scarcity of ventilators during the pandemic highlighted the need for scalable solutions and exposed vulnerabilities in traditional manufacturing and supply chains [2]. This led to a paradigm shift in healthcare infrastructure, requiring alternative, agile approaches for rapid emergency ventilator deployment. The World Health Organization's emphasis on critical preparedness and response actions resonated with these challenges, prompting a renewed focus on innovative solutions [3].
The COVID-19 outbreak has brought to light the necessity for creative and flexible approaches within the realm of healthcare infrastructure. [4]. Critical medical equipment, particularly ventilators, has faced shortages, necessitating strategic planning and resource allocation [5]. Research on ventilator stockpiling has emphasized the importance of learning from experiences to fortify healthcare systems against unforeseen challenges. The exploration of distributed manufacturing and open innovation perspectives introduces a paradigm shift in medical equipment production and distribution. Conventional supply chains faced limitations during the pandemic, highlighting the vulnerability of centralized production models. By considering alternative methodologies, healthcare systems can enhance their resilience and responsiveness to sudden surges in demand for critical medical equipment. The proposed project aims to improve global health preparedness by developing an affordable ventilator system with rapid deployability, addressing current gaps, and enhancing healthcare preparedness for future challenges [6].

1.1. Problem Statement

1.1.1. Ventilator Shortages in Healthcare System:

The COVID-19 pandemic has posed significant challenges in global healthcare, necessitating critical preparedness and response guidelines. However, ventilator shortages have ensnared the healthcare system, exacerbating the pandemic's ramifications and posing a significant threat to patient care.

1.1.2. Limited Accessibility and Affordability of Ventilators:

The COVID-19 pandemic has exposed the persistent shortage of ventilators in global healthcare, affecting severe respiratory conditions treatment and highlighting systemic deficiencies that predate the current crisis.

As the demand for ventilators experiences an unprecedented spike, the call for a diversified approach reverberates through the corridors of research and expertise. Wittbrodt et al.'s revolutionary life-cycle economic assessment of decentralized manufacturing using open-source 3-D printers presents a new way of thinking, providing creative solutions to overcome conventional supply chain obstacles. [7]. The broader perspective on distributed manufacturing by Srai et al. in [2] illuminates' opportunities and challenges, urging a reevaluation of conventional manufacturing paradigms in the quest for scalable solutions. The global healthcare ecosystem is facing a significant issue of accessibility and affordability of ventilators, particularly during the COVID-19 pandemic. To tackle respiratory challenges, a holistic strategy involving logistical improvements, strategic stockpiling, and innovative ventilator solutions is crucial for a resilient global healthcare system that can navigate uncertainties.

1.2. Objectives and Significance

Researchers in the field propose innovative solutions, offering an initial roadmap for the development process [8]. This approach facilitates not only ease of manufacturing but also enhances accessibility by utilizing materials widely available in various contexts. The fundamental concepts of open-source design are essential in guaranteeing the feasibility and availability of the ventilator. This openness accelerates the design process and adapts the ventilator to different manufacturing capabilities and resource availability. In the meticulous process of conducting a comprehensive evaluation and testing of the ventilator design, a synthesis of various insights from diverse sources forms the bedrock of a robust methodology. The overarching objective is not merely to ensure that the ventilator meets technical specifications but also to subject it to rigorous examinations, ensuring safety, efficacy, and reliability across a spectrum of healthcare settings. The foundational framework for technical specifications is derived from the exploration of low-cost portable mechanical ventilators [9].

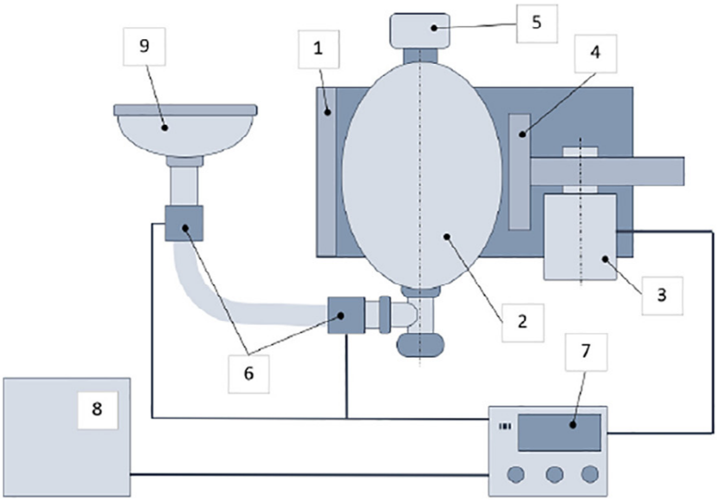

Figure 1: Standalone automated BVM-based resuscitation system, 1) bag mounting system, 2) Self-inflating bag, 3) Motor setup, 4) Compression mechanism (pusher), 5) Positive End Expiratory Pressure (PEEP) valve, 6) Feedback pressure sensors, 7) Control system, 8) Power supply with backup battery, 9) Air mask [9]

At its core, the system employs RepRap technology, a type of 3D printing technology known for its self-replicating capabilities, to manufacture certain components of the ventilator. This feature significantly contributes to the system's accessibility and affordability, enabling decentralized production and assembly. The ventilator operates based on a bag valve mask (BVM) system, a widely used manual ventilation device in healthcare. The automation of this system is facilitated through the integration of a mechanical arm, which compresses and decompresses the bag valve, controlling the flow of air to the patient. This automation is driven by a control system that coordinates the mechanical movements, ensuring precise and controlled ventilation. The control system is programmed to regulate parameters such as breath rate, tidal volume, and inspiration-expiration ratios (Fig. 1 [9]).

This paper is structured in the following fashion. The first part provides a detailed examination of affordable ventilators, including an explanation of the underlying concept. Section 2 presents the comprehensive overview of previous endeavors, pertaining to this field. Progressing further, section 3 consists of an exhaustive analysis of the methodology employed in the aforementioned system, presenting an operation of the system and its modeling and also provides an outline of the hardware components utilized and their implementation and the software development phase of the project. Section 4, presents the findings of the project thus far. The last chapter delivers a condensed and succinct conclusion to this report, effectively encapsulating the principal discoveries and perceptions acquired from the preceding chapters.

2. Literature Survey

Lai et al. propose a breathing circuit splitter to address ventilator shortages during pandemics. They highlight a pediatric hospital experience were adding Pall particulate filters to breathing circuits led to severe hypercapnia in smaller patients. The authors emphasize the need for careful consideration of real-time patient care and the potential challenges in correcting errors. The authors also present an innovative approach in the form of a three-dimensional printable Y-piece (Y-splitter), which includes an optional inspiratory limb flow limiter, designed to allocate the inspiratory and expiratory limbs of the ventilator among different patients. This approach addresses clinical practice challenges and emphasizes the importance of thorough evaluation of interventions [10].

Marcos Méndez Quintero presents a comprehensive exploration of an open-source ventilator design named “Open Ventilator”. Authored by Marcos Méndez, this paper contributes to the growing body of knowledge surrounding decentralized and accessible solutions for ventilator shortages during health crises, with a particular focus on the COVID-19 pandemic. The core of [12] revolves around the development and testing of the Open-Ventilator system, an open-source ventilator project designed to be affordable, easy to assemble, and adaptable to varying medical settings. The authors emphasize the urgency and severity of ventilator shortages during the pandemic and highlight the need for scalable, open-source solutions that can be rapidly deployed to address the surges in demand for critical medical equipment [11].

Husseini et al. [12] this paper delineates the progression and modeling of an economical and easily transportable mechanical ventilator crafted for situations of widespread casualties and settings with limited resources. The ventilator introduces an innovative method by employing a pivoting cam arm to apply pressure on a traditional bag-valve mask (BVM), thereby eradicating the necessity for manual operation of the BVM. The initial prototype, constructed from acrylic, is compact, measuring 11.25×6.7×8 cubic inches, and lightweight, with a weight of 9 lbs. The operation of the ventilator is facilitated by an electric motor that is energized by a 14.8V DC battery. It is equipped with the capability to modify the tidal volume to a maximum of 750 ml, alongside user-friendly input controls that manage both tidal volume and breaths per minute. Within the design of the prototype, there is integration of an assist-control function and a warning system that alerts in cases of excessive pressurization. Notably, the device demonstrates a low prototyping cost of $420, with a projected manufacturing cost of less than $200 in bulk production [12].

Panvent is a work presented in the paper, titled “The Pandemic Ventilator”, that details the design and construction of an open-source, low-cost ventilator aimed at addressing the ventilator shortages during the COVID-19 pandemic. The ventilator’s design is intended to be easily replicable using commonly available materials and components. The project emphasizes simplicity and accessibility, making it suitable for rapid deployment in emergency situations, especially in regions with limited resources. The design utilizes a bag-valve mask (BVM) as a fundamental component, driven by an automated mechanism to provide controlled ventilation. The BVM compression is achieved through the use of a mechanical system, eliminating the need for a continuous air supply or complex electronic components. This design choice simplifies the ventilator’s operation and enhances its reliability, making it suitable for scenarios where advanced medical infrastructure may be scarce [13].

D. Williams et al. presents an innovative approach in order to tackle the issue of shortages in ventilators, a low-cost, automated bag-valve mask (BVM) ventilator was proposed. This project is centered on the provision of a solution that is not only economically efficient but also straightforward to reproduce and implement in urgent circumstances, especially amidst the COVID-19 crisis. The core of the design revolves around the automation of the compression process of a standard Bag Valve Mask (BVM), thereby obviating the necessity for continual manual intervention and potentially alleviating the burden on healthcare resources. The ventilator prototype incorporates a mechanical system powered by a motor to compress the BVM, delivering controlled breaths to the patient. This design choice aims to strike a balance between simplicity and functionality, making the ventilator accessible in resource-limited environments. The system is designed with user-friendly controls, allowing for adjustable tidal volume and breaths per minute, enhancing its adaptability to different patient needs [14].

3. Methodology

The study developed a portable BVM compression system using an Arduino microcontroller as a temporary emergency ventilator. It features alarms, controlled breathing mode, and detailed software analysis, enhancing medical professionals’ response to emergencies. The system uses a medically approved BVM bag, a mechanism that propels it, generating necessary ventilation. This approach is not a novel concept, as previous open-source ventilators have used mechanical arms to provide ventilation.

3.1. Mathematical Modelling of the Proposed System:

This system uses a stepper motor to compress and release the bag-valve-mask (BVM) for negative pressure ventilation. Control switches and knobs modulate compression speed and volume using potentiometers and an LCD. It has three changeable parameters: tidal volume (VT), breathing rate per minute (BPM), and ratio of inspiratory to expiratory phases (I/E). VT and the I/E manipulation is done using rotary potentiometers, BPM is regulated through the utilization of a rotary encoder. The self-inflating bag’s compression is specified in Fig2 [9].

The actuator advances to the initial position through interaction with the boundary switch, modifying the volume of air delivered, and controlling the frequency of breaths per minute. A stepper motor with 1.8 degrees per step is recommended and taken. A micro-stepping multiplier (k) can increase the number of steps executed within a single revolution, promoting smoother rotation and enhanced stability. This method is achieved by implementing a micro-stepping multiplier with a range of 2 to 16.

The motor’s thrust is influenced by motor torque and gear diameter, as per an equation that confirms that the diameter of the gear directly influences the motor’s thrust.

$$F = \frac{2T}{R} \tag{1}$$

Where,
T- motor Torque,
R-Gear radius

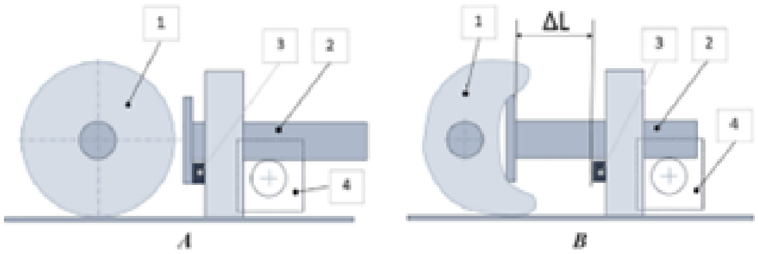

Figure 2: The process of compression of a self-inflating bag: A) initial homing position of the pusher, B) compression stage, 1) self-inflating bag, 2) pushing rod, 3) limit switch, and 4) stepper motor [9]

A series of controlled experiments showed that a herringbone gear with a diameter of 15 millimeters, can produce a high level of propulsive force while maintaining consistency in the interlocking contact points between its teeth. As shown in Fig. 3 , Tidal volume, BPM, and I/E functions are dependent on the quantity of motor steps. should be calculated as follows,

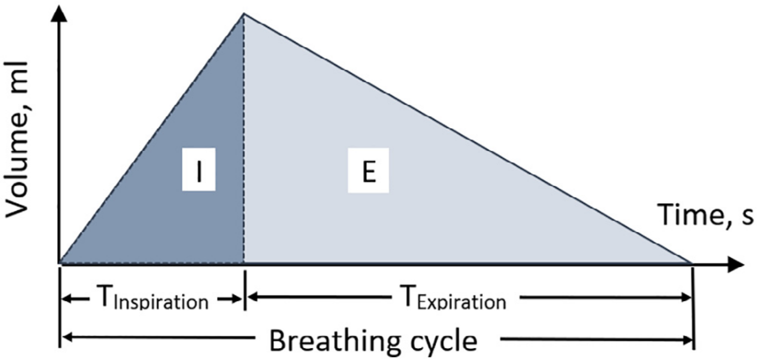

Figure 3: Breathing control Diagram [9]

$$n = \frac{\Delta L \cdot N}{\pi \cdot D} \tag{2}$$

Where,
D stands diameter of gear in mm
ΔL stands for pusher length in mm
N stands for steps in a complete revolution
Simultaneously,
N = k·365/1.8 steps
k = micro stepping multiplier
The stepper's motion is influenced by the value of k, which can be set to 4 or 2, depending on the desired torque. A large value of k leads to a smoother motion but decreases torque. An appropriate k value was chosen.

$$\Delta L = \frac{V_T + 83}{8.9} mm \tag{3}$$

Air leakage may occur as a result of the pressure sensor's mounting design, consequently resulting in a decline in the calibration curve's inclination. Thus,

$$n = \frac{(V_T + 83) \cdot 365 \cdot k}{8.9 \cdot 1.8 \cdot \pi \cdot D} \tag{4}$$

By manipulating I/E and BPM control knobs, it is possible to set the time delays between successive motor steps,

$$\Delta_{ti} = \frac{60}{n \cdot BPM \cdot (1 + \frac{1}{I/E})} s \tag{5}$$

Where,
Δ_{ti} = stands for time delays in sec
I/E=inspiration to expiration ratio

$$\Delta_{te} = \Delta_{ti} \cdot (I/E)^{-1} s \tag{6}$$

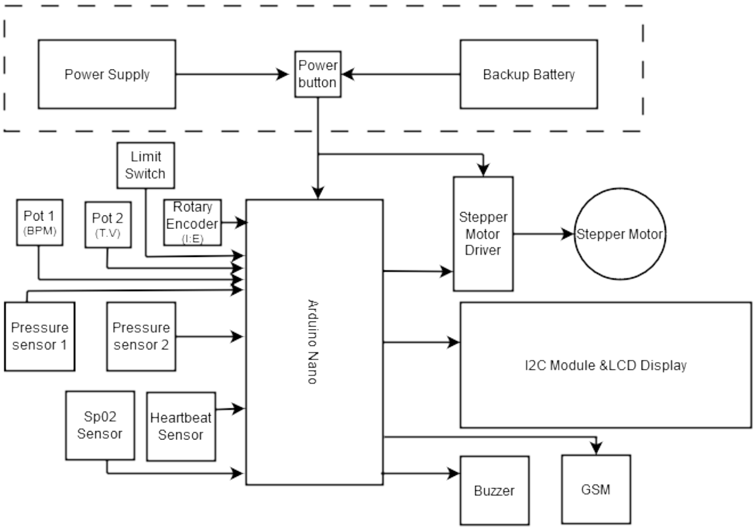

Figure 4: Block Diagram

3.2. Block Diagram

The depiction shown in Figure 4 effectively emphasizes the pivotal and central role that a microcontroller plays as the primary processing unit within the system, effectively coordinating and managing its various functions.

The ventilator system is a comprehensive system that uses three key control variables: BPM (beats per minute), TV (tidal volume), and I:E (inspiration to expiration ratio). The stepper motor is controlled by a dedicated driver, and the system also includes an LCD module and a limit switch for precise positioning. Other sensors monitor the patient, enhancing the system's functionality. A buzzer and GSM capability provide additional security, warning in risky situations. A secondary battery allows the system to be used in diverse environments. These unique elements work together to ensure efficient ventilation and overall system functionality.
The ventilator system is designed to be versatile and adaptable, making it suitable for various environments [15].

3.3. Hardware Development

The study uses open-source hardware and printed components to create an affordable and replicable ventilator system. It uses Arduino microcontrollers, electronics, and custom parts from a RepRap-class printer. Mechanical components are made using open-source CAD systems. A battery is included for temporary patient mobility.

3.3.1. Arduino Nano:

Arduino Nano is a compact, low-power microcontroller board popular among electronics enthusiasts for robotics, home automation, wearable devices, and education due to its Arduino Integrated Development Environment simplifying C++ programming [16].

3.3.2. NEMA 23 Stepper Motor:

NEMA 23 stepper motors are a type of stepper motor used for precise control of position and speed. They can move in distinct steps representing angular displacement, offering versatile arrangements with varying phase quantities and step angles. These motors can be electrically configured with two or more phases, adhering to a standardized step angle of 1.8 degrees per step [17].

3.4. Software Development

3.4.1. Software Architecture:

The project uses FreeRTOS within the Arduino framework to enhance the responsiveness and reliability of the respiratory support system. It includes functions like scheduling, dispatching, inter-task communication, and sync. The architectural design includes a schematic that enables smooth communication between categories of patients and nurses, facilitating the incorporation of extra pathways for diverse operations.

3.4.2. Software Design -Modularity and Code Structure

Real-time Parameter Adjustment and Display: The ventilator project uses real-time monitoring of vital variables like tidal volume, inspiratory-expiratory ratio, and breaths per minute. It's integrated with rotary potentiometers and a rotary encoder, creating an interactive interface. This holistic view of the ventilator's performance enhances its effectiveness and efficiency, enhancing its interactions among its components.
Dynamic Pressure and Flow Control: The system uses two BMP280 pressure sensors and an exponential smoothing algorithm to gather and analyze data on pressure variations. This ensures stability and minimizes fluctuations. The flow rate calculation is crucial for continuous

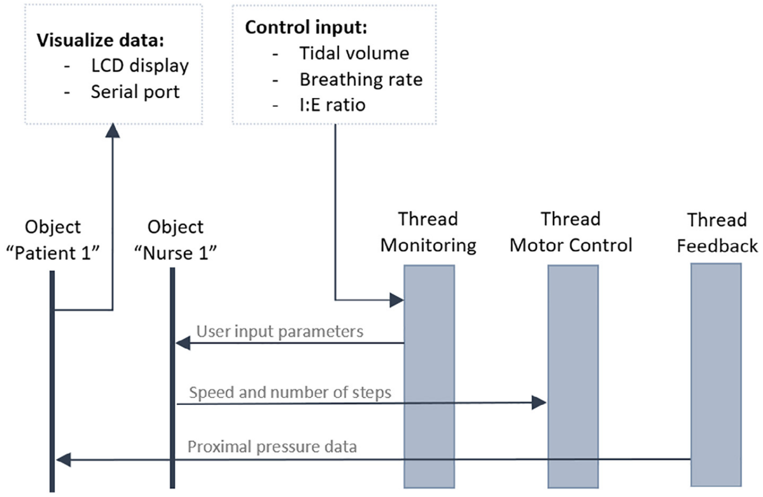

Figure 5: Software Architecture [9]

monitoring and detecting abnormalities. Alarm conditions are managed based on predetermined pressure thresholds, ensuring system safety. The complex process of computing pressure variations is essential for maintaining system stability and safety.
Orchestrating Ventilation Cycles: The task involves managing the ventilation system's breathing cycles, regulating the NEMA23 motor, and affecting tidal volume through piston manipulation. It's closely linked to the nurse's role, as they adjust breathing parameters. The ventilator uses interrupts from a rotary encoder for an interactive interface, crucial for maintaining patient respiratory health.

3.4.3. Essential Classes:

Patient and Nurse: The system consists of two primary classes: Patient and Nurse. The Patient class manages patient-specific variables and real-time data on LCDs, crucial for monitoring respiratory requirements. The Nurse class manages computations related to breathing parameters and synchronization with motor control, ensuring optimal functionality for each patient. The interaction between the two classes is essential for system effectiveness, with the Patient class relying on the Nurse class for motor control decisions.

4. Results

4.1. Tidal Volume Measurements

The system, as stated earlier, operates utilizing a mechanical system that is activated by a stepper motor. This particular system consists of a pusher mechanism, which is precisely programmed with specific parameters. Such configuration enables the determination of the delivered tidal volume. Equation 3 is used for this.

Table 1: Measured ΔL and the Calculated tidal volume

Tidal Volume (in ml)	ΔL measured(in mm)	ΔL calculated(in mm)
100	20	20.5
120	25	22.8
200	35	31.7
300	49	43
400	60	54.2
500	69	65.5
600	80	76.7
700	90	87.9

The system is tested for functionality by measuring the ΔL travelled by the pushing mechanism. Table 1 shows distance moved by pusher at set tidal volumes. These values are compared to how much the pusher should move to deliver the set tidal volume. The tidal volume from the measured distance moved, and its accuracy is calculated. The measured value is compared to values calculated from the previously mentioned equation. They are compared and plotted in figure 6. The tidal volume corresponding to these ΔL values are calculated and their accuracy to set tidal volume is shown in Figs. 7 & 8.

The disparities between the prescribed motion and the recorded motion are illustrated in Figure 6, demonstrating the variation in ΔL.

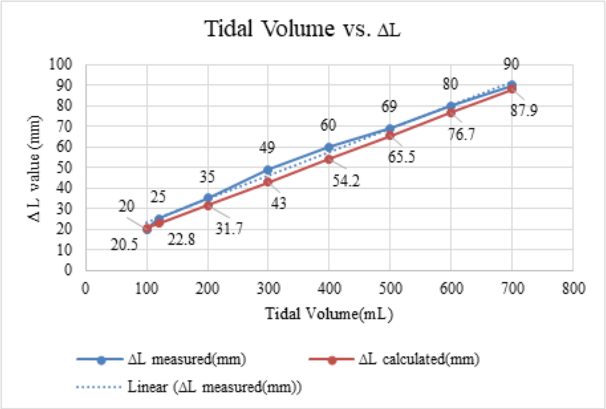

Figure 6: ΔL Deviation

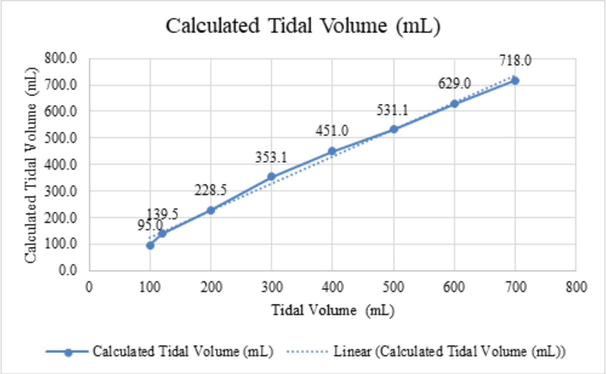

Figure 7: The disparity between set and calculated Tidal Volume

The deviation of tidal volume that is calculated and set tidal volume is shown in Fig. 7.

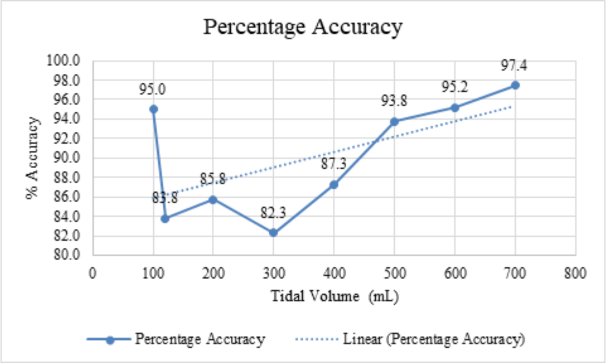

Figure 8: Accuracy of Tidal Volume

Fig. 8 shows the accuracy of Tidal volume is measured to compare with set tidal volume. This comparison not only highlights the proximity of the delivered tidal volume to the set value but also provides insights into the accuracy of the system.

4.2. Step Calculation

The calculation of the required quantity of steps for the stepper to achieve the prescribed tidal volume is determined through the utilization of the appropriate equation (equation 4). This value, in conjunction with the delay between steps, plays a crucial role in determining the system's ability to deliver precise ventilation. Consequently, the ventilation offered by the system strives to closely align with the predefined parameters.

The number of steps to the tidal volume set is shown in Fig. 9. It shows how many steps are needed to move the Δ L distance to deliver the set ventilation.

This gives a collection of the delays possible between the steps in the system to provide ventilation as close to set values as possible. The I:E values which governs the delay factor is set to 1:2. It shows that expiration takes twice as much time as inspiration.

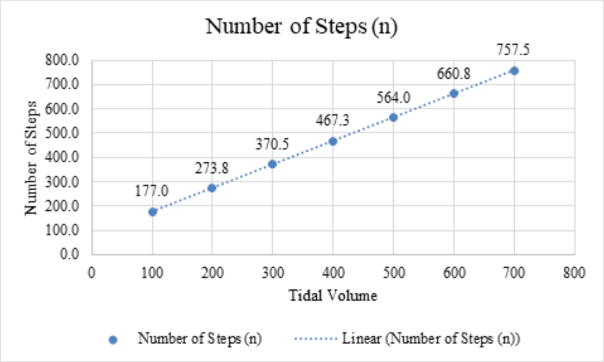

Figure 9: Number of steps to set Tidal Volume

Table 2: Delay between steps for different tidal volumes at different BPMs(Δ_{ti},Δ_{te})

	Tidal Volume (mL)						
BPM	100	200	300	400	500	600	700
10	(11.111, 22.222)	(7.143, 14.286)	(5.263, 10.526)	(4.167, 8.333)	(3.448, 6.897)	(2.941, 5.882)	(2.564, 5.128)
11	(10.101, 20.202)	(6.494, 12.987)	(4.785, 9.569)	(3.788, 7.576)	(3.135, 6.27)	(2.674, 5.348)	(2.331, 4.662)
12	(9.259, 18.519)	(5.952, 11.905)	(4.386, 8.772)	(3.472, 6.944)	(2.874, 5.747)	(2.451, 4.902)	(2.137, 4.274)
13	(8.547, 17.094)	(5.495, 10.989)	(4.049, 8.097)	(3.205, 6.41)	(2.653, 5.305)	(2.262, 4.525)	(1.972, 3.945)
14	(7.937, 15.873)	(5.102, 10.204)	(3.759, 7.519)	(2.976, 5.952)	(2.463, 4.926)	(2.101, 4.202)	(1.832, 3.663)
15	(7.407, 14.815)	(4.762, 9.524)	(3.509, 7.018)	(2.778, 5.556)	(2.299, 4.598)	(1.961, 3.922)	(1.709, 3.419)
16	(6.944, 13.889)	(4.464, 8.929)	(3.289, 6.579)	(2.604, 5.208)	(2.155, 4.31)	(1.838, 3.676)	(1.603, 3.205)
17	(6.536, 13.072)	(4.202, 8.403)	(3.096, 6.192)	(2.451, 4.902)	(2.028, 4.057)	(1.73, 3.46)	(1.508, 3.017)
18	(6.173, 12.346)	(3.968, 7.937)	(2.924, 5.848)	(2.315, 4.63)	(1.916, 3.831)	(1.634, 3.268)	(1.425, 2.849)

This is expressly shown in Table 2. The change in the delay for different BPMs are such as to satisfy the 1:2 ratio and the time for each breath. It is also similar with tidal volume, as the delay keeps decreasing.

4.3. Peak Flow Measurements

The peak flow parameter is a critical metric indicating the maximum flow rate achieved by a ventilation system under specific operational conditions. This metric serves as a comprehensive representation of the combined influence exerted by the tidal volume and respiratory rate on the actual peak flow values observed, thereby offering valuable insights into the system's overall capacity to effectively distribute airflow across a diverse range of ventilation parameters. In the context of the project under consideration, the peak flow metric represents the pinnacle of flow rate output attainable by the system in response to a specified tidal volume and breaths per minute setting. Experimental assessments were conducted to evaluate the system's peak flow velocity, with meticulous measurements being obtained under a controlled scenario featuring a consistent Inspiratory to Expiratory (I:E) ratio of 1:2. These outcomes were subsequently organized into graphical representations corresponding to various Breaths Per Minute (BPM) configurations. A detailed examination of Fig. 10 reveals the peak flow meter readings captured during the system's operation at different BPM settings, even when operating at predefined tidal volumes.
Peak Flow output of the system at low BPMS and set tidal volumes with linear relation is shown in Fig. 10.

In Table 3, the tidal volumes (in mL) ranging from 100 to 700 ml are matched with corresponding breaths per minute (bpm) settings of 12, 15, and 18, alongside their respective peak flow readings (in L/min).
With values from Table 3 relations for the three BPMs can be derived,
For a constant 12 bpm, Peak Flow = .1* Tidal Volume + 5
For a constant 15 bpm, Peak Flow = .1* Tidal Volume + 15
For a constant 18 bpm, Peak Flow = .1* Tidal Volume + 25
The table shows the increase in peak flow with increase in BPM. This demonstrates a linear and foreseeable correlation that facilitates the customization of the system for individual patients and their specific requirements.

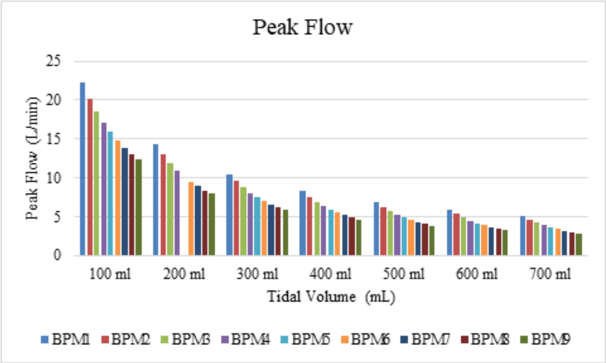

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Figure 10: Peak Flow for BPMs

Table 3: Peak flow Readings

Tidal Volume(in mL)	BPM	Peak Flow reading(in L/min)
100	12	15
	15	25
	18	35
200	12	25
	15	35
	18	45
300	12	35
	15	45
	18	55
400	12	45
	15	55
	18	65
500	12	55
	15	65
	18	75
600	12	65
	15	75
	18	85
700	12	75
	15	85
	18	95

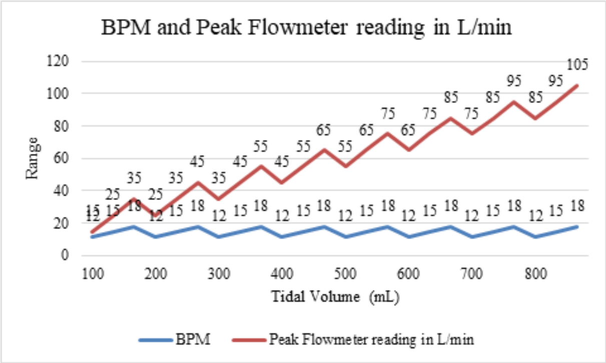

Figure 11: BPM and Peak flow difference

Fig. 11 shows the relation between increasing BPM with increasing Peak flow. It illustrates how the increase in BPM affects the peak flow of the system. Linearity of the relation is shown.

5. Conclusion

The development of the low-cost portable ventilator system represents a significant milestone in the ongoing efforts to enhance global health preparedness and response capabilities. By addressing the pressing need for affordable and scalable respiratory support solutions, this project has demonstrated the power of innovation and collaboration in overcoming healthcare challenges.The successful validation of the ventilator system for clinical applications underscores its potential to fill critical gaps in emergency respiratory care, particularly in the face of public health crises like the COVID-19 pandemic. Through a rigorous process of design, testing, and evaluation, this project has not only showcased the technical feasibility of the ventilator system but also highlighted its adaptability to diverse healthcare environments.Moving forward, the insights gained from this project can serve as a foundation for future advancements in medical technology and healthcare infrastructure. By prioritizing accessibility, affordability, and rapid deployability, the low-cost portable ventilator system offers a promising solution to bolster healthcare systems against unforeseen challenges and ensure the well-being of patients in need of respiratory support.As we continue to navigate the complexities of the global healthcare landscape, the lessons learned from this project underscore the importance of proactive preparedness, innovative solutions, and collaborative efforts in safeguarding public health. The journey towards reshaping emergency respiratory support is ongoing, and the development of this ventilator system marks a significant step towards building a more resilient and responsive healthcare infrastructure for the future.

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