A Low-Cost Portable Mechanical Ventilator—A Conceptual Design

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Abstract The current study is an attempt to review the-state-of-art for low-cost portable mechanical ventilators. Over the past few years, many engineers have developed low-cost ventilators, which offer many features of conventional hospital ventilators. Toward the direction of physically realizing an innovative mechanical ventilator, this paper discusses the idea of the design and fabrication of a reusable, low-cost portable mechanical ventilator. The conceptual design is aimed at attaining higher control on the number of operating modes and different parameters like tidal volume, breaths per minute, inspiration-to-expiration ratio, and positive end expiratory pressure. In the current scenario, these ventilators can be used in providing respiratory aid to COVID-19 patients and likewise also be used for similar casualty cases.

Keywords Mechanical ventilator · PEEP · I:E ratio · Tidal volume

1 Introduction

A ventilator, or sometimes known as respirator, is one of the most important life supporting medical equipment in a hospital. A ventilator provides breathing support to a patient by pushing in breathable air into the patient's lungs at the right time, with the right amount of oxygen, volume, and pressure [1, 2]. The different ways of ventilating a patient are by controlling the volume, pressure, flow, rate of flow, amount of oxygen, and allowing the patient to be in charge or the ventilator to oversee the breathing process. Though there are many simpler forms of the ventilator, the most sophisticated ones have many modes including assist mode (AC), pressure control mode (PC), positive end expiratory pressure (PEEP), and pressure support mode (PS) [2, 3].

In assist control (AC) mode (also known as continuous mandatory ventilation), a backup breathing rate is setup to give mandatory breaths to the patient in case he cannot trigger a breath. Usually, this is the most commonly used ventilator mode and

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the patient triggers the breaths. The patient tries to take a breath in, which causes negative pressure to be detected by the ventilator and as soon as the negative pressure is detected, it delivers a specific volume of air into the lungs. The volume is set by the medical staff usually in the range of 6–8 ml/kg of ideal body weight (IBW). The back-up rate makes sure that the patient never breaths less than the set value of breaths per minute (BPM) [3–6]. Depending on the compliance of lungs, giving in a specific volume of breath will result in pressure changes inside the lungs. This increase or decrease in pressure will be shown through a pressure read out and an alarm will be set up to notify it [1–3]. There comes the role of pressure control (PC) mode, which allows us to control the pressure and bring it back to acceptable range depending upon the compliance of the lungs and the volume of air given [4–6].

PEEP refers to a mode where a continuous pressure in the range of 5–20 cm of H20 is maintained inside the patients lungs in order to keep the alveolus open in case of invasive intubation and in order to keep the tongue forward (open airway) in case of noninvasive intubation [7]. The pressure support (PS) mode is similar to the PEEP settings but happens only on inhalation and the patient initiates the breathing process in which each breath has a specific amount of pressure [8]. All these features assure perfect breaths for the patient and thereby supports their valuable life in case of a disease affecting the lungs and thereby affecting the patients breathing capacity or during a lung injury.

Though ventilators are very important to the medical world, its acquisition is not so easy due to its high initial and maintenance costs and thereby, its numbers are very limited when compared to the amount of humans who might need it during a mass outbreak of a disease of some kind [9–13]. This has led to a lot of research and development to be done by engineers in the past few years in order to design such ventilators which can be easily manufactured by any manufacturing capacity. Most of such designs are based on Bag Valve Masks (BVM's) which are squeezed by electromechanical means in order to produce airflow at a set rate or volume. But the ability to blow air and being able to manufacture quickly and at high rates are not the only desired qualities that a fully functional ventilator must have. Such simple electromechanically operated ventilator designs bring in further problems such as Barotrauma which is the inflammation or rupture of alveolus due to the excess pressure caused by the forced in air [14–16]. Thus, these ventilators must be able to tightly control many important parameters to allow the patient to breathe well and to avoid further damages. The important functionalities include the ability to control tidal volume, pressure, breaths per minute, oxygen percentage, positive end expiratory pressure (PEEP), and the ability to have patient triggered breaths. Another important functional aspect of a ventilator is the ability to wean off the patient from the ventilator without any complications.

Though most of the existing ventilator designs maybe used as final option during an emergency, they are definitely not fit for long-term use for a patient who might need weeks of manual ventilation. This leads to the need for new innovative ideas to design and manufacture a low cost and easily manufacturable ventilator designs with features nearly equal to the most advanced ones [17–20]. Even though designing a ventilator with such high technological requirements with constraints of cost and raw materials is highly demanding, its promising to see some new designs in which many of the requirements are met and producing in large numbers require considerably low cost.

The current study is an attempt to review the state of art for low-cost portable mechanical ventilators and proposing an initial conceptual idea of our version of ventilator. Considering the current need, the current study is an attempt to develop a low-cost mechanical ventilator which would prove useful in providing respiratory aid.

2 Portable Low-Cost Ventilators

Toward the direction of developing low-cost ventilators, a portable ventilator was developed by Husseini and his co-workers which had a superior performance [13]. The overall cost of the ventilator was cut short by developing the robust system from low-cost parts. The air is pumped into the patient using the Ambu bag with the help of a pivoting CAM arm. The arm is driven by an electric motor using a 15 V DC battery. The CAM concept utilizes a crescent-shaped cam to compress the Ambu bag, which allows smooth, repeatable deformation to ensure constant air delivery. By controlling the angle of the CAM's shaft, the amount of air volume delivered was accurately controlled. This setup proved to be space efficient and has low power requirements to operate.

A cost effective and portable ventilator was developed by Ghafoor and co-authors in this context [21]. They have taken a very simple approach of compressing the Ambu bag, where an iron arm is placed on top of it to compress the bag. The movement is triggered by a motor with the help of two wooden blocks for support under the Ambu bag. The principal advantage of the prototype was the low power requirement and its lightweight. In this regard, Jürß et al. [22] developed a compact low-cost respirator which had superior advantages over the conventional ventilators. The developed design eliminated the need for respiration tubes and achieved the purpose by using a full-face mask.

Likewise, a cheap ventilator was designed and developed by Islam and co-workers [23] where the Ambu bag was operated by the action of a computer-aided manufacturing (CAM) arm which was controlled via a microcontroller. The main reason for selecting the cam arm was because the servo system provides a high torque. Also, the control signal was visualized by a platform known as the BIOPAC student's laboratory system in the developed design. The model proved to be compact and efficient. The model was shown to be successful in operating at different respiratory rates depending on the age of the patient. Another similar ventilator was developed by Hossain and co-authors [24] where the compressing of Ambu bag was achieved by two arms.

Moving forward in the recent advances, an improved ventilator was proposed by Zhang and co-authors [25] which offers essential pressure and volume control ventilator modes for critical patients. The proposed design of ventilator has volume and pressure control modes using various pressure sensors and solenoid flow valves which are controlled using microcontrollers and PID controllers. The design consists of a mixing tank which mixes air from a DC blower and oxygen from an oxygen supply and the mixture is then supplied to the patient at suitable levels and pressure which can be decided by the operator. The design also included features like adjustable tidal volumes, breath per minute, PIP, PEEP and humidity control.

Another one in the same league would be the portable ventilator suitable for army-based battlefield applications developed in 2004 by a group of scientists at John Hopkins University [26]. The two systems were named John Hopkins Applied Physics Lab's Mini Ventilation Unit (JAMU) and Far Forward Life Support System (FFLSS). The FFLSS was mainly targeted for military use while the JAMU was aimed at civilian use. The FFLSS system was microprocessor controlled, used standard army battery, had reconfigurable user interface and an LCD display. The system was able to monitor airflow and pressure to deliver optimal level of breaths. It also possessed ventilator modes such as assist control and mandatory breaths.

Similarly, an exhalation valve was developed by Douglas and co-workers [27] which incorporated the functions of both PEEP valve and exhalation valve. Sharp flow corners were reduced thereby in the airflow. The setup reduces the complexity and weight of the entire assembly. Likewise, an intelligent model for the mechanical ventilator was firstly developed in MATLAB/Simulink by Guler and Ata [28], after which a fuzzy-LABVIEW based mechanical ventilator prototype was practically designed by the authors. The fuzzy logic controller was used independently for both the simulation and experimental setup and were successfully applied to many systems. Other notable ventilator is the one developed by Williams and co-authors (2010). The authors demonstrated a cheap gas-efficient ventilator which could be fabricated from industrial components [29]. The ventilator had the advantage of delivering stable nitric oxide concentration by following volumetric principles. Catherine and co-workers [30] performed studies on ventilators with focus on the trigger of inspiration. The authors discussed on the influence of ventilator factors on patient effort or work of breathing, different triggering phases, post-triggering phases, ventilator factors as determinants of patient-ventilator interaction, and different ventilator modes for improving patient–ventilator interaction. Another similar ventilator in the same lines was also developed by Güler and Ata [31] for training purpose for clinicians and students which had superior control over setting the inspiration and expiration time.

In the context of studies related to using a single ventilator for multiple patients, a ventilator was developed by Siderits and team [32], wherein a 3D-printed manifold can be fitted to a ventilator in order to connect it to four masks at the same time. The 3D printing of this small manifold was performed by using fused filament deposition. Likewise, four lung simulators were added in parallel to a single ventilator using available tubings until the ventilator supplied enough air for the four lung simulators [33]. The setup was successful in running for 12 h in two separate modes: pressure control and volume control. A very recent ventilator developed by PulmCrit discusses the possibility of splitting a single ventilator to treat multiple patients without letting each other's ventilation requirements affect each other [34].

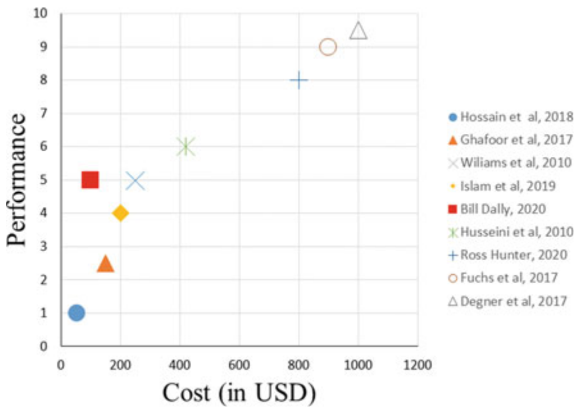


Fig. 1 Comparison of the performance and cost of prominent low-cost portable ventilators developed over the past decade

The most recently reported low-cost ventilator was the one developed by Scottish design engineer Ross Hunter in the wake of Covid-19 [35]. The ventilator was applauded globally for being effective in three modes of ventilation as well as being cheap. He has come up with a bellow design as it is an effective means to control air volume and pressure very accurately. This team has achieved PEEP by extending the bellows system so that it can contain even up to 8 L of air. This allowed for a continuous stroke during the expiration phase that maintains a set PEEP. The system could also accurately monitor the volume and pressure due to its positional control and pressure sensors. The group of doctors from Smiths Medical was also successful in developing ventilator of varying features [36].

Figure 1 shows the comparison of performance and cost of different low-cost portable ventilators reported in the last decade, based on the literature review. The performance index has been defined based on the features of each of the ventilators. These features include the number of operating modes, the control over different parameters (volume and breath rate per minute), the design factors (its compactness, strength and stability) as well as the maximum working hours. It is evident from the plot that even though many scientists have tried to incorporate the best features at a cheaper cost, it has remained a challenge till date.

3 Conceptual Design of the Proposed Low-Cost Ventilator

The proposed design is a low-cost, portable, electromechanically operated ventilator which can be used for both invasive and non-invasive type of ventilation. It is designed in such a way that it can be easily carried in an emergency. The air delivery system comprises of an Ambu bag which is pressed by an optimally designed convex pressing surface attached to a rack and pinion mechanism which converts rotary motion of the motor into linear motion required to press the Ambu bag. This design would enable superior control over breathing parameters such as Tidal volume, breaths per minute, I:E ratio, PEEP and has real-time data monitoring system and an alarm to warn pressure and volume discrepancies. The design also consists of a Hydroscopic condenser humidifier and filter (HCHF) to ensure proper humidification and filtering of the delivered air. An overview flowchart of the conceptual design is shown in Fig. 2 and the proposed pressing mechanism of the Ambu bag is shown in Fig. 3.

A Nema-17 bipolar stepper motor with a stall torque of 60 N-cm is selected for the design so that control over minute values of stroke length can be easily achieved. Figure 6 shows the arrangement of components for achieving the Ambu bag compressing using the rack and pinion arrangement. The stepper motor is controlled by a dual H bridge motor driver which is capable of supplying the motor's stall current and an Arduino MEGA microcontroller which is programmed to give control to the user over parameters such as Tidal volume, breaths per minute and I:E ratio. The control over all these parameters is gained by varying the stroke length, speed of each stroke, and the number of strokes of the rack and pinion mechanism. The relationship data between these and the delivered air volume and flow rate will be experimentally

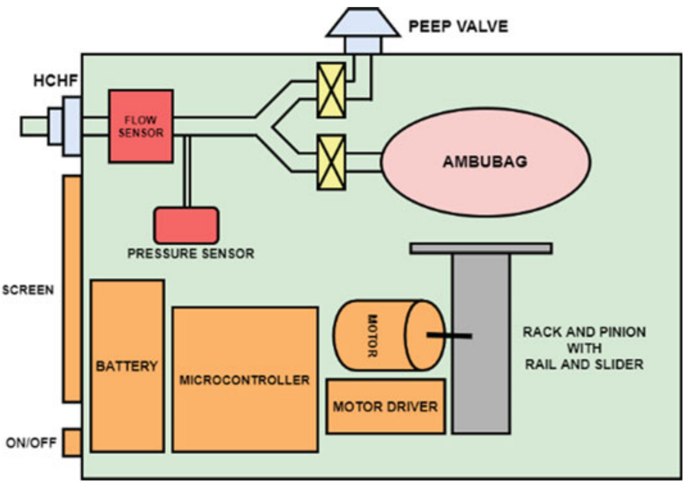
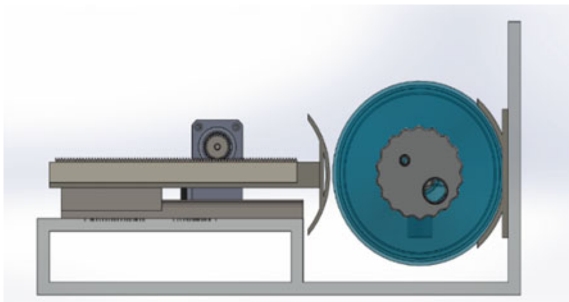


Fig. 2 Flowchart of the conceptual design

Fig. 3 Proposed compressing mechanism design where a convex arm presses the Ambu bag as shown



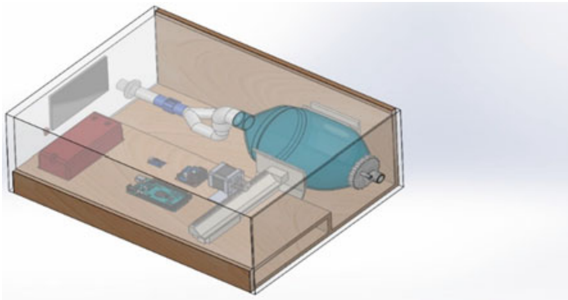


Fig. 4 Conceptual design of the ventilator

determined using computational fluid dynamics (CFD) simulation and the data is fed into the Arduino program. A solidworks model of the proposed design is shown in Fig. 4.

A WYE connecter is used to divert inspiratory and expiratory flow through two different tubes where one end is connected to the Ambu bag and the other end is connected to a PEEP valve which allows PEEP value to be toggled according to different patient requirements. The single end of the WYE connecter is connected to a pressure sensor and a flow sensor which allows real time monitoring of the patient's breathing parameters through an LCD display. A Sensirion SFM3300-AW mass flow sensor with 250 SLPM bidirectional capacity and an Adafruit MPRLS ported pressure sensor with 0–25 psi sensing range was chosen for the design. The system can be powered by a battery pack or directly from a wall outlet, depending on the situation. A 12-V, Dakota LiFePO4 battery pack with a capacity of 10,000 mA-h was chosen to power the design and it would be enough to power the ventilator for approximately 3 h without any external power. The complete circuit schematic of the proposed ventilator design is shown in Fig. 5.

Figure 6 shows the step by step breakdown of the proposed ventilator design's working. It shows various input points, decision points, and input to output calculation points during the working of the ventilator along with the pressure/volume alarm trigger and patient initiated breath trigger mechanism.

The design incorporates a real-time patient data monitoring system which allows to monitor critical breathing parameters through flow-time graph, volume-time graph, and pressure–time graph of the patients breaths and an alarm to warn pressure and volume discrepancies which is unavailable in almost all of the low-cost ventilator designs. The design also consists of a hydroscopic condenser humidifier and filter (HCHF) to ensure proper humidification of the air before delivering it to the patient and filtering the exhaled air before releasing it into the atmosphere to avoid contamination. The optimally designed 3D-printed convex pressing surface allows maximum air to be squeezed out of the Ambubag (as depicted in Fig. 3) with minimum work done to deliver any amount of tidal volume. The 7-inch LCD display consists of a user-friendly interface which allows real time monitoring and swift way to make necessary changes to the input parameters without interfering with the working of the ventilator.

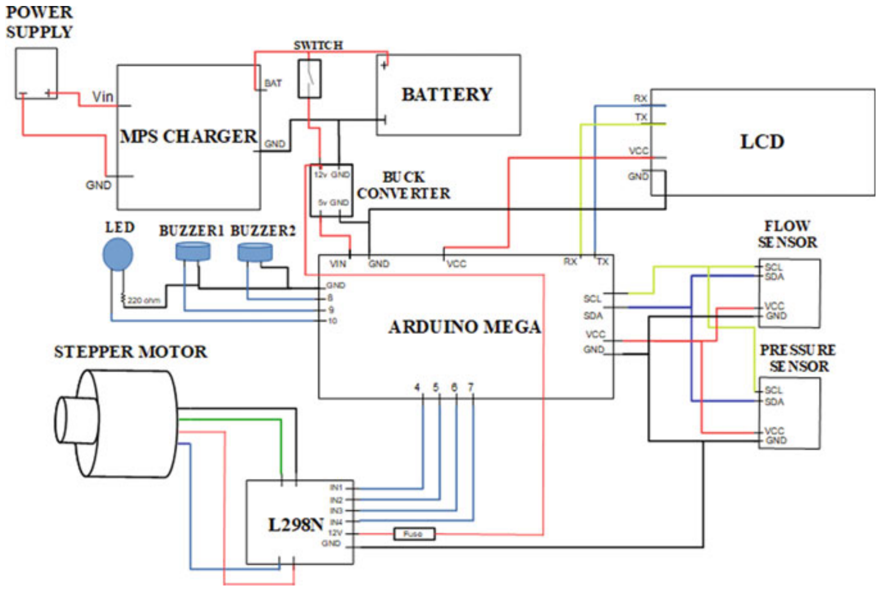


Fig. 5 Circuit schematic of the proposed ventilator

4 Conclusions

The emergence of novel Coronavirus infection in Wuhan, since December 2019 and its rapid spread has led to a global threat. This scenario has led to the inevitable need for the detection, diagnosis, prevention, and protection among the world population. In the wake of such a pandemic, the need for low cost and easily manufactural ventilators abruptly rise to uncontrollable levels. This situation can be overcome by increasing the production capabilities of ventilator manufacturers by increasing the number of ventilators through an easy and fast adaptable way.

Over the past few years, many engineers have developed low-cost ventilators offering many features of conventional hospital ventilators. This utilizes various sources of air such as the conventional bag valve masks, air compressors, etc., coupled with various range of mechanisms to achieve the necessary ventilator features. Our proposed low cost, portable, electromechanical ventilator incorporates some of the major and most critical features of a ventilator such as control over tidal volume, breaths per minute, I:E ratio, PEEP, and patient data monitoring system into a design suitable for emergency situations.

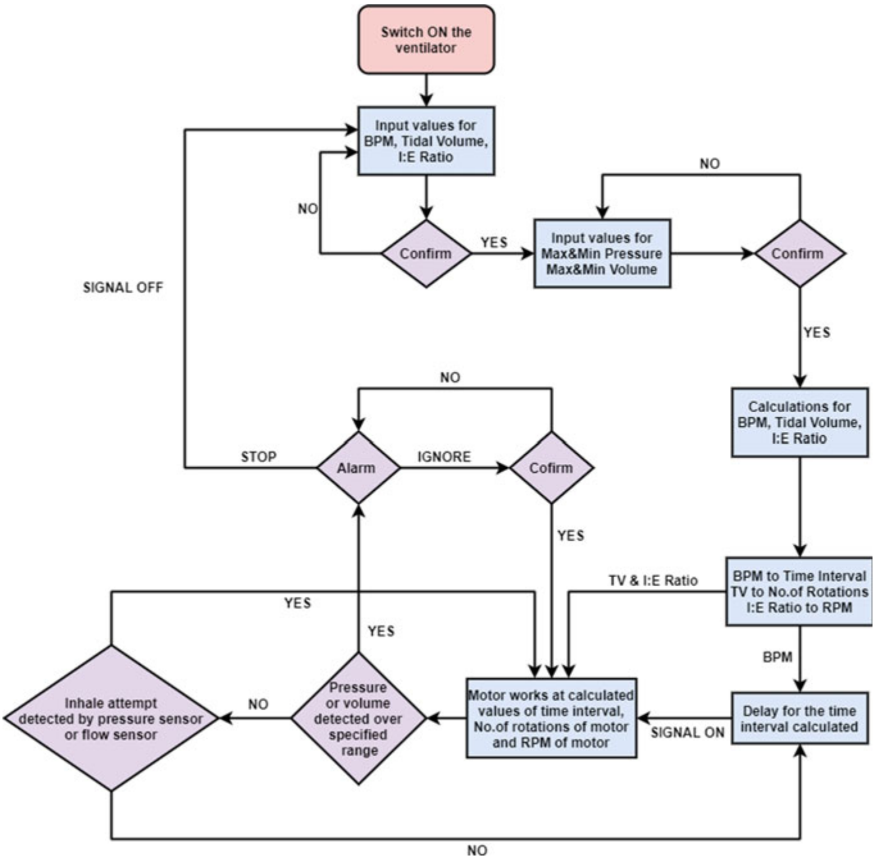


Fig. 6 Process flowchart of the ventilator

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