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REVIEW PAPER

Recent advances in low-cost, portable automated resuscitator systems to fight COVID-19

Vishal Kumar[1] · Ravinder Kumar[1] · Mohit Kumar[1] · Gurpreet Singh Wander[2] · Vivek Gupta[2] · Ashish Sahani[1]

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Abstract
World is fighting one of its greatest battle against COVID-19 (a highly infectious disease), leading to death of hundreds of thousands of people around the world, with severe patients requiring artificial breathing. To overcome the shortage of ventilators in medical infrastructure, various low-cost, easy to assemble, portable ventilators have been proposed to fight the ongoing pandemic. These mechanical ventilators are made from components that are generally readily available worldwide. Such components are already associated with day-to-day gadgets or items and which do not require specialized manufacturing processes. Various designs have been proposed, focussing on meeting basic requirements for artificial ventilation to fight the ongoing pandemic. But some people are against the usage of these mechanical ventilators in real-life situations, owing to poor reliability and inability of these designs to meet certain clinical requirements. Each design has its own merits and demerits, which need to be addressed for proper designing. Therefore, this article aims to provide readers an overview of various design parameters that needs to be considered while designing portable ventilators, by systematic analysis from available pool of proposed designs. By going through existing literature, we have recognized multiple factors influencing device performance and how these factors need to be considered for efficient device operation.

Keywords Low-cost ventilators · Automated resuscitator systems · COVID-19 treatment · Ventilator design criteria · Design optimization · I/E (Inspiration and Expiration)

1 Introduction

Coronavirus disease-2019 (COVID-19) is a highly infectious disease caused by novel coronavirus, causing severe respiratory illness which has infected over 103 million people and is responsible for more than 3.071 million deaths Globally (as on April 23, 2021) [1]. This disease majorly affects respiratory tract, which can progress to more severe or potentially deadly conditions such as acute respiratory distress syndrome (ARDS) or hypoxemia, owing to widespread inflammation of the lungs [2–4]. From early years, mechanical ventilators play a crucial role in fighting not only COVID-19 but various other diseases such as polio [5] and influenza [6] leading to severe respiratory failure, as it assists patients breathing while underlying disease runs its course [7, 8]. This has led to an increased surge in the demand of mechanical ventilators, with 3–26% of patients infected with COVID-19 (percentage varies across age groups and severity of symptoms) requiring mechanical invasive and prolonged ventilation [9–11]. However, the disruption in supply chains, transport restrictions and various other factors collectively in the ongoing pandemic has put pressure on supply of ventilators, aimed to reduce the mortality rates [12].

Cheaper alternatives for mechanical ventilation, especially automated artificial manual-breathing units (AMBU) bags, have received wide attention from clinicians, researchers and policy makers, owing to fast production, economical deployment and easy accessibility to a larger portion of the population all across the world. Automated AMBU bags or resuscitator devices aim to assist patient breathing via compressing and releasing the AMBU bags at specific frequency, while delivering oxygen to meet the breathing

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✉ Ravinder Kumar
2018bmz0007@iitrpr.ac.in

[1] Department of Biomedical Engineering, Indian Institute of Technology, Ropar, India

[2] Hero Dayanand Medical College (DMC) Heart Institute, Ludhiana, India

rate, pressure, tidal volume and other needs of individual patients [7]. Apart from this, these systems provide edge over their manual counterparts, allowing staff to perform other critical tasks relevant to patient healthcare, rather than manually bagging patients. Additionally, owing to simple design, low-cost, portability, battery or mains-in powered, simple control systems with few knobs to control variables, these kinds of systems can be easily used during transportation of patients without even requiring specialized training to operate these devices (depending upon situation to situation). Keeping these advantages in mind, various low-cost automated resuscitator designs have been proposed by various research groups across globe to fight with ongoing pandemic.

However, there is an urgent need to objectively evaluate the recent surge in low-cost resuscitator systems designed all over the world to fight the ongoing COVID-19 pandemic.

Various factors need to be considered for selecting the best design among various reported designs. These include actuator mechanism (optimum torque, minimal wear and tear, noise reduction etc.), sensors and life-support alarms installed, medical efficacy (Positive-end expiratory pressure (PEEP), tidal volume, peak pressure, breaths per minute (BPM), inhalation/exhalation ratio (I/E), fraction of inspired oxygen (FiO_2)), economic viability, user-interface (display, control systems, connection ports etc.), repeatability or robustness of system and clinical trials. To allow users and researchers to better design these portable mechanical ventilators, we have presented a systematic review depicting the advantages and limitations of various proposed resuscitator systems, based on the factors illustrated in Fig. 1. For our analysis these factors are considered on the basis of the guidelines provided by the World Health Organization (WHO) and Medical & Health products regulatory agency (MHRA) [13, 14]. The basic description for each of the factors (based on the guidelines by WHO and MHRA) considered while comparing the performance of various mechanical resuscitators is described as below:

- **Actuation Mechanism:** Component used for delivering the optimum amount of oxygen within prescribed

Fig. 1 Basic functional requirements of low-cost, portable mechanical ventilators

pressure and volume limits by pressing AMBU bag or some other resuscitator system is termed as actuator. The actuation assembly should operate with minimum wear and tear along with minimum noise production to ensure efficient device operation.

- **Sensors and Alarms:** To ensure delivery of oxygen at prescribed pressure and volume limits, mechanical resuscitator system is fitted with various sensors providing feedback to actuator assembly to meet the required demands. Also, proper alarm systems should be installed to alert authorities in case of system failure or improper functioning of device.
- **Medical Efficacy:** This factor determines the system efficiency to met required air supply demands within prescribed limits. The air supply must meet various specifications such as Positive-end expiratory pressure (PEEP), tidal volume, peak pressure, breaths per minute (BPM), inhalation/exhalation ratio (I/E), fraction of inspired oxygen (FiO2) at prescribed limits to ensure proper treatment.
- **Cost:** The cost of the designed resuscitator system should be within the reachable budgets (depends on location, economic policies and availability of parts in given region) to ensure easy accessibility even in remote regions of the world.
- **User-interface:** To ensure easy and fast operation of the system, system should be with user-friendly interface so that medical staff can operate the system even without proper training about the functioning of the resuscitator system.
- **Repeatability/Robustness:** The system should operate continuously at prescribed parameters to ensure robust operation even under hospital's high load conditions. Also, the system should not drift from the prescribed limits with time so that clinical staff can operate the device even without regular inspections.
- **Clinical Trials:** Even if the system meets all the prescribed limits, clinical trials are mandatory to ensure proper functioning of the resuscitator system over patients of different age, sex, medical conditions etc. To ensure proper functioning the resuscitator system must get proper FDA approval enabling device to be used on patients in real-life conditions.

This will not only help the readers to design systems according to need, but also provide insights to design next-generation automated resuscitators to deal with current and future pandemic situations.

2 Search methodology

2.1 Search strategy

The systematic search was performed using three search engines Web of Science (Clarivate), Google scholar and IEEE Xplore. The focus of the search strategy was to retrieve articles related to low-cost portable automated resuscitator systems to fight Covid-19. The year of publication did not limit the search strategy. We have not included publications that were published in 2021. Relevant articles were obtained using selected keywords that were used alone or in combination to retrieve relevant articles, such as "Low-cost ventilators" and "automated resuscitator". Search terms considered appropriate for this systematic review were "Covid-19 treatment" or "Ventilator design criteria" or "Design optimization" or "I/E inspiration and expiration ratios" and "Low-cost ventilators" or "automated resuscitator".

3 Study selection

Papers resulting from systematic search were evaluated based on set criteria for inclusion or exclusion of retrieved articles listed in Table 1. Titles of the article were considered first, if found relevant, then abstract was screened. The study was selected from all similar keywords used to retrieve relevant articles.

We had started the search by using the following keywords with or without the combination "Covid-19 treatment" or "Ventilator design criteria" or "Design optimization" or "I/E inspiration and expiration ratios" and "Low-cost ventilators" or "automated resuscitator".

For example, "low-cost ventilators" at Web of Science(clarivate) retrieved 400 articles, out of which 10 articles were found relevant based on title and abstract

Table 1 Inclusion and exclusion criteria for study selection

Inclusion criteria	Exclusion criteria
Studies of mechanical ventilators involving various actuator mechanisms	Studies without mechanical ventilators are excluded
Studies involving various modes of ventilation operation	Studies that don't provide information about ventilation modes such as pressure or volume mode are not included
Studies of low-cost portable ventilators involving various sensors used	Studies about various high-cost ventilators that require specialized instrumentation are not included
Studies involving ventilator design criteria and their optimization	All studies related to human testing which don't provide technical description of ventilators are not included

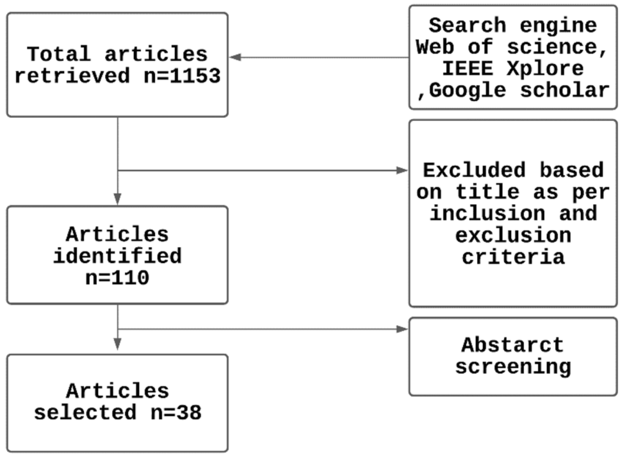


Fig. 2 Flow diagram of systematic literature search

similarly searched with other keywords like "Ventilator design criteria" at Web of science retrieved 510 articles out of which 8 articles were selected from them based on their titles and abstract. We had also searched with the title of the paper at google scholar and we retrieved 303 articles out of which 15 articles were suitable for the study.

Duplicate articles retrieved from google scholar, IEEE Xplore were excluded. Articles from books, conference articles, review articles, guidelines from government agencies, institutes and WHO were also considered. The review of the full text was performed for selected articles. The flow diagram of the systematic literature search is shown in Fig. 2. This paper does not require IRB approval or Ethical clearance.

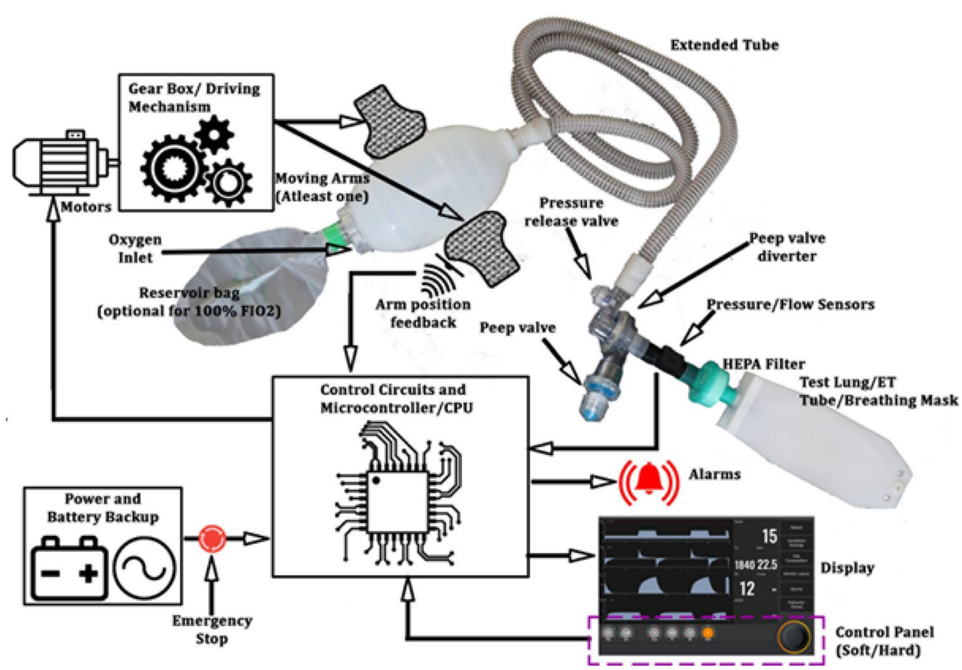
4 Concept and design

The equipment used in medical healthcare requires proper consideration and has to undergo thorough clinical trials, so that it can be used in real-life situations. All the parts used in such devices need to be medically authenticated and should operate continuously with minimal wear and tear during high load conditions for long durations. Even though many designs have been proposed to automate the resuscitator systems, the basic strategy remains almost the same, as depicted in Fig. 3. Figure 3 is the layout of all the necessary components which are being used in automated resuscitators. The main components used in automated resuscitators are described below, which are often arranged compactly for easy handling and transportation.

4.1 Actuation mechanism

Compressing and releasing the AMBU bag or other air pumping mechanism in a controlled way is the main objective of these low-cost easy to assemble mechanical systems. In most of the designs, the airbag, which is fixed so as to avoid slippage or other losses in energy transfer, is pushed mechanically via pressing a mechanical arm (one or two) which are powered by mechanical motors (stepper, servo, linear actuators etc.) [15]. The motion of these arms is controlled by giving a particular number of steps by motors, so as to meet the tidal volume, pressure, BPM and various other parameters. Moreover, some feedback system may also be integrated into the system to monitor

Fig. 3 Schematic depicting various components and operation of automated resuscitator ventilators



that the arms can compress the resuscitator bag to a specific limit before motors can withdraw back arms. Also, usage of one or two arms can lead to certain advantages or disadvantages which are discussed later.

4.2 Sensors

Sensors are one of the significant components of the automated resuscitator, which are being used to take feedback and timely send it to the control unit. All sensors choice of selection is generally based on the three parameters specificity, accuracy and stability. These majorly include a pressure sensor and a flow sensor. The system can be driven to meet various criteria such as tidal volume, pressure, BPM etc., for an efficient replacement of the ventilator. By taking the data from these sensors, researchers have been able to make feedback systems to meet minimum pressure and tidal volume needs without feedback from patients or clinicians. Other sensors, such as temperature sensor to monitor temperature build-up in the system, ultrasound sensor to ensure airbags are getting compressed and also protect any interference among the arms, and others, can also be installed so as to provide more control and feedback loops for efficient working of the device.

4.3 Valves

Various valves are used for an efficient and continuous supply of airflow from airbags to patient. These valves help set minimum or maximum pressure or tidal volume limits to improve oxygenation of blood or avoid damage to the lungs of patient. For instance, a positive end-expiratory pressure (PEEP) valve maintains a minimum amount of pressure inside the patient lung above atmospheric pressure to avoid lung collapse. Likewise, the peak inspiratory pressure (PIP) valve set the upper limit for pressure build-up inside the lungs, after which pressure will start to drop to avoid any lung damage. Besides, to change the ratio of oxygen in pumped-air, O_2 reservoir can be connected to airbag through bag refill valve. Finally, the pumped air is delivered to patient via proper patient connector port through patient valve. This patient valve acts as air inhalation point and serves as exhalation point from which CO_2 can then be removed using an expiratory valve (fish mouth type) for efficient ventilation. Additionally, some filters can also be incorporated in airflow path to increase air quality.

4.4 Controller and display

The main objective of automated mechanical resuscitators is to assist patient breathing by compressing and releasing airbag in a controlled way. To achieve this, the motors (run by their respective driver modules) are generally controlled via readily available, easy to program Arduino controllers. By taking feedback from various sensors, these Arduino boards can be programmed to run motors at a specific speed to meet required tidal volume, pressure, BPM, inhalation/exhalation ratio etc. Also, the data retrieved from various sensors are fed off to a graphical user interface (GUI) digital display, showing the pressure build-up, the volume of air delivered, BPM and others, enabling clinicians to monitor patient health. Moreover, a simple controller in the form of a dial or touch screen is provided to facilitate easy control of the parameters mentioned above, according to patient need or undertaken therapy [16].

4.5 Life support alarms

The ventilator systems used in assisting patient breathing are made in a way so that they can operate without any wear and tear or any other malfunctions for a longer duration of operations. As in medical emergency, reliability is more often preferred than costly equipment, as a minor fault can lead to a life-threatening event. But even if, in some case, the automated mechanical resuscitators fail to meet patient needs, these systems are installed with emergency life-support alarms. Suppose if there is pressure build-up above PIP or below PEEP or the system cannot meet the minimum tidal volume requirement. In that case, a high-sounding automated alarm will pop off, alerting the clinical staff to make necessary arrangements to avert undesired event. Even an emergency stop system is installed in some designs so as to manually stop pumping action, in case the system is pumping air out of control, which can damage the patient lungs or lead to other complications.

5 Existing reported designs

Various research groups have presented different designs for low-cost, easy to use automated mechanical ventilators as viable replacement for ventilators to fight with the ongoing pandemic. Each of these design uses the same basic approach as discussed in the above section. But these differ based on actuator mechanism, modes of ventilation operation, sensors used etc., providing each design with their own merits and demerits, which has been briefly described below.

5.1 MADVent

Developed by a team of researchers from the University of California, San Diego, this design aim to provide a low-cost alternative to expensive ventilators to fight COVID-19 [17]. This system operates in single-pressure mode and is installed with various life-support alarms to detect system failure or unintended pressure build-up. It is powered by a stepper motor whose motion can be controlled via a simple controller, with a single-arm pressing against the resuscitator bag. A backup battery is also provided to ensure continuous operation in case of power failure. The estimated cost of this prototype is estimated to be around 250$. The system cannot operate in volume-controlled mode, and the resuscitator bag can dislocate (as it is pressed from one side and no support is provided at ends) during operation for long hours. Also, the PEEP valve is located near the resuscitator bag rather than mouth, leading to accumulation of CO2 in the air pipe (exhaled by patient), leading to back-flow or adrift from the prescribed oxygen supply. The other most important aspect is that the device was tested for 24 h in normal and extreme operations, so stability might be an issue.

5.2 Artificial breathing capability device (ABCD)

Developed by a team of scientists from PGIMER, Chandigarh, ABCD is an automated AMBU bag system (powered by stepper motor) with controlled PIP, ventilation rate, I/E ratio to assist patient breathing [18]. It has been installed with various intelligent features, such as self-regulatory checks, auto cut-off during coughing and different life-support alarms to alert authorities of blockage or system failure. Moreover, it has been tested with adult and paediatric size resuscitator bags. It has undergone continuous rigorous testing for more than 60 days under different settings. The cost of this compact, robust design is estimated to be around 800$ (which can be reduced to 400$ for mass production), offering ventilation for a wide range of population age, ranging from adults to children. Though this design provides better control over I/E ratio, it does not give any control to enable system operation in volume-controlled mode. Also, the system design is expensive as compared to other mechanical ventilators offering almost similar performance criteria. The additional advantage of this device is that it is clinically validated and approved.

5.3 SVASTA, PRANA and VaU

A group of engineers developed these three different ventilators at Vikram Sarabhai Space Centre, India [19]. SVASTA (Space Ventilator Aided System for Trauma Assistance) operates on compressed air without any electricity. It can work in different modes via varying mechanical settings alone. PRANA (Programmable Respiratory Assistance for the Needy Aid) is an automated AMBU bag compressing system, which can operate in both pressure and volume-controlled modes, with precise control over I/E ratio, tidal volume, PIP, among others. VaU (Ventilation assist Unit) is a pneumatic state-of-art ventilator, equivalent to commercially available ventilators that can operate in dual mode: use air/oxygen from the hospital or uses air from ambient. SVASTA is very easy to operate and has minimum electricity dependence (making it viable to use in power failure scenario) but suffers from poor control over ventilation parameters. PRANA can be easily assembled and requires only easily available, low-cost parts but require manual check-ups and replacement of AMBU resuscitator on a timely basis. VaU is the most efficient system with utmost control over ventilation parameters, but many sensors and feedback systems make it costly. The device is not yet clinically approved and validated.

5.4 Automated Bag-valve mask (BVM)

Developed as early as 2010 by researchers at Massachusetts Institute of Technology, USA, this design marks the first attempt to automate AMBU resuscitators to be deployed as ventilators in case of the pandemic [20]. Even though it was designed almost a decade before the emergence of the COVID-19 pandemic, researchers had carefully engineered ventilation parameters to meet tidal volume, PEEP, BPM of patients while minimizing its cost (~ $420 for prototype) and less than $200 for bulk manufacturing. In this design, the actuator mechanism is powered using pivoting cam arm, which can be easily powered using a 14.8 VDC battery. Moreover, all the accessories used were arranged in a very compact manner, taking its weight to mere 4.1 kgs making it easy to handle and transport without much effort. Though it was the first reported study demonstrating automation of AMBU resuscitators, they have not conducted any test results either on test lung or human trials to prove the efficacy of the proposed device.

5.5 Non-invasive bilevel pressure ventilator

Developed by a group of scientists from Spain, they presented a non-invasive, low-cost, easy-to-build portable ventilator using a high-pressure blower to push air to assist patient breathing [21]. Along with providing control over basic ventilation parameters such as I/E ratio, breathing rate, they also tested their prototype on 12 patients against a commercially available ventilator (Lumis-150, Resmed). They observed better patient therapy using the proposed prototype. The low cost of this device makes it feasible to be easily assembled and used in low/middle-income countries. But this design does not provide any control to operate their device in pressure or volume-controlled modes. Moreover, it uses a high-pressure blower to push air, resulting in air heating after continuous use.

5.6 Low-cost mechanical ventilator

Another team of scientists from Spain and Brazil also developed a low-cost portable ventilator, using rack and pinion arrangement to compress AMBU resuscitators, assisting patients' breathing [22]. They provided precise control over the I/E ratio, oxygen delivery percentage and volume delivered per breath. Along with this, they offered a complete description of electronics used in the device to replicate system designs for easy deployment. But this design is also unable to operate in volume-controlled mode. Also, the PEEP valve is connected far away from patient exhalation, leading to the accumulation of CO2 in air delivery pipe, leading to an inaccurate O_2 delivery ratio.

We have prepared a Pugh concept selection chart [23] to compare various reported low-cost portable ventilators. The parameters used for rating the performance of various recently designed mechanical resuscitator systems are in accordance with the guidelines issued by WHO for invasive and non-invasive ventilators for adult and paediatric use [13, 14, 26]. The ranking is thus done by carefully analysing the operational capabilities of different resuscitator designs as provided in the literature. Thus, we have rated the performance of these designs in multiple sections of device performance to the best of our knowledge, as shown in Table 2. The quality index parameter ranging from (1–5) is assigned for each section of device performance. The general description supporting the indexing can be described as: 1: Poor, 2: Fair, 3: Moderate, 4: Good and 5: Excellent.

Calculating the total points, design B-(ABCD) and G (*Non-invasive bilevel pressure ventilator*) got 29 points which is the highest among all the listed ventilator devices and emerged as a clear winner (a significant contributing factor of clinical trials). Suppose we exclude clinical trials (as almost all designs are undergoing clinical trials). In that case, nearly all designs score nearly 24 points on our performance criteria, showing that most of the groups are catching up to meet the basic requirement to assist patient breathing, helping clinicians fight with ongoing pandemics.

In addition to the above-mentioned designs, some other portable ventilators based on various approaches have been proposed. Like, a team of scientists from DRDO, India proposed a low-cost ventilator, DEVEN, that releases compressed air in a controlled fashion [27] and a team from UK used a compressed gas source [28] to assist patient breathing suffering from ARDS. Other innovative designs, such as pushing an air tube in a controlled fashion [29] or directly supplying oxygen from hospitals at controlled pressures, have also been reported [30], which can play crucial role in fighting the ongoing pandemic. A unique approach has also been reported in contrast to the automatic compressing and releasing of resuscitator bags. Using a bubble helmet covering the patient head connected via special collar to deliver air showed significant reduction in mortality rate compared to face masks [31]. Also, bench-testing from the conventional mechanical ventilator designs from various manufacturers has also been done, providing better useful insight to design next-generation ventilators [32].

Even though the progress in developing automated resuscitator systems is impressive, most of these proposed designs have not undergone rigorous clinical trials to get FDA approvals for safe operation in clinical trials. Certified ventilator systems have certain advantages like controlling the air flow for much longer inhalation times as per patient requirement, monitoring temperature and humidity of inhaled air and many others [25]. Also, some of the designs does not use FDA approved accessories to develop these systems to lower the cost of the system, which may affect the medical efficacy of proposed designs in long term [24]. Therefore, proper care must be taken to meet the guidelines provided by various organizations (WHO, FDA etc.) to ensure proper implementation of treatment using mechanical resuscitator systems. Thus, we have seen various designs have been reported with their own merits and

Table 2 Comparison of performance efficacy of various published low-cost portable ventilator designs using Pugh concept selection chart

Performance Criteria	Design							
	A	*B*	*C*	*D*	*E*	*F*	*G*	*H*
Actuation mechanism	3	4	3	4	4	4	4	4
Sensors and Alarms	4	4	2	4	5	3	4	4
Medical Efficacy	3	4	3	3	4	2	5	4
Cost	5	3	5	4	2	4	3	4
User-interface	4	5	3	3	4	3	4	4
Repeatability /Robustness	4	5	3	3	4	2	5	3
Clinical trials	1	4	1	1	1	1	4	1
Total Points	**24**	**29**	**20**	**22**	**24**	**19**	**29**	**24**

[a] A-MADVent, B-ABCD, C-SVASTA, D-PRANA, E-VaU, F-automated BVM, G-Non-invasive bilateral pressure, H-low-cost mechanical ventilator, ventilator performance is given quality index ranging from 1–5 depending on device efficacy in various sectors of device performance

Table 3 Comparison of performance of various low-cost open- source portable ventilator designs

Name	Mechanism	Features	Drawbacks	Cost, Processibility	Ref
MIT emergency ventilator	Compressing AMBU resuscitators using gears and motors	Controllable I/E, BPM, tidal volume, FiO_2, pressure, PEEP valve along with life support alarms	PEEP valve is situated far away from air exhaust from patient which can lead to accumulation of CO_2 in air pipe	Moderate cost, requiring certain advanced manufacturing tools	[35]
ApolloBVM	Compressing AMBU bags using rack and pinion arrangement	Controllable BPM, tidal volume, pressure, PEEP valve along with providing emergency stop button	Operation in volume mode is not possible along with system accessories including actuation mechanism is very exposed (can lead to device deterioration with time)	Less than $300 with ease of material availability and easy processibility	[36]
OpenVent-Bristol	AMBU bag compression with one arm powered by geared DC motor	Controllable BPM, tidal volume, pressure, PEEP valve, with capability to operate in both pressure and volume-controlled modes	CO_2 exhaust is situated far away from patient leading to accumulation of CO_2 in air pipe	Less than $499.47 with very compact design and easy AMBU bag replacement	[37]
VITAL	Air compressor to push air assisting patient breathing	Controllable tidal volume, BPM, FiO_2, PEEP along with tested for continuous 20 days operation	Air compressor can lead to heating under high load situations	Relatively costly with requiring specialized parts	[38]
OP-Vent	Directly uses compressed air which is released by taking feedback from solenoid valve, flow meter and pressure sensor	Precise control over tidal volume, BPM, PEEP pressure, with capability to operate in both volume and pressure-controlled modes	Compressed air has to be provided externally which can be difficult to arrange sometimes	Less than $400 with easy availability of parts	[39]
RepRapable automated BVM	Compression of AMBU bag with one arm using stepper motor	Made mostly from 3D printed parts with precise control over tidal volume, I/E, BPM	Most parts are 3D printed reducing device robustness and durability over time	Less than $180 and made using easily available 3D printing	[40]
AIRone	Uses compressed gas source which is then regulated using set of proportional valves	Controllable I/E, BPM, tidal volume, FiO_2, PEEP with electronic display showing flow and pressure readings	Uses compressed gas which needs to be readily available along with lack of rigorous testing	Comparatively high cost requiring specialized parts	[41]
Ambo Vent	Compresses AMBU bag with one arm from above using motors	Operate in volume-controlled mode with precise control over I/E, tidal volume, BPM and PEEP valve	AMBU bag is not fixed and is compressed from one direction which may lead to displacement under continuous rigorous operation	Easy to assemble with cost lying around $500–800	[42]
AARMED	Compress AMBU Resuscitator using belt-drive systems powered by stepper motors	Operation in both volume and pressure-controlled modes, with precise control over PEEP, tidal volume, I/E, BPM	Flow sensor used may not be commonly available in some parts of world	Easy to assemble using common manufacturing processes	[43]
Coventor	AMBU bag resuscitator is compressed using solid arm from one side (vertically)	Provides control over I/E, BPM, tidal volume and other basic parameters. Along with robust operation, this device received FDA approval	Unable to be operate in volume-controlled mode. Also, AMBU bag need continuous monitoring or changes owing to damage from compression from one side	Uses easy and standard manufacturing processes bringing the cost of device to as lower as $150	[44]

demerits to treat COVID-19 patients. Many more designs are being developed, but have not been published, as they are still in testing phase or under peer-review process. But these designs are available as open-source designs which have been elaborated in next section.

6 Open-Source designs

In response to fight with an ongoing pandemic, various research groups and tech companies have provided various open source, low-cost, easy to assemble, automated resuscitator systems, so that people don't have to worry about taking various permissions or pay for patented technology, for treatment of patients requiring ventilation. Also, with time, since the onset of pandemic, the design schematic has been becoming more and more standardized, taking focus just from delivering air to patients to provide precise control over various ventilation parameters, as per WHO regulations [13]. Some of the designs has been elaborated in Table 3, as shown below. The Pugh concept chart has not been used to compare the performance of these open-source designs, as data supporting these resuscitator designs has not gone through any peer review process (so it may be subjected to some dispute). Other designs are constantly being developed and uploaded as open-source designs. But all these designs use more or less the same schematic as discussed in above sections.

Table 3 provides a brief outline of various open-source designs that are still undergoing multiple developments to get FDA clearance (except Coventor, FDA approved) and VITAL (Ventilator emergency use authorization, FDA)). The information gathered from various open-source and reported designs makes it clear that if one tries to emphasize more on improving one sector of device performance. For instance, a volume-controlled mode is essential for efficient treatment of patients ailed with COVID-19, but by doing that we have to integrate a flow sensor, which can cost in excess of 100$, making device expensive. Similarly, if one tries to provide more feedback for efficient control by installing various sensors, such as a temperature sensor to monitor temperature build-up in a device, or ultrasound sensors for precise actuator movement, better alarm systems, its cost will rise. Also, if one tries to make system attractive by providing touch screens or bigger display screens, it will lead to cost accumulation. Even the transportation costs should be kept in mind, as some of these parts of device performance, other sectors may get effected too. For instance, a volume-controlled mode is essential for efficient treatment of patients ailed with COVID-19, but by doing that, we have to integrate a flow sensor, which can cost in excess of 100$, making the device expensive. Similarly, if one tries to provide more feedback for efficient control by installing various sensors, such as a temperature sensor to monitor a temperature build-up in the device, or ultrasound sensors for precise actuator movement, better alarm systems, its cost will rise. Also, if one tries to make the system attractive by providing touch screens or bigger display screens, it will lead to cost accumulation. Even the transportation costs should be kept in mind, as some of these parts may not be easily available throughout globe. Moreover, by integrating various parts, the system's power consumption will increase with the requirement of more sophisticated control boards to control the system, which will also increase the final cost of the system. Therefore, all the factors whether its actuation, medical efficacy, sensors and alarms, display and control system, need to be properly optimized while keeping the cost of the system in mind, so as to achieve the main objective of providing artificial ventilation at low costs, available to everyone.

7 Conclusions

By systematically analysing various published and open-source portable mechanical ventilators, we have identified various parameters that need consideration for designing low-cost, easy to assemble, portable ventilators to fight the ongoing pandemic. We have seen that if we focus more on one aspect of the device (say sensor and alarm systems), the other aspect will get badly affected (increased cost). So, all the factors described in this study need to be considered while designing low-cost, portable, but at the same time efficient mechanical ventilator systems. It is remarkable how these designs have been evolving in such a short span of time. And this review will further help in providing insight into designing next-generation portable mechanical ventilators. However, some have speculated that the use of these automated mechanical ventilators can compromise the safety of patients [33, 34]. As these systems are being developed in many stages: R&D by researchers, testing by clinicians and mass production by manufacturer, some gaps may be there at each stage of development. Proper feedback loops should be there at each stage of development, so that everyone can learn from the mistakes or challenges faced at various stages.

The common problems such as putting exhaust valve near patient to stop accumulation of CO_2 in air pipe, proper sterilization of air ducts after use, providing better control over ventilation parameters, operation in pressure and volume-controlled modes, needs to be integrated in future portable ventilator designs, for better outcomes. Moreover, these designs need to be put into test in real-life conditions, where they have to operate continuously for days (even without supervision) under high load conditions in hospitals. Along with complete bench-testing of these ventilators is required, to provide better insight to fill the gaps in the performance of these low-cost-portable designs. The manufacturer also need to play a vital role, as they need to ensure that every system is in accordance with the guidelines provided by various health organizations, rather than making quick profits taking advantage of ongoing situations. Government bodies can also interfere at this stage to ensure that proper instrumentation and methodology has been used for developing the automated mechanical resuscitator systems. Thus, the collective efforts of engineers, doctors, scientists and even policy makers are needed for better designing and implementation of these low-cost portable mechanical ventilators to effectively fight against the current and future pandemics.

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Declarations

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