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Review

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ResQvent: A Practical Solution for Addressing the Needs of Mechanical Ventilation in Low Resource and Income Healthcare Settings

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Abstract

Respiratory emergencies are common and can require intensive management with complex medical equipment. Experiences from global pandemics such as Coronavirus disease-2019 have shown collapse of healthcare infrastructure and spikes in mortality because of shortage of critical equipment, such as mechanical ventilators, especially in under resourced settings. In this article, we present a brief review of medical literature regarding established and readily available blueprints for ventilator systems. We also present our design relevant to under resourced areas called the ResQvent, which is a portable artificial manual breathing unit add-on device that can be automated to allow cyclical compression of the bag to provide adequate ventilation according to standard recommendations for infants, children and adults. Powered by 220-240 V electrical supply, this 18x8x8 inches, extremely portable device can prove to be a game changer in providing temporary automated ventilation at a reasonable cost. ResQvent has been successfully bench tested for accuracy on simulation software. With the continued motivation arising from the pandemic, we assume similar projects will attract attention; however, efforts are still required to design policies and arrange dependable financial resources for the creation and evaluation of open-source ventilators.

Keywords: COVID-19, respiratory emergencies, prototype, ventilator

Introduction

Coronavirus disease-2019 (COVID-19), which is caused by infection from Severe acute respiratory syndrome-Coronavirus-2, is very dangerous as it threatens to overpower the existing medical healthcare system, resulting in increased mortality rates (1,2). Within the medical infrastructure, there is a limited inventory of equipment, and it lacks the overall capacity to cope with an overwhelming influx of patients during pandemics. As a result, people suffer globally due to a combination of COVID-19 illness and limited accessibility to specific equipment (3). Mechanical ventilators are an important example that has now been proven to be in a critical short supply in the odds of such circumstances (4).

Previous research has shown that intensive care units are insufficiently equipped to handle the majority of patients in need of ventilator support during pandemics (5,6). While certain countries, such as the United States, possess ventilator stockpiles (7), it is widely agreed upon that the existing supply is inadequate for significant pandemics (8). Consequently, ethical rationing may be required to allocate ventilators rather than relying on a first-come first-served basis (9).

The prevailing healthcare system relies on widely manufactured ventilators sourced from a small group of providers. This model falters when confronted with an abrupt surge in demand for intricate devices such as mechanical ventilators during a pandemic. The bulk of medical equipment is tightly patented by a few medical corporations. Furthermore, entities that do not actively practice medicine continue to obstruct the implementation of medical treatments, even in the midst of the present COVID-19 pandemic (10).

With the recent progress and incremental adoption of small-scale open-source manufacturing technologies (11), a different

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methodology called mass-distributed manufacturing has surfaced. Under this framework, designs are generated and openly shared through the internet with open-source licenses, enabling others to replicate the designs using their own equipment (12). Open-source scientific hardware has achieved tremendous triumph (13), presenting custom equipment that is comparatively inexpensive and exhibits superior performance compared to proprietary scientific tools (14). In the current scenario, this approach would, to some extent, address the shortages of medical supplies (15), especially in relation to ventilators (16).

Brief Literature Review

In the realm of peer-reviewed literature, most ventilator devices use a standard artificial manual breathing unit (AMBU) bag, which undergoes rhythmic compression using either a mechanical or pneumatic design. These compression are controlled by a microcontroller. The controls, which represent the most complex element of these designs, rely on Arduino technology that can be programmed or activated using existing source codes. It is noteworthy that a significant number of low-cost designs employ the bag approach, while commercial mechanical ventilators do not incorporate bags, bellows, or pistons due to concerns surrounding performance. Now, we will delve into the discussion of three distinct categories of cost-effective ventilators.

Both continuous positive airway pressure (CPAP) and bilevel positive airway pressure machines have been converted into ventilators by including an oxygen concentrator and viral high-efficiency particle air (HEPA) filter (17). Sleep apnea machines, specifically CPAP devices, come with a high price tag and can present obstacles regarding availability in settings lacking sufficient resources. This restriction impedes the swift deployment of these devices.

Researchers have also constructed conventional ventilators using readily available components from nonclinical supply chains. A number of these devices have acquired Emergency Use Authorization from the Food and Drug Administration, including the ventilator intervention technology accessible locally produced by the Jet Propulsion Laboratory of the National Aeronautics and Space Administration (18), and the Mechanical Ventilator Milano developed by Elemaster S.P.A. Tecnologie Elettroniche (19). These prototypes rely on several components that may not be suitable for efficient mass production and rapid deployment within a condensed timeframe.

Several universities have been actively pursuing simplified solutions by automating the operations of a standard manual AMBU bag. Table 1 provides a compilation of open-source ventilator projects based on the AMBU system, accompanied by relevant specifications. AMBU-based ventilators possess certain advantages, including easy accessibility, a basic mechanism with a minimal number of components, cost-effectiveness, and the ability for swift deployment. Most of the currently available designs heavily rely on a 3D printing for the assembly process. However, the production of such components on a large scale can become challenging during lockdowns, and they may also have a limited lifespan, potentially leading to device malfunction (20-24).

Innovation

As described, the AMBU bag remains a portable, simple, and easily accessible airway device under resourced settings; however,

Table 1. List of open source AMBU-based ventilator projects

Name	Developers	Characteristics	Source
AmboVent (20)	Innovators in Israel	Open sourceobot arm for compression has a backup battery and a cutoff for high resistance/ pressure	https://github.com/AmboVent-1690-108/ AmboVent
ApolloBVM (21)	Rice University	Open source, rack and pinion based, adult and child settings, 24 hour operational	http://oedk.rice.edu/apollobvm
Emergency Ventilator/ E-Vent (22)	MIT	Open source motor-driven cam mechanism for squeezing AMBU bag has assist control mode to detect pressure	https://e-vent.mit.edu/
OpenVent-Bristol (23)	Innovators in the UK	Open source, motorized arm to enable squeezing, referenced from existing open source	https://openventbristol.co.uk/
AmbuBox (24)	University of California, Davis	Open source, no moving parts, lightweight	https://www.ucdavis.edu/coronavirus/news/ uc-davis-engineers-clinician-develop-low-cost-portable-ventilator

BVM: Bag Valve Mask, MIT: Massachusetts Institute of Technology, UK: United Kingdom, AMBU: Artificial manual breathing unit if used manually, it can be highly dependent on interprovider variability and fatigue; making it less effective than a mechanical ventilator (25-28).

Our team aimed at combining the positive aspects of ventilation systems and ensuring that the resulting product remains accessible and affordable without compromising on the effectiveness of the proposed ventilator. The need for this innovation arose especially in the setting of decreased mechanical ventilators available for COVID-19 patients, especially in the setting of a resource-limited country such as Pakistan.

Keeping the above considerations in mind, we invented “Rapid Rescue Ventilator” (ResQvent) (Figure 1). Our overall goal was to create an automated, reliable, and long-lasting attachment that could fit onto a standard AMBU bag and automate compression and air supply. As seen with other similar models (20-24), the attachment had to function smoothly with relatively little human interference as the intent is to free up medical care providers from the AMBU bag operation. We aimed to target total expenses at approximately USD 150, which is far less compared to other low-cost pandemic portable ventilators (21,29,30).

The time our device can run without human intervention is around 6 h without power supply. We believe that this time should be sufficient while trying to find a reliable power supply source. When connected to a power supply, the device will work indefinitely while using a standard voltage between 220 and 240 V with no special requirement. During this, the device can accurately supply properly timed breaths with a margin of error less than 10%. The device can act as potentially life-saving ventilation equipment until a mechanical ventilator is arranged, saving lives that may be lost due to lack of medical and human resources.

The time the device takes from start to the first compression cycle values set according to standard recommendations (30-32) is approximately 45 seconds. Measuring 18x8x8 inches with a weight of around three kilograms, ResQvent is easy to position and carry around device. We believe that ensuring compactibility and portability for such device is important so it can be easy to maneuver across different environments.

The functioning of ResQvent is divided into five components:

1) Securing the AMBU bag

This is done via properly securing the device to the patient for ventilation. We designed the device to be used for noninvasive and invasive ventilation. The noninvasive mode of the device requires the AMBU bag to be connected via tubing to an appropriate-sized mask secured to the conscious patient to make an effective seal. This mode enables the device to serve as a conduit for continuous oxygen delivery while being able to provide continuous positive pressure ventilation through manual control of positive end expiratory pressure (PEEP) valve. For the invasive mode, the patient would have to be intubated and connected to the AMBU bag. In addition, the automation device must be properly secured with the AMBU to ensure proper ventilation and no errors during cyclical compression via metallic sliders fixed on the base of the assembly. A HEPA filter can be

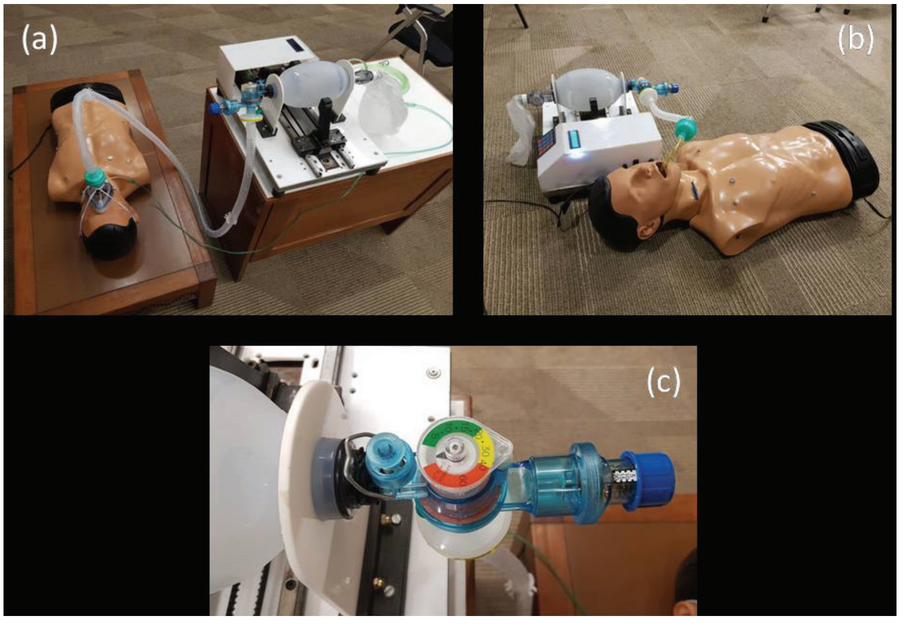

Figure 1. Rapid rescue ventilator (ResQvent). Panel (a): A screenshot demonstrating the noninvasive mode of ventilation. Panel (b): A screenshot demonstrating the invasive mode of ventilation. Panel (c): A screenshot of the manometer for safe tidal-volume delivery and the positive end-expiratory pressure valve

placed on the ventilator circuit near the patient to reduce the risk of aerosolization of viral particles. The device is well secured when stationary to prevent excessive movements of the entire structure

2) Powering the device

ResQvent is powered using a standard 220-240 V energy supply. This is needed for proper functioning of the compression mechanism and the display unit, aiding in the monitoring of the device.

3) Controlling/adjusting the device

Using Arduino software that operates the microcontroller, ResQvent provides the user with the ability to independently adjust the amount and rate of compression.

4) Compressing the bag

A "level controller" is used to control and monitor the amount and rate of compression. These variables can be adjusted manually courtesy of the Arduino microcontroller, which provides input to the stepper motor. The stepper monitor then controls the input of the desired compression level data to provide sufficient amount and rate of ventilation to the patient by consistently controlling the compression of the AMBU bag while considering preliminary factors such as speed and power. All of this compression meta-data can be entered using a basic keypad.

5) Monitoring outcomes

The compression-level data, respiratory rate, and other important ventilation variables are displayed on a laser color display monitor for easy user operability.

A portable breathing circuit on one limb was constructed and tested by engineers and doctors on a test lung using Arduino software. It was connected to the test lung for device reading. Using simulation software such as MatLab/Simulink and LabVIEW, we helped develop system design platforms and development environments, enabling better visualization and accuracy in predicting research and project outcomes. We used the Hamilton ventilation website simulation software to confirm the results. There, we mimicked the conditions and looked at how a portable ventilator responds. Figure 2 graphically demonstrates the various ventilation and volume-pressure loops generated by our device. The model was calibrated to our prototype in two steps. If the lung port was blocked, the parameters of the PEEP and pop-off pressure relief valves were first calibrated by comparing the model output with the measured output. In this series of studies, when the solenoid valve was opened and closed, the pressure at the inlet to the solenoid control valve was monitored as a function of the total inlet gas flow rate. The experiments used PEEP values of 2, 5, and 10 cm H_2O. The set pressure difference and maximum valve-opening area for each pressure relief valve in the model were modified to best suit the measured data. The Simscape logging mechanism is used to find

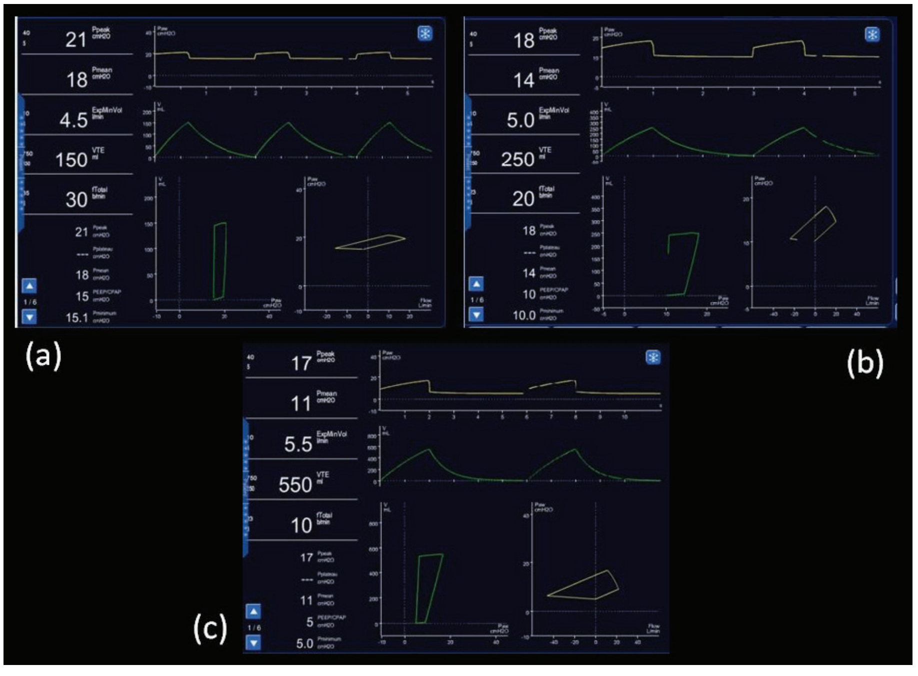

Figure 2. Graphical user interface (GUI) for different patient categories. Panel (a): GUI of infant setting using the compression 150 mL set at a rate of 30 compression per minute. Panel (b): GUI of child setting using the compression 250 mL set at a rate of 20 compression per minute. Panel (c): GUI of adult setting using the compression 550 mL set at a rate of 10 compression per minute

the simulation results. The temperature and relative humidity of the air flowing through the inspiratory and expiratory tubes are displayed. We used an Arduino Nano 3 microcontroller (ATmega328 microcontroller) to develop an electronic pulse train signal responsible for regulating the respiratory rate and inspiratory time. In the pneumatic signal circuit, the microcontroller triggers a solenoid valve connected to the exhalation manifold. Two potentiometer microcontrollers were employed to accept user input for controlling the respiratory rate and inspiratory time. Additionally, two push buttons have been incorporated, enabling the user to select a positive airway pressure and either lock or unlock the potentiometer button. The respiratory rate can be adjusted while the inspiratory time is governed through a pneumatic signal, which in turn controls the input of the electronic microcontroller. To assess the performance of the portable ventilator, we conducted evaluations using the ASL5000 breathing simulator. This simulator incorporates a realistic lung model capable of autonomous breathing and is calibrated to match the ventilator prototype, thereby accurately simulating ventilator behavior.

ResQvent's present design can secure the AMBU bag and provide therapeutic-specific ventilation to infants, children, and adults through a simple user interface. However, we believe that the device can be made more robust by installing an external protective casing to make it more durable in harsher surroundings. Cooling mechanisms such as a miniaturized fan can be installed in the assembly for managing device overheating. In terms of testing, ResQvent needs to be tested thoroughly for accuracy of volume and frequency over a wide range of conditions and over longer periods of time so that it can be used confidently in life saving situations.

Conclusion

Although promising but with further refinements, ResQvent can prove to be a game changer with an excellent potential of being utilized in low resource setting hospitals, clinics as well as the austere pre-hospital environment.

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Ethics

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Authorship Contributions

Concept: M.A.B., Design: M.A.B., A.S.A., Data Collection or Processing: M.A.B., A.S.A., Analysis or Interpretation: M.A.B., A.S.A., Literature Search: M.A.B., Writing: M.A.B.

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