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Portable Low-Cost Ventilator For Sustainable Healthcare

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Abstract

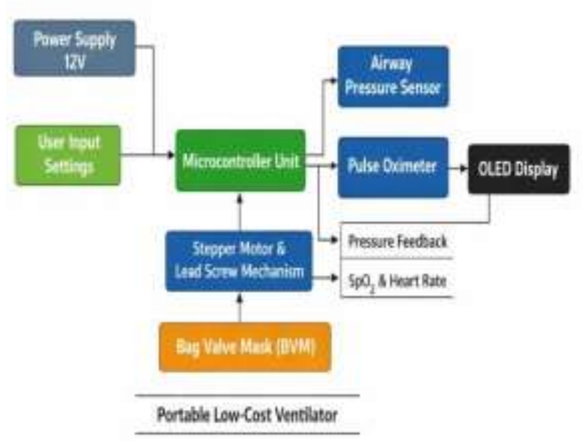
This paper presents the design and development of a portable, low-cost mechanical ventilator intended for emergency respiratory support in resource-constrained healthcare environments. The proposed system automates a conventional Bag Valve Mask (BVM) using a stepper motor– driven lead screw mechanism to deliver controlled ventilation. Key parameters such as tidal volume, respiratory rate, airway pressure, and inspiration–expiration ratio are regulated using a microcontroller-based control unit. Real-time feedback from an airway pressure sensor and a pulse oximeter ensures patient safety by preventing over-pressurization and maintaining adequate oxygenation. Experimental evaluation using an artificial lung model demonstrates stable and repeatable ventilation performance within clinically safe limits. Due to its low power consumption, portability, and affordability, the proposed ventilator is well suited for use in rural healthcare centers, ambulances, and emergency disaster-response situations.

Keywords -Ventilator, Bag Valve Mask (BVM), Low-Cost, Low-Power, Portable, Automated Ventilation

Introduction

Respiratory failure caused by chronic pulmonary diseases, infections, trauma, and environmental factors remains a major global healthcare challenge. Mechanical ventilators are essential life-support systems for patients who are unable to maintain adequate spontaneous breathing. However, conventional intensive care unit (ICU) ventilators are expensive, complex, and require skilled operation and maintenance, which limits their availability in rural and resource-constrained regions. During large-scale emergencies such as pandemics, natural disasters, and mass casualty incidents, even well-equipped healthcare systems experience severe shortages of ventilators.

In many emergency and pre-hospital settings, manual Bag Valve Masks (BVMs) are widely used due to their simplicity and low cost. However, prolonged manual operation leads to operator fatigue and inconsistent ventilation, increasing the risk of lung injury and inadequate oxygen delivery. Automating the BVM mechanism offers a practical approach to providing controlled ventilation while maintaining affordability and portability



This paper proposes a portable, low-cost ventilator system that automates a conventional BVM using an electromechanical actuation mechanism. The system incorporates a microcontroller-based control unit, airway pressure monitoring, and oxygen saturation measurement to ensure safe and reliable ventilation. The primary objective of this work is to develop an economical and energy-efficient ventilator suitable for emergency use in ambulances, rural healthcare centers, and disaster-response environments.

Literature Survey

Aït-Khaled *et al.* (2001) studied the burden of chronic respiratory diseases in developing countries and highlighted the lack of adequate prevention and treatment infrastructure. The authors emphasized that limited access to mechanical ventilators significantly increases mortality rates, indicating the need for affordable respiratory support systems[1]

Chan-Yeung *et al.* (2004) analyzed the prevalence and impact of chronic obstructive pulmonary disease (COPD) in Asia and Africa. Their work identified respiratory failure as a leading cause of hospitalization and stressed that insufficient ventilatory support in rural regions worsens patient outcomes[2]

Kerechanin *et al.* (2004) focused on the development of field-portable ventilator systems for domestic and military emergency medical response. The study demonstrated that simplified, portable ventilators can effectively deliver life-saving respiratory support in emergency conditions[3]

deBoisblanc (2005) reported experiences from Hurricane Katrina, highlighting the severe shortage of ventilators and collapse of hospital infrastructure. The author emphasized the necessity of independent, portable ventilation systems during disaster situations[4]

McNeil (2006) discussed potential ventilator shortages during a severe influenza pandemic in the United States. The report revealed that even advanced healthcare systems lack sufficient emergency ventilator capacity, strengthening the case for scalable low-cost ventilator designs[5].

Klein and Nagel (2007) examined mass medical evacuation challenges during Hurricane Katrina and documented reliance on manual Bag Valve Mask ventilation due to equipment shortages. Their findings further supported the need for automated BVM-based ventilators in emergency healthcare[6].

Webster (2008) provided standardized definitions and clinical explanations of mechanical ventilation and artificial respiration, forming the foundational medical understanding required for ventilator system design.[7]

Centers for Disease Control and Prevention (2009) reported on the strategic stockpiling of emergency ventilators for public health emergencies. The study acknowledged that while preparedness improved, high costs and limited availability remained major concerns[8]

Proposed Method

The proposed ventilator system is designed to provide controlled and reliable mechanical ventilation by automating a conventional Bag Valve Mask (BVM). Instead of manual compression, the BVM is actuated using an electromechanical mechanism driven by a stepper motor coupled with a lead screw assembly. This configuration enables precise and repeatable control of bag compression, allowing accurate regulation of ventilation parameters.

A microcontroller-based control unit governs the entire breathing cycle. User-defined parameters such as respiratory rate, tidal volume, and inspiration-to-expiration (I:E) ratio are processed by the controller to generate appropriate motor control signals. During the inspiration phase, the stepper motor compresses the BVM to deliver a controlled volume of air to the patient, while during expiration the motor halts or slightly reverses to allow passive exhalation.

To ensure patient safety, the system operates in a closed-loop manner using continuous feedback from an airway pressure sensor and a pulse oximeter. If airway pressure approaches a predefined safety threshold, the controller automatically adjusts motor speed or stroke length to prevent over-pressurization. Oxygen saturation and heart rate are monitored in real time to assess the patient's respiratory condition. All critical parameters are displayed on an onboard OLED screen, enabling easy monitoring by medical personnel. This method provides a safe, low-cost, and portable ventilation solution suitable for emergency and low-resource healthcare settings.

System Overview

The proposed ventilator system is designed around a compact and modular architecture suitable for emergency and portable applications. It utilizes a conventional Bag Valve Mask (BVM) as the air delivery unit, which is automated using a stepper motor– driven lead screw mechanism. This arrangement enables precise control of bag compression, allowing accurate regulation of ventilation parameters such as tidal volume and respiratory rate. A microcontroller-based control unit coordinates the inspiration and expiration phases of the breathing cycle.

Patient safety and monitoring are ensured through integrated sensing and display modules. An airway pressure sensor continuously monitors pressure to prevent over-inflation, while a pulse oximeter measures oxygen saturation and heart rate in real time. All critical parameters are displayed on an OLED screen for easy observation by medical personnel. The system is powered by a regulated 12 V supply, making it suitable for use in ambulances, rural healthcare centers, and emergency situations.

Key Steps of the Proposed Method

The operation of the proposed ventilator begins with system initialization and sensor calibration. The microcontroller initializes the airway pressure sensor and pulse oximeter to acquire baseline patient parameters. User- defined inputs such as respiratory rate, tidal volume, and inspiration–expiration ratio are then set, which determine the timing and stroke length of the breathing cycle.

During the inspiration phase, the microcontroller generates control signals to drive the stepper motor, which compresses the Bag Valve Mask through a lead screw mechanism. This controlled compression delivers a precise volume of air to the patient while the airway pressure sensor continuously monitors pressure levels. If the pressure approaches a predefined safety threshold, the controller automatically adjusts motor speed or displacement to prevent lung injury.

In the expiration phase, the motor halts or slightly reverses to allow passive exhalation of air. Simultaneously, oxygen saturation and heart rate are monitored in real time using the pulse oximeter. All ventilation parameters and patient vitals are displayed on the OLED screen, and the system continuously repeats the closed-loop cycle to provide stable and safe ventilation.

Results and Comparative Analysis

The proposed portable ventilator was tested using an artificial lung model to evaluate its performance and reliability. Experimental results showed stable ventilation with controlled tidal volumes ranging from 300 to 550 mL, suitable for adult emergency respiratory support. The system maintained a respiratory rate between 12 and 28 breaths per minute with a consistent inspiration–expiration ratio. Airway pressure was continuously monitored and remained within the clinically safe range of 10–22 cm H_2O, with no pressure overshoot observed during prolonged operation.

The integrated MAX30100 pulse oximeter provided reliable oxygen saturation and heart- rate measurements, with SpO_2 accuracy within ±2% compared to a commercial pulse oximeter. The ventilator operated continuously for over three hours using a regulated 12 V power supply without overheating or mechanical failure. These results confirm the stability, safety, and energy efficiency of the proposed system for emergency and portable healthcare applications.

Comparison Table:

Parameter	Conventional ICU Ventilator	Proposed Portable Ventilator

Cost	Very high (₹5–10 lakh)	Very low
Portability	Limited	High
Power Consumption	High	Low
Ventilation Control	Advanced multi-modes	Essential pressure control
Monitoring Features	Comprehensive	SpO_2, pressure, heart rate
Maintenance	Expensive	Minimal
Suitability for Rural Use	Low	High

Challenges and Limitations

Despite its advantages, the proposed portable ventilator has certain challenges and limitations. The system primarily supports basic ventilation modes and does not include advanced features such as volume-controlled ventilation, pressure support ventilation, or synchronized patient triggering found in ICU ventilators. The reliance on mechanical components like the stepper motor and lead screw may introduce wear and tear over prolonged use, affecting long-term reliability. Additionally, the accuracy of ventilation depends on proper calibration and correct placement of sensors, which may be challenging in emergency or untrained settings.

Another limitation is the absence of integrated alarms for critical conditions such as apnea, power failure, or sensor malfunction, which are essential in clinical environments. The system is also dependent on a continuous power supply, limiting its operation time in remote areas without battery backup. Moreover, the device has not yet undergone extensive clinical trials, and therefore its performance on diverse patient conditions requires further validation before large-scale deployment.

Future Scope

The proposed ventilator can be enhanced by incorporating advanced ventilation modes and adaptive control algorithms to improve patient–ventilator synchrony. Integration of audible and visual alarm systems for pressure anomalies, power loss, and sensor failure would significantly improve patient safety. Adding a rechargeable battery module and solar charging support can extend its usability in rural and disaster-affected regions.

Future developments may also include wireless connectivity for remote monitoring and data logging through IoT platforms. The use of machine learning algorithms to adjust ventilation parameters based on patient feedback could further optimize respiratory support. With proper clinical validation and regulatory approval, the system has strong potential to serve as a cost-effective and reliable solution for emergency and low-resource healthcare settings.

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