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Original Research Article

Automated low-cost monitoring and ventilation: enhancing Bag-Valve-Mask (BVM) use in emergency response

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Abstract: Manual bag-valve-mask (BVM) ventilation is a critical emergency response technique; however, studies show that practitioners often deliver unsafe tidal volumes, pressures, and breath rates, increasing the risk of lung injury, gastric inflation, or hypoxia. This study developed an automated BVM system to ensure accurate and consistent positive pressure ventilation while providing real-time monitoring of tidal volume, peak pressure, and breath rate. The system integrates a stepper motor-driven compression mechanism, an orifice-based flow sensor, and an LCD interface for user adjustments and real-time feedback. Testing demonstrated that the automated system successfully maintained ventilation within a safe range, with tidal volume values deviating by no more than 100 mL from calibrated Douglas Bag measurements. Stepper motor-controlled compression exhibited a linear relationship with tidal volume, with optimal airflow delivery occurring between 90° and 252° of rotation. Finite Element Analysis validated the compression arm's mechanical reliability, showing minimal deformation (0.005 mm) under 2.8 Nm of force. To enhance portability and efficiency, additive manufacturing was utilized to fabricate all the key components, including the compression arm and tidal volume sensing system. A Generative Design optimization approach further reduced material usage while maintaining structural integrity, improving weight efficiency without compromising performance. The flexibility of 3D printing allowed for rapid prototyping and design iteration, making the system adaptable to various BVM models. This study demonstrates the potential of automated BVMs to improve emergency ventilation, reduce human error, and enhance patient safety. Future work will focus on exploring applications in pre-hospital and community-based ventilation solutions, similar to public access defibrillators.

I. Introduction

Non-Invasive Positive Pressure Ventilation (NIPPV) is a critical intervention for patients experiencing respiratory distress, requiring resuscitation, or needing assisted ventilation [1]. One of the most commonly used devices for NIPPV is the Bag Valve Mask (BVM), which consists of a self-inflating bag that is manually squeezed to push oxygenated air through a mask worn by the patient. A typical BVM setup includes an inlet valve, an outlet valve, and tubing that directs airflow while allowing the expulsion of exhaled gases [2].

A fundamental challenge in BVM use is ensuring consistent and precise delivery of ventilation, particularly in prolonged or emergency scenarios where manual operation can lead to fatigue or inconsistency. Both over-ventilation and under-ventilation can cause severe medical complications, significantly increasing the risk to patients. Over-ventilation may result in gastric inflation, pulmonary edema, barotrauma, or even lung rupture, whereas under-ventilation can lead to hypoxia, organ failure, and reduced overall physiological function [3],[4]. Studies have consistently shown that manual ventilation often leads to unsafe flow rates, with practitioners delivering an average of 193% of the intended tidal volume [5]. Additionally, due to the standardized size of BVMs, excessive ventilation volumes are frequently delivered to both pediatric and adult patients, surpassing safe levels [6]. Further research has demonstrated that mean flow rates, tidal volumes, and peak pressure levels often exceed recommended limits, highlighting the inadequacy of subjective assessments such as visual chest rise [5,7]. Even when using the recommended single-finger compression technique, standard BVMs frequently provide tidal volumes

exceeding the safe range. Misuse of grip techniques, such as applying two or three fingers, exacerbates this issue, often surpassing the typical requirement of 400–500 mL per breath for an adult [6].

Despite the critical nature of controlled ventilation, most commercially available BVMs lack integrated monitoring or feedback mechanisms for tidal volume, pressure, or breath rate. This absence of real-time data results in highly variable and often unsafe ventilation delivery, even among trained professionals. Current clinical guidelines recommend ventilation within safe limits—approximately 12 breaths per minute (BPM), with tidal volumes of 400 mL for females and 500 mL for males, and a peak inspiratory pressure of 15 cm H_2O. Exceeding 21 BPM, 800 mL of tidal volume, or 25 cm H_2O can lead to severe internal damage and increased mortality risk [5],[8],[9]. Recent models such as those by El-Hadj [10] and Kshetry [11] were developed in response to ventilator shortages during the COVID-19 pandemic. While these and other emergency systems—like the MIT Emergency Ventilation Project—enabled rapid hospital deployment, they often lacked portability and real-time monitoring, limiting their utility outside clinical environments.

The system described in this paper advances the field by integrating low-cost sensing, modularity, and real-time feedback within a compact form factor. Its unique compatibility with standard BVMs, along with intuitive manual controls and sensor-driven automation, offers a practical and sustainable solution for field use. Unlike hospital-based systems or keypad-driven designs like the automated BVM [12], which can be complex under pressure, this system prioritizes ease of use. Despite over a decade of innovation, no existing solution fully combines portability, real-time feedback, and intuitive control for emergency responders.

Manual ventilation remains prone to error, reinforcing the need for automation. By monitoring tidal volume, breath rate, and pressure in real time, this system enhances patient safety, reduces human error, and supports high-stakes applications—from paramedic response to disaster relief and military use.

A key factor in the development of this automated BVM system is the use of additive manufacturing (AM), which enables rapid prototyping and cost-effective production. Unlike conventional manufacturing methods, AM allows for the creation of lightweight yet durable components, ensuring the device remains, portable and easy to carry in emergency settings. Additionally, the modular design approach facilitated by AM makes it adaptable to different BVM models, allowing for quick modifications based on patient requirements or clinical preferences [13]. By leveraging rapid prototyping, design iterations can be tested and refined efficiently, reducing development time while maintaining affordability [14]. This approach also ensures that the system can be manufactured at a fraction of the cost of traditional ventilators, making it a viable solution for both high-resource and low-resource settings. The ability to 3D print complex geometries further enhances the device's functionality, integrating sensor housings, pressure regulators, and customized valve systems into a compact and efficient form.

Beyond professional medical use, a portable, automated BVM has the potential for broader community applications, enabling first responders, flight attendants, and law enforcement personnel to administer safe ventilation without extensive training. In the long term, this technology could contribute to the development of widely accessible emergency ventilators, akin to public defibrillators, improving survival rates in out-of-hospital cardiac arrest and respiratory failure cases.

This paper discusses the design and development of an automated BVM system that provides personalized, real-time-controlled ventilation to patients in emergency response scenarios. By optimizing tidal volume delivery, monitoring peak pressure values, and utilizing additive manufacturing for cost efficiency, portability, and adaptability, this innovation aims to reduce the risks associated with manual ventilation and improve patient outcomes.

II. Material and methods

The development of the device followed a structured, iterative design approach to ensure that it met the functional, performance, and regulatory requirements necessary for safe and effective emergency ventilation. This section details the design specifications, development methodology, and key engineering decisions made during the process.

Various sensing mechanisms, actuation methods, and control strategies were explored, leading to the selection of an optimized system that integrates automation with paramedic oversight. The following subsections describe the design specification, and key technical developments, including the chosen ventilation mechanism, tidal volume sensing approach, and system integration.

II.I. Design Specifications

The design of the device follows a set of well-defined specifications to ensure it meets functional, performance, and ethical standards. Table 1 outlines these specifications, developed using an optimized Pugh's Design Specification Methodology [15].

The key considerations include reliability, size and weight, optimizing portability without compromising durability; power consumption, and manufacturability, selecting cost-effective processes that support scalability. Additionally, ergonomics has been a central factor in the design, ensuring user comfort and ease of operation.

Table 1: Design Specification, based on Pugh's Design Specification.

Area	Specification	Explanation
Function	Reliable	As a life-supporting device, it must consistently provide ventilation without failure. It should also accurately sense and monitor critical patient parameters.
	Size and Shape	Designed for emergency response, ensuring it fits through confined spaces and remains as small as possible for ease of transport and use.
	Electric Supply	Operates efficiently on minimal power, ensuring extended functionality when running on a battery pack.
	Weight	Should be easy to carry and transport without adding strain to emergency responders.
	Maintenance	Requires infrequent servicing and calibration while maintaining optimal functionality.
	Users	Designed to accommodate the needs of both patients and care providers, ensuring ease of use and patient comfort.
	Performance	Capable of delivering Positive Pressure Ventilation (PPV) at controlled and optimal rates for patient safety.
	Ergonomics	Designed for ease of grip, carrying, and operation during high-pressure emergency situations.
Production	Materials	Constructed from biocompatible, medically certified materials suitable for prolonged use.
	Manufacture	Optimized for cost-effective, scalable production without compromising quality.
	Finishes	Designed with smooth surfaces and no sharp edges to prevent harm to patients or users.
	Supply	Suitable for high-volume manufacturing while maintaining affordability and reliability.
Outcome	Patentability	Offers a unique and innovative solution compared to existing ventilation devices.
	Suitability	Meets all performance and usability requirements, ensuring adaptable ventilation in a user-friendly and rapid-acting system.
	Testing	Demonstrates compliance through rigorous testing, ensuring accurate and consistent performance.
Ethics	Sustainability	Designed with sustainability principles in mind, aligning with GreenerNHS initiatives for eco-friendly healthcare solutions. (https://www.england.nhs.uk/greenernhs/).
	Disposal	Maximizes device lifespan while minimizing waste from disposable components.
	Standards	Designed to adhere to relevant medical standards and regulations without compromising functionality.
	Safety	Prioritizes patient and caregiver safety by minimizing risks and ensuring reliable performance in critical conditions.

Additional performance targets were included: tidal volume deviation within ±50 mL for typical operation; peak pressure capped at 20 cm H_2O for safety, consistent with standard emergency ventilation guideline.

II.II. Design and Development

Initial Design Concept

The evaluation of different design concepts highlighted the importance of both automation and manual control in ensuring effective ventilation. As depicted in Fig. 1, the proposed solution integrated automated value detection with adjustable controls, allowing paramedics to tailor ventilation based on patient needs while still benefiting from automated sensing.

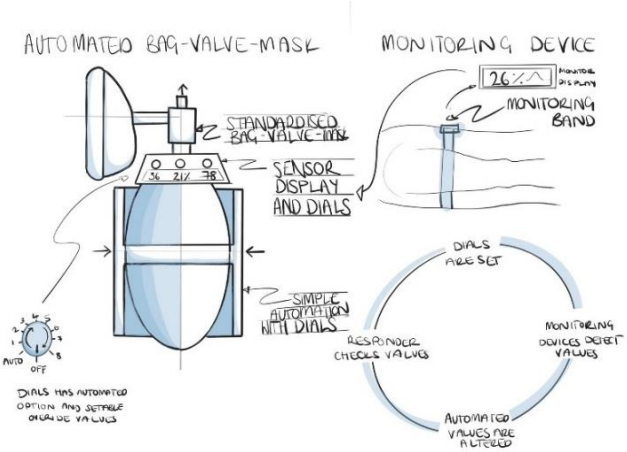

Figure 1: Concept of an Automated BVM with control dials and data monitoring.

This approach balanced user control with the ability to monitor critical values, ensuring safer and more adaptable ventilation. Regarding the actuation mechanism, the scissor-style closure was identified as the most suitable due to its resemblance to manual ventilation techniques used by trained professionals, enhancing usability and familiarity. The final design direction combined these two key elements, refining both automation and actuation to optimize functionality. Additionally, critical monitoring and delivery parameters were evaluated, with BPM, tidal volume (TV), and inspiratory-to-expiratory (I:E) ratio being prioritized to ensure effective positive pressure ventilation (PPV). Peak volume monitoring was also included as a safety feature to detect excessive pressure and provide warnings when necessary.

Tidal Volume Sensing

The development of the tidal volume (tV) sensing aspect involved assessing potential components, designing for fluid dynamics, and identifying the necessary equations for accurate calculations. Initially, a differential pressure sensor was considered for precise pressure drop readings; however, its high cost rendered it unsuitable for a single-use application. Instead, a lower-cost alternative was implemented by utilizing two absolute pressure sensors to

monitor pressure drop effectively. Future iterations may explore integrated differential sensors to evaluate trade-offs in accuracy, reusability, and calibration simplicity.

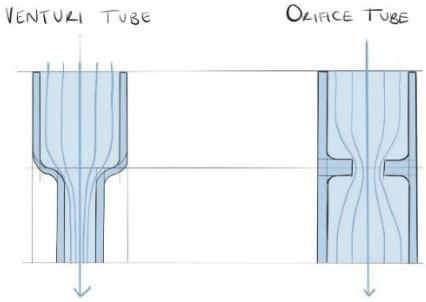

Figure 2: Venturi and Orifice Tube.

The concept development explored both the Venturi effect and orifice-based methods, as shown in Fig. 2, to convert two pressure readings into a volumetric flow rate. While both approaches proved effective, the orifice method was preferred due to its ability to maintain consistent tubing size, simplifying integration within existing systems while minimizing material waste [16]. 3D printing played a crucial role in the development of the tidal volume sensing system, enabling rapid prototyping and iterative design improvements. The orifice-based pressure drop system required precise geometric constraints to function correctly, which were easily refined using additive manufacturing. By leveraging 3D printing, custom orifice plates and sensor housings were produced with high accuracy, ensuring optimal airflow and minimal turbulence. Additionally, this approach allowed for quick validation of different designs without the need for expensive tooling, significantly accelerating the development process. The flexibility of 3D printing also facilitated the integration of sensor mounts and connectors directly into the printed components, reducing assembly complexity and potential leak points.

The volumetric flow rate through the orifice was calculated using an orifice flow equation derived from the **Bernoulli and continuity equations**, with an added discharge coefficient to account for non-ideal flow behaviour [17]:

$$Q = C_d \frac{\pi}{4} D_2^2 \sqrt{\left(\frac{2(P_1 - P_2)}{\rho(1 - d^4)}\right)} \quad (1)$$

where:

C_d = 0.6 (discharge coefficient)

D_2= 0.01m (orifice diameter)

P_1, P_2 = pressures before and after the orifice

ρ = 1.3 kg/m³ (air density)

d = 0.45 (orifice ratio)

This equation reflects the combination of energy conservation (Bernoulli) and mass conservation (continuity), adjusted for viscous losses through the inclusion of C_d. The **instantaneous volume** during each sampling period (0.25s) was then computed using:

$$Volume = Q \times 10^2 \times 0.25 \quad (2)$$

The **simplifications** assumed incompressible, steady and laminar flow conditions for ease of calculation but ensuring the approach remained **suitable for prototype validation**. A 0.25 s sampling rate was chosen as a trade-off between system simplicity and sufficient resolution. While this reduces peak flow fidelity during fast transitions—unlike clinical systems sampling at ≥100 Hz—it remains adequate for prototyping. Future work will target higher sampling rates and refined calibration methods (e.g., lookup tables) to improve flow estimation accuracy in laminar regimes. Equation (1) was used to determine tidal volume across the orifice, derived from Bernoulli's equation. Given time constraints and the complexity of airflow behaviour, flow was assumed to be laminar and incompressible for simplification. The flow rate was converted into millilitres (Equation (2)) for the volume over a 0.25-second period, which was then summed across a full breath cycle to calculate tV. Additionally, peak pressure values were converted to cm H_2O for LCD display alongside the tV and set values. While the simplified equations do not fully capture the intricacies of respiratory flow dynamics, they provide a foundational approach that can be refined with further computational analysis.

Control Process

The system control process was designed to manage tidal volume sensing, pressure monitoring, and compression actuation in a structured manner.

Figure 3: Schematic of the control process.

The flowchart (Fig. 3) outlines the sequence of operations, ensuring smooth functionality from power-on to breath cycle execution. Upon power-up, the system initializes the tidal volume and peak pressure sensing modules. The inhalation process is detected first, triggering sequential pressure readings at 0.1-second intervals from both pressure sensors. These readings are converted into flow rate values, and the total flow for each period is used to compute tidal volume. Peak pressure is identified and stored for display, alongside the tidal volume measurement. The compression control sequence follows, regulating the mechanical actuation. Rotary encoders play a key role in adjusting breath timing and compression parameters:

- Rotary Encoder 1 determines the breath period by computing 60/value, ensuring synchronization with the required respiratory rate.
- Rotary Encoder 2 defines the number of steps required for compression, scaled by a factor of 10 to achieve the desired stroke.
- Rotary Encoder 3 governs inhalation and exhalation timing, calculating distinct compression and release periods.

A stepper motor executes compression, moving forward for inhalation and reversing for exhalation, following the step values set by the encoders. This ensures precise and repeatable breath cycles tailored to the user's needs. By integrating real-time pressure sensing with motorized actuation, the system effectively simulates natural breathing patterns, providing a controlled and cost-effective respiratory support solution. The current actuation system operates in an open-loop configuration, meaning the compression is not dynamically adjusted based on patient airway feedback. Although real-time sensing of pressure and flow is implemented, this data is not yet used to close the control loop. Integrating a closed-loop feedback system in future versions will allow adaptive ventilation based on patient-specific respiratory mechanics, enhancing safety and clinical relevance. While the interface with rotary encoders and an LCD is cost-effective and functional, its usability under stress conditions remains a concern. The addition of visual scales, intuitive presets, and labelled encoder functions is under consideration to improve accessibility, particularly for first responders without technical training.

Final Concept and Integrated System Design

The final concept (Fig. 4) integrated a tidal volume sensing unit, a display unit, and a compression mechanism into a single system designed for real-time respiratory monitoring and assistance. Finite Element Analysis of the designed components was performed on Fusion 360 to ensure part strength, presented in the results section. The value sensing unit consisted of a mask attachment connected to a bag-valve mechanism, where two MPX5010DP pressure sensors, by NPX, UK, measured differential pressure across a 3D-printed orifice-based flow restriction. This setup enabled accurate tidal volume estimation while maintaining a low-cost, single-use approach. The display unit provided real-time feedback on tidal volume, peak pressure, and respiratory cycle settings, allowing users to adjust parameters as needed. It included a fan-vented casing for cooling and a microcontroller-driven interface for seamless data processing and display. The compression unit utilized a stepper motor-driven mechanism to regulate airflow through controlled compression of the bag-valve mask. The rotary encoder-based control system enabled precise adjustments for inhalation and exhalation periods, ensuring flexibility for different respiratory needs. A final render of the design is shown in Fig. 5.

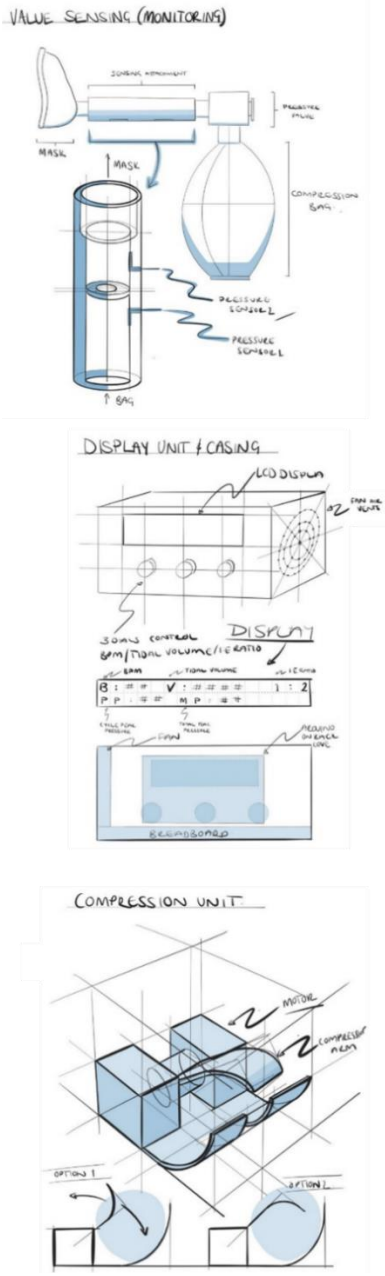

Figure 4: Final concept showing the sensing, display and compression unit.

Figure 5: Final render of the design with the mask and BVM.

3D Printing was used to manufacture the housings and some key components of the system.

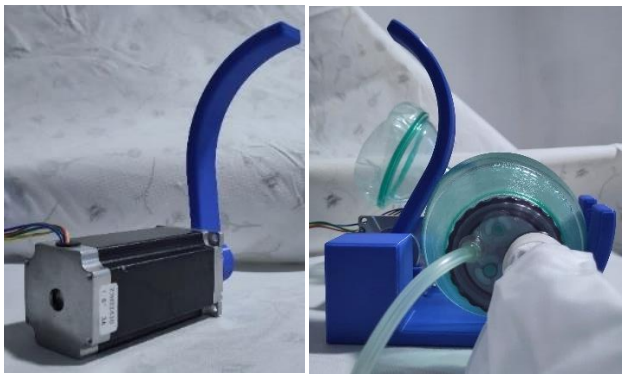

Figure 6: Motor with compression arm and base plate.

The compression mechanism, Fig. 6 features a stepper motor-driven arm designed to regulate airflow by precisely compressing a bag-valve mask (BVM), ensuring controlled inhalation and exhalation cycles. The frame and mounting brackets for securing the BVM were 3D-printed to achieve a lightweight, customizable, and cost-effective design (Fig. 7).

Figure 7: Optimised 3D-printed bracket for BVM.

Figure 8: Orifice tube with embedded sensors for tidal volume calculation.

The tidal volume sensing unit (Fig. 8) included a 3D-printed orifice-based flow restriction, enabling differential pressure measurements via MPX5010DP sensors for accurate tidal volume estimation. Additionally, the display unit housed a microcontroller and was enclosed within a 3D-printed, fan-ventilated casing to manage heat dissipation. The use of additive manufacturing allowed for rapid prototyping and design iteration, making the system adaptable for different respiratory requirements while maintaining a low-cost, single-use approach. Calibration tests were performed to ensure adequate performance.

Generative Design

To further enhance the efficiency and performance of the automated ventilation system, Generative Design (GD) was used to optimise the compression arm, reduce weight, improve structural integrity and optimise material distribution while maintaining the required force application for consistent ventilation.

Figure 9: Generative design for the compression arm.

The GD study was setup with the engaging components of the assembly as preserves [18]. Fig. 9 shows the generatively optimised compression arm. Additive manufacturing enables the manufacturing of these organic components developed using the algorithm-driven topology optimisation. While the compression arm was optimized via Generative Design and fabricated through additive manufacturing (AM), similar geometries could potentially be realized through high-precision CNC machining or investment casting. However, AM offers distinct advantages in design freedom, weight reduction, and integration of internal features, making it the preferred method for prototyping.

III. Results and Discussion

The testing phase evaluated the accuracy of the orifice-based tidal volume (tV) sensing system, the compression system's performance for controlled ventilation, and the stepwise motor speed adjustments to maintain safe tV ranges. The results were analyzed for repeatability and safety compliance, ensuring that the initial ventilation settings provide a baseline level of support while real-time adjustments maintain safe ventilation rates.

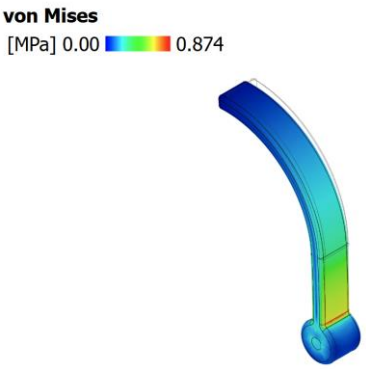

Figure 10: von Mises Stress.

The finite element analysis (FEA) of the compression arm assessed the structural integrity under applied force. The simulation results showed a maximum von Mises stress of 0.874 MPa (Fig. 10) when 2.8 N of force was exerted at the contact point with the Bag-Valve-Mask (BVM) bag. Additionally, the displacement analysis demonstrated minimal deformation, with the largest movement recorded at 0.005 mm, ensuring mechanical stability during repeated compressions. The optimised compression arm led to a 12% reduction in the weight of the component, improving portability and increasing the mechanical load capacity to 6.2 N with a minimum factor of safety (FoS) of 3.4, and enabling reliable operation for longer NIPPV cycles.

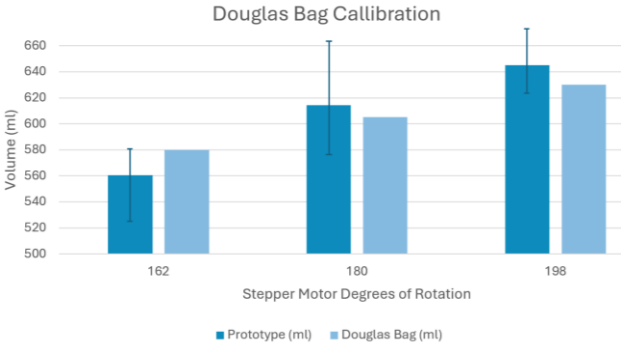

Figure 11: Flow volume comparison for prototype and Douglas Bag

To validate the tidal volume accuracy, calibration tests were conducted using Douglas Bag testing at different stepper motor rotation angles. This involved collecting tidal volume data using two different methods: (i) direct Douglas Bag collection, and (ii) the prototype's orifice-based sensor. The comparison between prototype sensor readings and Douglas Bag measurements, as shown in Fig. 11, demonstrated a strong correlation. At 162° rotation, the prototype recorded approximately 560 mL, whereas the Douglas Bag measured 580 mL. Similarly, at 180° rotation, the prototype and Douglas Bag values were 620 mL and 610 mL, respectively. At 198° rotation, the prototype estimated 650 mL, compared to 640 mL for the Douglas Bag. The system demonstrated reliable volume estimation, confirming its ability to monitor and adjust tidal volume in real time.

The Douglas Bag method was selected for its precision in capturing ventilated air volume, though it is less common in device testing. Five trials were conducted under room temperature and pressure conditions, with the bag calibrated using a standard spirometer. Figure 12 reports tidal volume data, not flow rate, which should be clarified for interpretation. The system exhibited a deviation of ±100 mL in tV readings, with greater variation occurring at extreme compression angles due to bag deformation and non-linear flow dynamics. These deviations remain within clinically acceptable limits for emergency ventilation and will be reduced with more robust flow calibration.

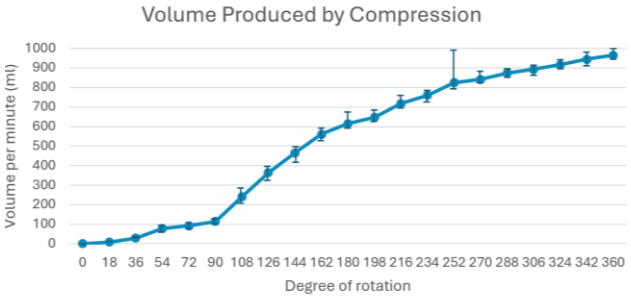

Figure 12: tidal volume data for prototype and Douglas Bag

The relationship between stepper motor rotation and delivered tidal volume was examined, as depicted in Fig. 12. The data followed a predictable trend, where increasing stepper motor rotation corresponded to a proportional increase in delivered tidal volume. From 0° to 360° rotation, the tidal volume output followed a near-linear progression, reaching approximately 950–1000 mL per minute at the highest rotation setting. This confirms that the system can deliver controlled and scalable tidal volume output, essential for adaptive ventilation. Real-time monitoring and system feedback were verified using an LCD display which consistently showed accurate volume reading demonstrating high precision and minimal deviation. This validates the integration of the sensing and feedback mechanism, ensuring real-time monitoring and adjustments for safe and effective ventilation.

The developed system provides an innovative approach to mitigating errors in manual ventilation, ensuring patient safety through controlled and customizable tidal volume delivery. The calibration assessment demonstrates strong agreement between prototype measurements and those from the Douglas Bag, with a deviation within ±100 mL. This accuracy is sufficient for monitoring but could be improved with a higher-precision pressure sensor, balancing cost and performance. The stepper motor compression tests validate the expected relationship between rotation and delivered tidal volume, where compression effectiveness increases within 90° to 252° of rotation before tapering off. However, deviations in tidal volume readings—particularly at 252° rotation due to bag movement—highlight the need for enhanced stability mechanisms. The system's mean standard deviation of

51.2 mL suggests a tolerance of ±26 mL, though outliers indicate the potential for greater variation, reaching ±172 mL in extreme cases. These inconsistencies could be addressed through refined fluid dynamics modelling and higher-accuracy sensors to enhance reliability. The integration of real-time monitoring on the LCD display supports continuous feedback and user confidence, reinforcing the system's potential to improve emergency ventilation procedures. However, practitioner training and liability concerns remain critical challenges. Further refinements, including user-centric design enhancements such as larger displays and refined controls, along with comparative testing against manual ventilation, will be essential for advancing the solution towards clinical implementation.

IV. Conclusions

This study presents a novel approach to improving manual ventilation in emergency response scenarios through an automated, controlled ventilation system that ensures consistent and patient-specific tidal volume delivery. The literature review highlighted significant inconsistencies in manual ventilation, where practitioner ability and inherent limitations of the bag-valve mask (BVM) system often result in suboptimal patient outcomes. In response, the system was developed with key design objectives: monitoring and maintaining consistent ventilation, reducing the risk of over- or under-ventilation, and improving practitioner confidence through an intuitive interface.

The final prototype successfully controls BPM, tidal volume (tV), and I:E ratio, while also monitoring peak pressure (pP) values to ensure ventilation safety. Integrated alarm systems provide real-time feedback for harmful ventilation parameters, reinforcing patient protection. The system's proof-of-concept testing confirmed that it delivers ventilation within an appropriate range, though further sensor accuracy improvements and comparative testing against manual ventilation are necessary to validate its clinical effectiveness.

Beyond emergency response, this technology has wider applications in settings such as aircraft, disaster relief, and community-based emergency care, where early intervention can be critical. By following the model of public defibrillator deployment, automated ventilation could significantly enhance pre-hospital emergency care, improving survival outcomes before paramedics arrive. While refinements are needed for clinical integration, the developed system represents a meaningful advancement toward safer and more effective emergency ventilation.

Acknowledgments

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Author's statement

Authors state no conflict of interest. No animal experiments were carried out. Consent was obtained from all persons involved in this study.

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