Design and Study of a Portable High-frequency Ventilator for Clinical Applications

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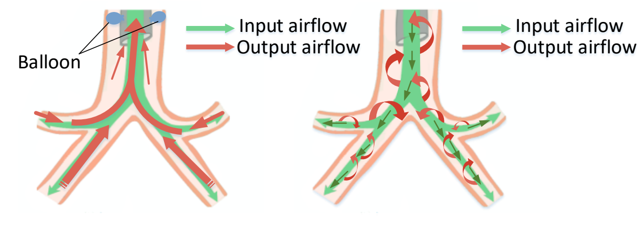
***Abstract*— Treatment costs for ventilator-dependent patients are a substantial burden not only for their family but also for medical systems in general. Recently, using high-frequency ventilators have been shown to reduce the risk of lung injury through low-volume airflow. However, the machines used today remain bulky, costly, and only for use in hospital settings. To provide intermediate therapy for patients between hospitalization and complete discharge, a portable, light-weight high-frequency ventilator is an urgent need. This work presents the design of a portable high-frequency ventilator and a study of its practicality for further clinical medical applications. Through the integration of advanced electronics and mechanical instruments, we develop a portable high-frequency ventilator with reconfigurable oxygen flow rate, applied pressure, and air volume for the needs of individual patients. A miniaturized portable high-frequency ventilator with digital controller and feedback system for stabilization and precision control is implemented. The efficiency of CO_2 washout using the proposed ventilator has been demonstrated in animal trials.**

***Keywords*: high-frequency ventilator, integration, portable medical instruments**

I. Introduction

To improve the use of resources in intensive care units and reinforce quality in healthcare, there is a clear medical foundation for the utility of ventilators. For patients in ambulances or non-hospital environments, light and portable devices may be the best choice for treatment since using portable ventilators may better support homecare contexts by mitigating the heavy burden on patients and medical services. According to statistics, 5.7 million people suffer from irreversible lung injuries caused by inappropriate ventilator settings [1][2] and 2.2 million have lost their lives [3][4]. To avoid incorrect settings caused by human error and improve the efficiency of available ventilators, systems that can feedback current patient information to the ventilators are therefore urgently needed.

As one of the most common hospital instruments, ventilators are widely used to maintain sufficient oxygen for intubated patients or those suffering heart failure. Currently, there are many ventilation machines which can be categorized into three types according to method of operation: positive pressure, negative pressure, and high-frequency ventilators. Conventional positive and negative pressure ventilators are prevalent in medical facilities as they have similar frequencies and tidal volumes to natural respiration.



(a) (b)

Fig. 1. Airflows resulting from the use of (a) conventional ventilators and (b) high-frequency ventilators.

Although conventional ventilators help patients maintain respiration functionality, this is often accompanied by organ damage due to the large volume of the air injection [5][6][7]. For example, the use of positive pressure ventilators usually results in a higher airway pressure of about 30~40 cmH_2O. A larger tidal volume may lead to a higher peak inspiratory pressure (PIP) and cause chronic lung injury of patients undergoing long-term treatment. A common complication of ventilator-dependent patients is pulmonary barotrauma, which may engender cell degeneration in endothelial tissue, affect the cardiopulmonary system, and cause a degradation in air exchange efficiency in severe cases. Hence, this work proposes a portable high-frequency jet ventilator (HFJV) to avoid such injuries during long-term treatment while maintaining the functionality of conventional ventilators.

II. High-frequency jet ventilators

In contrast to conventional ventilators, high-frequency machines use a much higher jet frequency than a natural respiratory rate. The main advantage of this over a conventional positive pressure ventilator is the smaller tidal volume. By maintaining regulated inflation of the lung over a specific period, high-frequency ventilators can boost the air exchange volume using lower airway pressure. Moreover, the small injection volume can avoid lung injury from the use of ventilators and prevent both inappropriate airway pressure elevation and over inflation of the alveoli.

The most common difficulty for patients weaning from ventilators is the imbalance between mechanical ventilation and the patient's own respiratory system which can result in significant cardiopulmonary impact. Fig. 1(a) shows the airflow resulting from conventional ventilators: A balloon is used within the patient's airway to avoid air escaping directly. This balloon can cause discomfort for the patient.

High-frequency ventilators generate a specific airflow pattern in comparison to traditional systems. As input air flows deep in the lungs, its center moves faster due to friction at the tracheal wall, known as Taylor dispersion. The airflow close to the tracheal wall is therefore relatively slow, and the waste air flows out alongside it (Fig. 1(b)). Because of the high operating frequency and the airflow characteristics, the air exchange efficiency of high-frequency ventilators is higher than that of conventional systems. In addition, the small injection volume because of the high flow rate means that appropriate use of high-frequency ventilators can substantially eradicate patient dependency.

Another strength of the high-frequency ventilator over conventional machines is the practical convenience and comfort for patients. With a smaller injection volume, a thinner tube can be used to replace endotracheal tubes with tracheostomy tubes. Tracheostomy tubes not only enable patients to speak and to feed orally but also eradicate the use of the balloon in the throat which significantly reduces the unpleasant conditions of ventilator-dependent treatments. Moreover, among the various kinds of high-frequency ventilator, high-frequency jet ventilators (HFJVs) have a relatively smaller injection volume and a higher flow rate, resulting in lower average airway pressure, and the ventilator can be easily controlled.

Although much research has proved that high-frequency ventilators can decrease the airway pressure and thus minimize possible lung injury [8][9], most are mainly designed for infant healthcare and specific disorders, but adult applications are still limited. This work presents a portable high-frequency ventilator for adults in clinical scenarios such as first-aid in the emergency room, during transportation for an injury, and for patients whose hospital discharge is imminent but who still require respiration aid. By implementing advanced electronic and mechanical integration techniques, an adjustable ventilator that responds to embedded sensors is proposed.

III. Methods and Materials

Ventilators use two control mechanisms that are either volume or pressure limited. The volume-limited mechanism is based on controlling the inspiration volume. If the patient's pulmonary resistance is large or compliance is small, under the same tidal volume, the PIP enlarges and barotrauma may occur. The pressure-limited approach controls the PIP wherein, under the same pressure setting, the tidal volume varies according to the different conditions of each patient's lungs. To avoid the risk of triggering barotrauma, a pressure-limited mechanism was chosen in this design. The development of the proposed portable HFJV can be separated into two parts: the design of the ventilator system and the verification of its functionality.

A. Airflow Adjustment

Fig. 2 presents the schematic diagram of the proposed ventilator's architecture. The ventilator has adjustable controls for the flow rate, oxygen concentration, pressure, and injection volume using electronic valves and a control interface. The main components are the flow control valves, flow meters, check valves, a gas chamber, and a solenoid valve. The flow control valves are used to regulate the relative flow of air and oxygen to reach different mixture concentrations. The flow meters measure the air and oxygen flow rates and then derive the concentration of oxygen in the air mixture. The system employs automatic digital control, modifying the flow rate to the expected value.

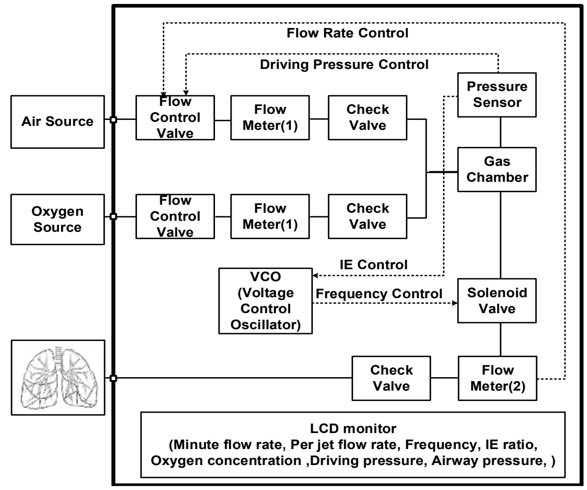


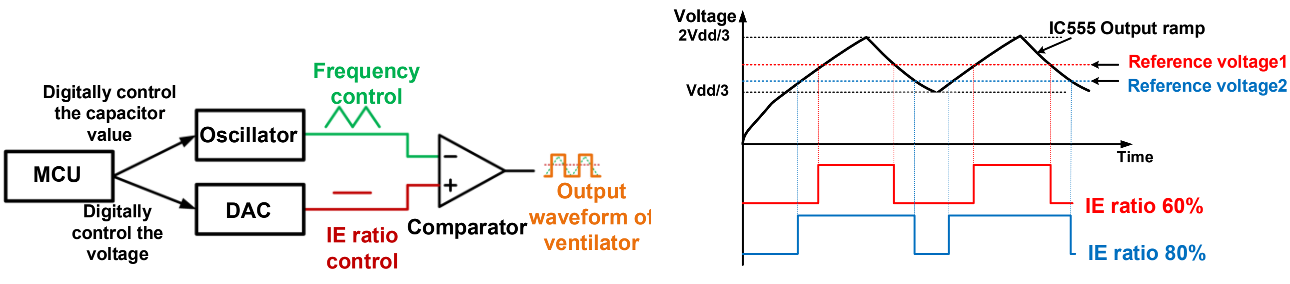
Fig. 2. The architecture of proposed HFJV.

The air and oxygen sources are directly connected in the clinic, and a fixed pressure of 50 psi is applied. To address the high pressure from the sources, the ventilator has a buffered air chamber in the first stage where pressure is monitored by flow meters and controlled by adjustable flow control. The mixed gas flows into the gas chamber to be blended. Finally, the mixed gas then passes through the solenoid valve to reach the output terminal of the ventilator. In a comparison between the oxygen concentration measured by the proposed ventilator and commercially available machines, the proposed HFJV performs with good linearity and accuracy in the clinically accepted range of 20%~100%. This demonstrates that control of oxygen concentration by this method is as precise as the existing concentration meters.

B. Pressure Feedback Technique

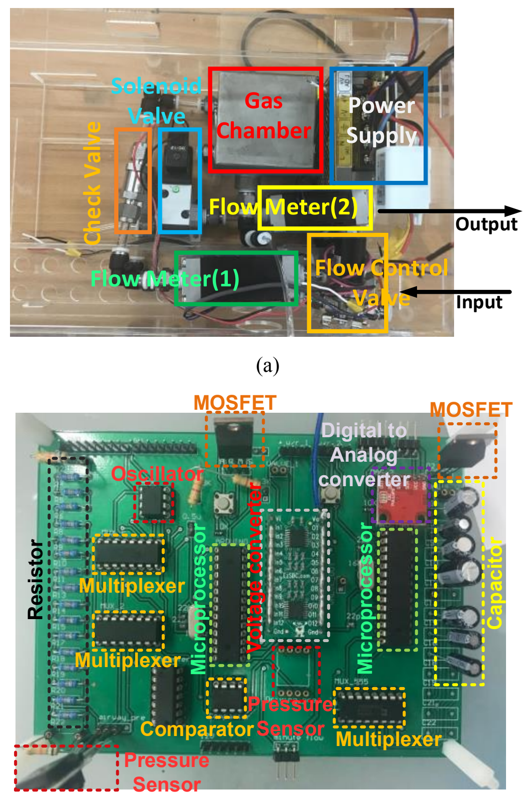
The parameters in a high-frequency ventilator system, including the driving pressure (DP), inspiration:expiration (I:E) ratio, output flow rate, and output frequency, dramatically affect the gas exchange efficiency of the lungs. The I:E ratio is defined as the ratio of the duration of the inspiratory phase to the duration of the expiratory phase. To introduce a stable and tunable DP, a pressure feedback control technique is implemented to dynamically adjust the air flow and I:E ratio for the required levels. This pressure feedback system consists of flow control valves, a gas chamber, a pressure sensor, and control circuits. When the volume and temperature of the gas chamber remain unchanged, the air pressure is proportional to the number of gas molecules. Therefore, the ventilator can reach the desired DP by accurate airflow control.

The pressure feedback system achieves optimal DP and output flow by implementing flow and pressure feedback. When the ventilator is initiated, the system compares the set



(a) (b)

Fig. 3. (a) Frequency control mechanism; (b) I:E ratio control by comparator.



(a)

(b)

Fig. 4. Proposed HFJV set up showing (a) the ventilator module and (b) the control circuit board.

and measured values instantly. If the measured value is smaller than the setting, the system sends feedback information to the flow control valves, raising the output flow. When the DP is insufficient, the system reduces the I:E ratio. In this mechanism, under the same output flow, the DP can be increased effectively. If oxygen concentration is insufficient, the system directly regulates the flow control valves, increasing the flow of pure oxygen. A programmed microcontroller adjusts these critical parameters of the ventilator.

C. Frequency Control

By utilizing a feedback mechanism and the consequent adjustment of parameters, the proposed HFJV can efficiently and precisely attain required levels. In addition, the ventilator includes a frequency control block composed of an oscillator, microprocessor, digital-to-analog converter (DAC), and comparator (Fig. 3(a)). A switchable capacitor array was used to reach a constant injection frequency in the range of 1–4 Hz. By creating a reference voltage with the DAC and comparing the output ramp from an oscillator with the adjustable reference voltage, an adjustable I:E ratio in the range of 10%~70% can be realized. Fig. 3(b) presents the waveforms of the controllable I:E ratio. The ramps are the charging and discharging curves of the switchable capacitor in the oscillator. A different I:E ratio is achieved through comparison of different reference and ramp voltages. When the capacitor is changed, the time ratio of the voltage being higher than the reference voltage over the whole period will remain the same. Hence, controlling the I:E ratio is independent of frequency.

IV. Results and Discussion

Fig. 4 presents details of the proposed HFJV set up and control circuit board. To verify the system's functionality and the effects on air exchange efficiency, animal experiments were performed at Mackay Memorial Hospital Animal Laboratory, Damsui, Taiwan with six pigs (Landrace) with an average weight of 36 kg.

The first experiment aimed to validate the effect of adjusting DP on air exchange efficiency under the same flow rate and frequency conditions. The air exchange rate of the subjects was lowered to mimic oxygen deficiency. The oxygen concentration of the ventilating system was set to room air (FiO_2 at 20% of O_2), and the frequency applied was 2 Hz, 3 Hz, and, 4 Hz. To maintain a flow rate of 14.4 L/min, the I:E ratio was adjusted according to differences in frequency and DP.

Fig. 5 (a, b) illustrates the average concentration of arterial carbon dioxide ($PaCO_2$) and oxygen (PaO_2) in the blood of the subjects. The initial values of $PaCO_2$ and PaO_2 are 62.5 mmHg and 61.6 mmHg, respectively. It can be observed that when DP increases, and the jetting and air exchange rates rise, $PaCO_2$ decreases and PaO_2 increases.

The second experiment was designed to verify the effect of the proposed HFJV on oxygenation in acute respiratory distress syndrome (ARDS). Before the experiment, subjects were injected with oleic acid to initiate ARDS. When PaO_2 concentration drops below 60 mmHg, the HFJV starts to assist air exchange. The ventilator was initially set at an injection

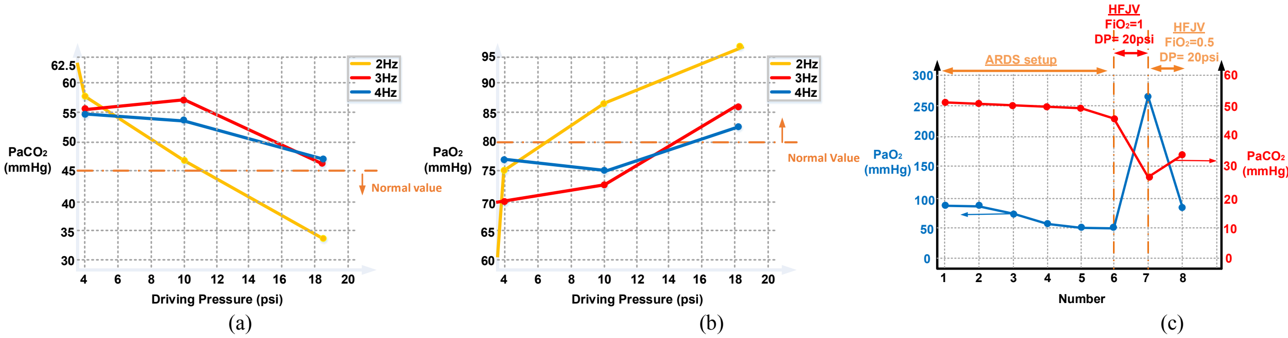


Fig. 5. Under different operating frequencies, (a) $PaCO_2$ concentration decreases and (b) PaO_2 concentration increases with changes in DP, and (c)changes to $PaCO_2$ and PaO_2 concentrations in ARDS as affected by the HFJV.

frequency of 2 Hz, a tidal volume of 3 mL/kg, FiO_2 of 1.0, and a DP of 20 psi. The experimental results indicate that oxygenation was boosted from 50 mmHg to 260 mmHg after HFJV use, and also that $PaCO_2$ concentration declined. Moreover, FiO_2 was reduced to 0.5 which further decreases the $PaCO_2$. Both experiments validate that the HFJV could effectively improve patients' air exchange rates.

V. Conclusion

The proposed system achieves a tunable DP range of 5~45 psi, an I:E ratio of 10~70%, oxygen concentration of 20%~100%, and a flow rate of 0~40 L/min. All parameters are displayed on an LCD monitor and controlled from a computer interface. The proposed ventilator has a compact size of 20 x 15 x 17 cm^3 which is much smaller than existing HFJVs, and the experimental results suggest the robustness and effectiveness of the proposed system. With its portable design, configurable features, and instant feedback control, this HFJV could be employed in clinical as well as non-hospital settings including ambulance and home healthcare, making the medical treatment more convenient.

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TABLE I.
Specification of Proposed Ventilator

Specification	value
Flow per minute	0~40 (L/min)
Flow per once	0~160 (mL)
Output Frquency	2~4 (Hz)
Oxygen/Air ratio	20~100 (%)
I:E ratio	10~70 (%)
Tunable parameters	Oxygen concentration, Gas chamber pressure, I:E ratio, Output frequency
Parameters shown on monitor	Flow per minute, Flow per once, Oxygen concentration, Front-end pressure, airway pressure, Gas chamber pressure, I:E ratio, Output frequency

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