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RESEARCH ARTICLE

A Multivent System for Non-Invasive Ventilation: Solving the Problem of Ventilator Shortage During the COVID-19 Pandemic

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ABSTRACT The COVID-19 pandemic has caused a severe global problem of ventilator shortage. Placing multiple patients on a single ventilator (ventilator sharing) or dual patient ventilation has been proposed and conducted to increase the cure efficiency for ventilated patients. However, the ventilator-sharing method needs to use the same ventilator settings for all the patients, which cannot meet the ventilation needs of different patients. Therefore, a novel multivent system for non-invasive ventilation has been proposed in this study. The close loop system consists of the proportional valve and the flow-pressure sensor can regulate the airway pressure and flow for each patient. Multiple ventilation circuits can be combined in parallel to simultaneously meet patients' ventilation demands. Meanwhile, the mathematical model of the multivent system is established and validated through experiments. The experiments for different inspired positive airway pressure (IPAP), expired positive airway pressure (EPAP), inspiratory expiratory ratio (I:E), and breath per minute (BPM) have been conducted and analyzed to test the performance of the multivent system. The results show that the multivent system can realize the biphasic positive airway pressure (BIPAP) ventilation mode in non-invasive ventilation without interfering among the three ventilation circuits, no matter the change of IPAP, EPAP, I:E, and BPM. However, pressure fluctuation exists during the ventilation process because of the exhaust valve effect, especially in EPAP control. The control accuracy and stability need to be improved. Nevertheless, the novel designed multivent system can bring innovation to the current mechanical ventilation system and solve the problem of ventilator shortage for major, new, and emerging respiratory infectious diseases in the future.

INDEX TERMS Mechanical ventilation, multivent system, pneumatic system, proportional control.

I. INTRODUCTION

The novel coronavirus has spread to more than 200 countries and regions, with more than 440 million confirmed cases and a mortality rate of 49% for high-risk patients [1], [2]. Mechanical ventilation is an essential medical method that uses ventilators to assist patients in breathing and maintain patients' airway patency and oxygenation. In particular, the patients infected with COVID-19 need the support and treatment of the ventilator to maintain the gas exchange capacity and blood oxygen saturation [3].

The COVID-19 pandemic has caused a severe global problem of the shortage of ventilators. Due to the limitation of the current ventilator driving mode, a single ventilator can only be used by one patient. Many patients with acute respiratory distress syndrome (ARDS) caused by COVID-19 died from not receiving timely respiratory support treatment. Therefore, placing multiple patients on a single ventilator

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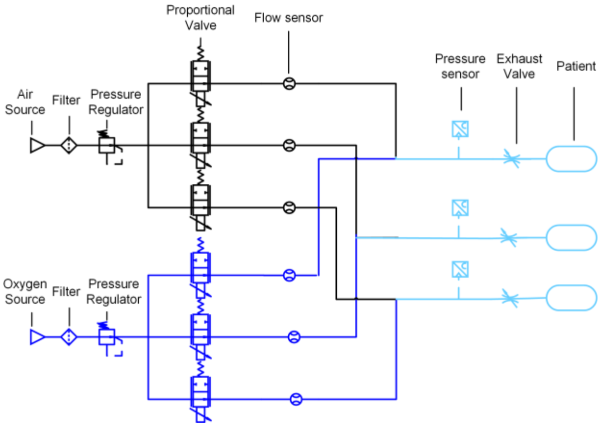

FIGURE 1. **The structure of the multivent system for non-invasive ventilation.**

(ventilator sharing) has become a research direction to solve the ventilator shortage problem.

Modern ventilators often use compressors or blowers to supply air and oxygen. In invasive ventilation, inspiratory and expiratory tubes are separated. While in non-invasive ventilation, only one tube is used, and the expired air is exhausted from the exhaust valve. The splitters separate the inspiratory air of two patients and converge the expiratory air to the ventilator for multiple patients on a single ventilator. Meanwhile, the one-way valve, positive end-expiratory pressure (PEEP) valve and flow restrictors were also used to regulate the airflow for each patient. Plummer et al. [4] and Plummer et al. [5] proposed splitting ventilation tubes from one ventilator. During the COVID-19 pandemic, many researchers have conducted theoretical and experimental research on this system. Plummer et al. [4], [5] proposed a method for identifying the respiratory mechanical parameters of patients with multiple ventilator users and adjusting the ventilator setting parameters according to the identification of respiratory mechanical parameters. Martinsen et al. [6] conducted a technical evaluation of sharing one ventilator for multiple people. The results show that the tidal volume significantly varies for patients with different compliance. Silva et al. [7] proposed a concept of a three-way valve for multiple people to share a ventilator. Both pressure transducers and controllers would be used for monitoring each patient under the same ventilator. Roy et al. [8] reviewed the literature on the mechanics and implications of inline PEEP valves. The results show that the adjustable inline PEEP valves in ventilation circuits for multiple patients using one ventilator have not been achieved. Bunting et al. [9] designed an inline PEEP valve by adding a collar to a conventional PEEP valve.

The clinic results demonstrated the feasibility of multiple ventilation using one ventilator. Stiers et al. [10]successfully used the split ventilator system in a pair of ventilated sheep with different lung compliance. Levin et al. [11] evaluated the split ventilator system on patients with COVID-19. Clarke et al. [12] analyzed the effect and possibility of the split ventilator method on different targets for limbs. The experiment results demonstrated that this method could simultaneously ventilate two test lungs with different compliances. Meanwhile, Dual Patient Ventilation (DPV) method has been introduced [13], [14], [15], [16], [17]. This method needs to assess patient compatibility first and select the patients with similar compliance, resistance, needs of airway pressure, tidal volume, or other ventilator settings and respiratory system mechanics.

Although sharing a ventilator or DPV could improve ventilator efficiency, it must use the same ventilator setting for all patients. This method not only cannot meet the ventilation needs of different patients but also brings the risk of hyperventilation or hypoventilation [18], [19]. Some researchers and clinicians noted that sharing a ventilator or DPV brings too much risk and difficulty to patients and medical staff. Moreover, they would not recommend these methods for patients with COVID-19 [20], [21], [22].

To our knowledge, there are no methods to overcome the problems of split ventilators or DPVs. Therefore, we proposed a novel mechanical ventilation system for the different needs of multiple patients in this study. The whole system is built based on the pneumatic system. The group of proportional valves was used to regulate each patient's airway pressure and flow. Because of the function of the proportional valve, each patient can be ventilated individually. The ventilation settings can match the needs of each patient. Only the non-invasive ventilation function of this system is presented in this study. The invasive ventilation experiments are undergoing now. We believe this multivent system would help solve the problem of ventilators shortage during the COVID-19 pandemic. Besides, this system may innovate the current mechanical ventilation system.

II. METHODS

A. THE MULTIVENT SYSTEM FOR NON-INVASIVE VENTILATION

The structure of the multivent system for non-invasive ventilation proposed in this study is presented in Figure. 1. The air source and oxygen source from the compressed air and oxygen central stations supply the compressed air and high-pressure oxygen, respectively. The filters conduct the impurity filtration of compressed air and oxygen. Then the pressure is regulated through the pressure regulators to meet the use conditions of the pneumatic proportional valves. The proportional valve and flow sensor form a closed-loop control. The oxygen concentration and flow of air oxygen mixing can be adjusted through the proportional valves.

Moreover, the pressure sensor is used to measure the output pressure of the system. Besides, combined with the proportion valves, the output pressure can be adjusted according to the demand of patients. As for non-invasive ventilation, only one tube is used for inspiration and expiration. The exhaust valves have connected the patients and tubes in series.

Two proportional valves, two flow sensors, one pressure sensor, and one exhaust valve can be combined as a ventilation module. Each module could be used for the ventilation of

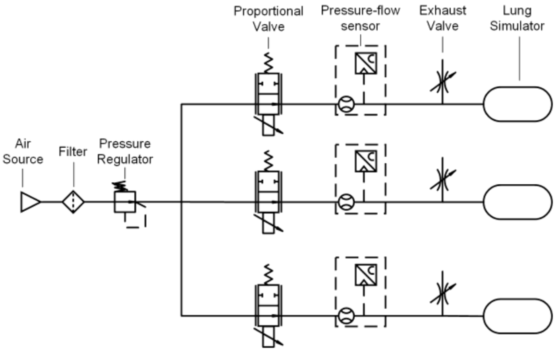

FIGURE 2. **The diagram of the multivent system used in this study.**

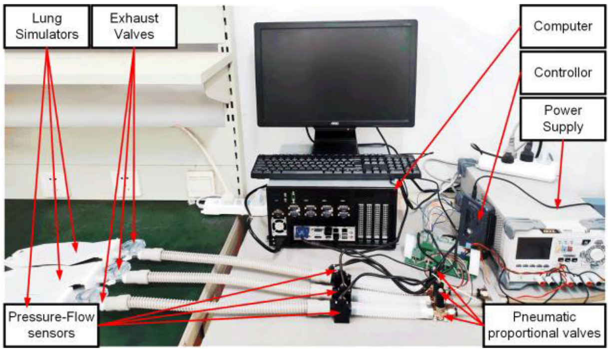

FIGURE 3. **The experimental system of the multivent system for non-invasive ventilation.**

a single patient. The distributed mode can connect more modules to the compressed air and oxygen pipe network. Because of the control characteristics of a proportional valve, each module can be controlled individually. The pressure control ventilation (PCV), pressure support ventilation (PSV), or volume control ventilation (VCV) modes can be achieved by the closed-loop control of proportional valves. The ventilation parameters like pressure, tidal volume, or respiratory rate are set according to the demand of each patient. Moreover, there is no interference between patients.

B. MATHEMATICAL MODEL OF THE MUTIVENT SYSTEM

Since the pressure change is pretty tiny in the lungs during the respiratory process, the inspiration and expiration process can be considered an isothermal process. The pressure can be derived from the air state equation (PV=mRT) [23], [24], [25].

$$\frac{\mathrm{d}p_l}{\mathrm{dt}} = \frac{\mathrm{d}(mR\theta)}{\mathrm{dt}} = \frac{R\theta q V_l}{V_l^2 + CmR\theta} \tag{1}$$

where p_l is the pressure in the lungs. R and θ are the gas constant value and air temperature, respectively. Q_{l} and V_{l} are the air mass flow rate and air volume in the lungs. m represents the air mass in the lungs. C is respiratory compliance which reflects lung elasticity. The compliance C can be expressed as:

$$C = \frac{\mathrm{d}V_l}{\mathrm{d}p_l} \tag{2}$$

According to ISO6358 [26], [27], the mass flow rate through the proportional valve and exhaust valve can be calculated through the equations below.

$$q = Sp_u\frac{\phi}{\sqrt{\theta}}$$
$$\phi = \begin{cases} \sqrt{\frac{k}{R}(\frac{2}{k+1})^{\frac{k+1}{k-1}}} & \frac{p_d}{p_u} \le 0.528 \\ \sqrt{\frac{2k}{k-1}\frac{1}{R}\left[\left(\frac{p_d}{p_u}\right)^{\frac{2}{k}} - \left(\frac{p_d}{p_u}\right)^{\frac{k+1}{k}}\right]} & \frac{p_d}{p_u} > 0.528 \end{cases} \tag{3}$$

where q is the mass flow rate, and S is the effective area. p_u and p_d represent upstream and downstream pressure, respectively. k is the specific heat value of air. R and T are the gas constant value and air temperature, respectively.

Specifically, the regulator regulates the inlet pressure of the proportional valve pin, which is mostly higher than 200 kPa (absolute pressure). Meanwhile, the outlet pressure of the proportional valve can be regarded as the same as p_l. During mechanical ventilation, the p_l is less than 40 cmH$_2$O, so the p_l/p_{in} is always smaller than 0.528. Therefore, the mass flow rate through a proportional valve can be expressed as:

$$q_p = S_p p_{in}\sqrt{\frac{k}{R\theta}(\frac{2}{k+1})^{\frac{k+1}{k-1}}} \tag{4}$$

where S_p is the effective area of the proportional valve, which can be adjusted proportionally by the current.

The air flows from the lungs to the exhaust valve during exhalation. The outlet pressure of the exhaust valve is equal to the atmospheric pressure p_a, which is 100 kPa (absolute pressure). The p_a/p_l is always bigger than 0.528. Therefore, the mass flow rate through the exhaust valve can be expressed as:

$$q_e = S_e p_l\sqrt{\frac{2k}{k-1}\frac{1}{R\theta}\left[\left(\frac{p_a}{p_l}\right)^{\frac{2}{k}} - \left(\frac{p_a}{p_l}\right)^{\frac{k+1}{k}}\right]} \tag{5}$$

C. THE EXPERIMENT SETUP OF THE MULTIVENT SYSTEM

Because of the adverse impact of COVID-19, the oxygen source is unavailable in this study. Only the air source was used in the experimental study. The diagram of the experiment system is shown in Figures. 2 and 3. Meanwhile, the pressure-flow sensor (FS6122, Siargo Ltd, Sampling frequency:200 Hz) measured the airflow and pressure signals. Three pneumatic proportional valves (PVQ31, SMC Ltd) adjust the airflow. Three exhaust valves (Philip Respironics INC) were used for exhalation. The pressure regulator (AR20, SMC Ltd) regulates the inlet pressure of proportional valves. Three lung simulators are used as the patient's lungs. The accuracy of the sensor and valves are presented in Table 1. The controller is the NI my RIO (NI myRIO-1900, National Instruments Ltd). The computer (IPC-5120, Advantech Ltd)

TABLE 1. **The detailed information of the instruments used in this study.**

Instrument	Accuracy
Proportional valve	Less than 3 %F.S
Pressure regulator	Less than ±1 %F.S
Pressure-flow sensor	Flow:±(2.5+0.5 %F.S) Pressure:±1.0 %F.S

TABLE 2. **The coefficients and constant values of mathematical models.**

Parameter	Value
p_a	100 kPa
C	20 ml/cmH$_2$O
θ	293.15 K
R	287 J/(kg·K)
k	1.4
S_p	2.5 mm^2
S_e	10.8 mm^2
T_p	0.01
T_e	0.03

monitors and collects data. The whole experimental system is presented in Figure. 3.

This study uses the biphasic positive airway pressure (BIPAP) mode for ventilation. The proportional integral derivative (PID) control strategy is adopted in this study. The control method can be expressed as follows:

$$u = k_p \cdot e(t) + k_i \cdot \int e(t) \cdot \mathrm{d}t + k_d \frac{\mathrm{d}e(t)}{\mathrm{d}t} \tag{6}$$

k_p, k_i, and k_d are the coefficients of the PID controller, which are 1.025, 0,002, and 0.015 in this study. $e(t)$ is the error between the output and setting value. u is the control value.

The proportional and exhaust valves can be considered as the one-order delay elements [28]. The transfer function of proportional and exhaust valves can be expressed as:

$$G(s) = \frac{S}{Ts + 1} \tag{7}$$

where S and T are the effective area of the valve and time constant, respectively.

III. RESULTS AND DISCUSSIONS

A. MODEL VALIDATION

The coefficients and constant values for mathematical models are calculated through experiments or manuals and presented in Table 2. The effective areas and time constants for the proportional and exhaust valves are defined as S_p, T_p, S_e, and T_e, respectively. The experimental setting parameters like inspired positive airway pressure (IPAP), expired positive airway pressure (EPAP), inspiratory expiratory ratio (I:E), and breath per minute (BPM) for model validation are shown in Table 3. The Matlab Simulink is used for model simulation. The time step is 0.01 s, the same as the experimental control period. The simulation and experimental results are presented in Figure. 4. The experimental video is supplied in Supplementary materials A. A total of five periods are adopted for both simulation and experiments.

TABLE 3. **The experimental setting parameters.**

Parameter	Value
IPAP	20 cmH$_2$O
EPAP	5 cmH$_2$O
I:E	1:1
BPM	15

It can be seen from Figure. 4 that the simulation curve is consistent with the experimental curve, which validates the accuracy of the mathematical model. According to Figure. 4(a), the error of IPAP between simulation and experiment is within 5%. However, as for the EPAP, the error varies from 0 to 20% during the expiration process, which is worse than the IPAP in the inspiration process. The reason is that the pressure control needs to be more precise and accurate when the airflow is small, which occurs in the EPAP control process. The slight change in the proportional valve output may result in a significant pressure fluctuation. Although the airflow is not concerned in BIPAP mode, we still compare the airflow results and show them in Figure. 4(b). Because the exhaust valve remains open during the inspiration and expiration, it brings disturbance, which is evident in the ventilation process's simulation and experimental curves. Meanwhile, the disturbance frequency in the experimental curve is much smaller than in the simulation curve. The reason is that the simulation study does not consider air mass and tube compliance. These two factors may significantly reduce the disturbance frequency. Besides, the influence of the exhaust valve may result in difficulties in pressure control, especially in EPAP control.

B. THE MULTIVENT SYSTEM PERFORMANCE UNDER DIFFERENT IPAP

In order to test the performance of the multivent system under different IPAP settings, the experiments have been conducted in different IPAP settings for three circuits. The experimental parameters settings are presented in Table 4. The results in six periods are shown in Figure. 5. The experimental video is supplied in Supplementary materials B. Figure 5 shows that the multivent system can realize the BIPAP ventilation mode. There is no interference among the three ventilation circuits. However, similar to Figure. 4, the control effect of

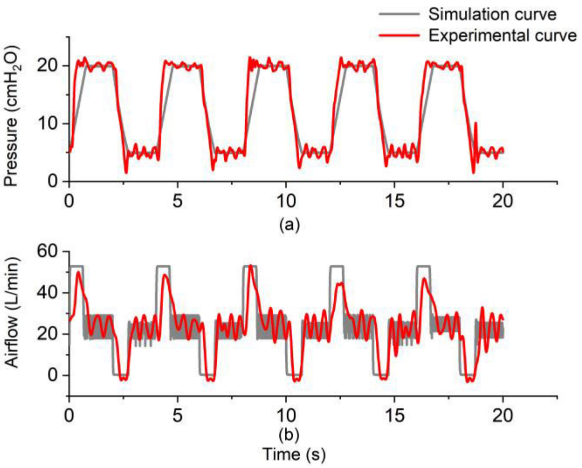

FIGURE 4. The simulation and experimental results of the multivent system (a). Airway pressure curves in five ventilation periods (b). Airflow curves in five ventilation periods.

EPAP is worse than IPAP, which is caused by the influence of the exhaust valve and the performance of the proportional valve. Besides, the control error of EPAP increases with the IPAP increasing. The maximum control error of EPAP reaches 40% when IPAP is 30 cmH_2O. The high pressure in the lungs may cause high airflow through the exhaust valve in expiration, which increases the control difficulty in pressure compensation of EPAP.

Meanwhile, more air is supplied to the lungs for higher IPAP, which needs more time for expiration. The exhalation may become incomplete under the same I: E and BPM, as seen in Figure. 5(c). It is a common problem for ventilated patients, requiring automatically adjusting ventilation parameters.

C. THE MULTIVENT SYSTEM PERFORMANCE UNDER DIFFERENT EPAP

Similar to the previous experiments, the multivent system performance under different EPAP settings has been analyzed. The experimental parameters settings for three different EPAPs (0, 2.5, and 5 cmH_2O) are presented in Table 5. The airway pressure for three ventilation circuits is shown in Figure. 6. According to Figure. 6(a), the control error of EPAP is pretty tiny when the EPAP is 0 cmH_2O. The reason is that the proportional valve remains closed during expiration, ensuring that the airway pressure can change to zero. As for Figures. 6(b) and (c), an obvious control error exists for EPAPs. When the EPAP is set to 2.5 cmH_2O, the airway pressure presents a low-frequency oscillation in the expiration process. The errors vary from 0 to 20%. However, the airway pressure shows a higher frequency oscillation in expiration when the EPAP is 5 cmH_2O than when the EPAP is 2.5 cmH_2O. Relatively, the maximum control error is about 20%. The performance of the proportional valve causes these phenomena. The hysteresis characteristics of the proportional valve are apparent when the flow is low.

TABLE 4. The experimental setting parameters for different IPAP in three circuits.

Paramet er	Circuit 1	Circuit 2	Circuit 3
IPAP	20 cmH_2O	25 cmH_2O	30 cmH_2O
EPAP	5 cmH_2O	5 cmH_2O	5 cmH_2O
I:E	1:1	1:1	1:1
BPM	15	15	15

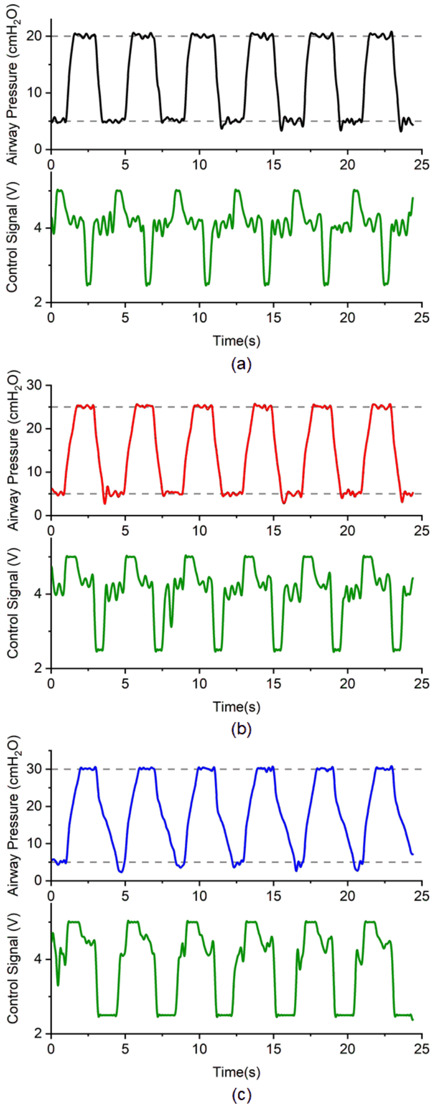

FIGURE 5. The airway pressure of multivent system for different IPAP (a). Circuit 1 (IPAP=20 cmH_2O) (b). Circuit 2 (IPAP=25 cmH_2O) (c). Circuit 3 (IPAP=30 cmH_2O).

D. THE MULTIVENT SYSTEM PERFORMANCE UNDER DIFFERENT IPAP, I:E, AND BPM

The experiments for different IPAP, I:E, and BPM in three ventilation circuits have also been conducted. The parameter settings and airway pressure are presented in Table 6 and Figure. 7, respectively. The experimental video is supplied

TABLE 5. The experimental setting parameters for different EPAP in three circuits.

Parameter	Circuit 1	Circuit2	Circuit 3
IPAP	20 cmH_2O	20 cmH_2O	20 cmH_2O
EPAP	0 cmH_2O	2.5 cmH_2O	5 cmH_2O
I:E	1:1	1:1	1:1
BPM	15	15	15

TABLE 6. The experimental setting parameters for different IPAP, I:E, and BPM in three circuits.

Parameter	Circuit 1	Circuit 2	Circuit 3
IPAP	20 cmH_2O	25 cmH_2O	30 cmH_2O
EPAP	5 cmH_2O	5 cmH_2O	5 cmH_2O
I:E	1:1	1:2	2:3
BPM	15	20	12

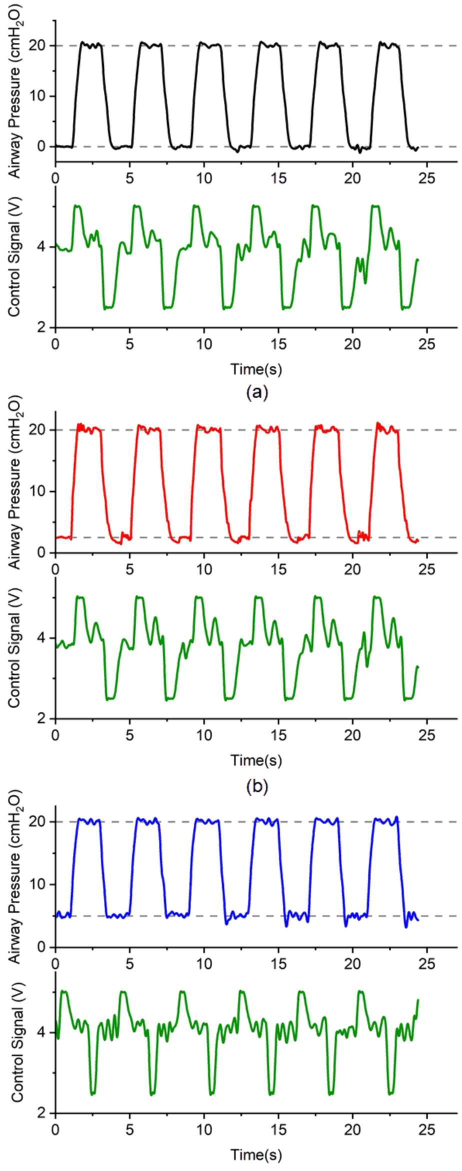

FIGURE 6. The airway pressure of multivent system for different EPAP (a). Circuit 1 (EPAP=0 cmH_2O) (b). Circuit 2 (EPAP=2.5 cmH_2O) (c). Circuit 3 (EPAP=5 cmH_2O).

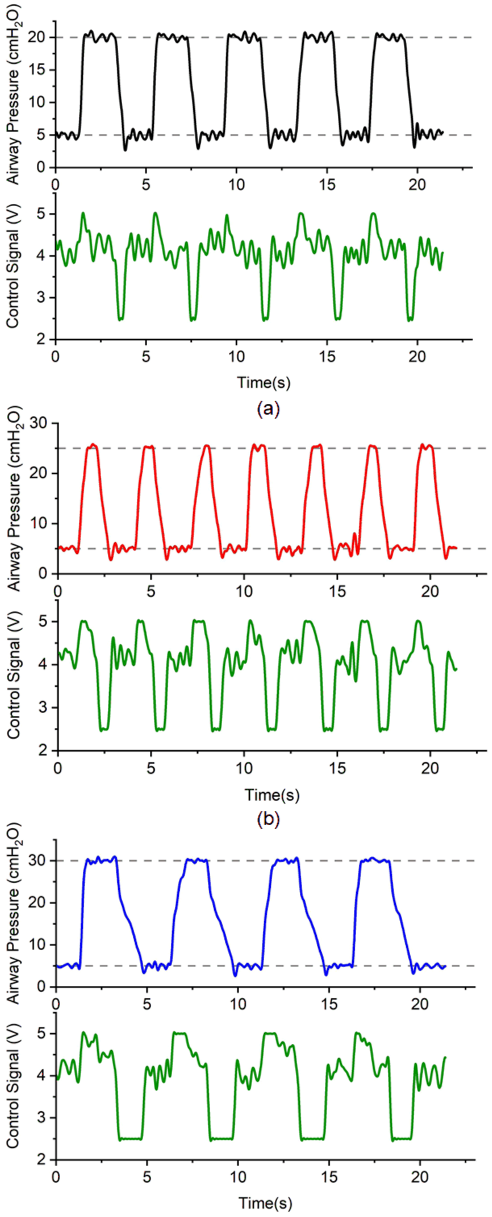

FIGURE 7. The airway pressure of multivent system for different IPAP, I:E, and BPM (a). Circuit 1 (b). Circuit 2 (c). Circuit 3.

in Supplementary materials C. The video and Figure. 7 shows that the three ventilation circuits can work independently under different IPAP, I:E, and BPM. Similar to Figures 4, 5, and 6, the pressure fluctuations are evident in the expiration processes. As Figure. 7(b), insufficient inhalation exists when the I:E is 1:1. It indicates that the 1-second inspiration for 20 ml/cmH_2O lung compliance is not enough. Besides, compared with Figure. 5(c), as shown in Figure,

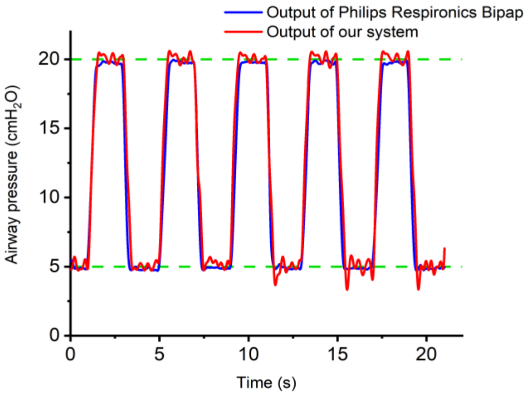

FIGURE 8. **The comparison of airway pressure for Philip BIPAP ventilator and the multivent system.**

incomplete exhalation is relieved by increasing the exhalation time. 7(c).

E. THE PERFORMANCE COMPARISON WITH PHILIP BIPAP VENTILATOR

In order to test the performance of the multivent system, the Philip BIPAP ventilator (Philip Respironics INC) is used for comparison. The airway pressure curves of the Philip BIPAP ventilator and the multivent system are presented in Figure. 8. The parameter settings are the same as in Table 2. Five periods of ventilation are shown in Figure. 8. It can be seen that the fluctuations of the Philip BIPAP ventilator are much lower than that of the multivent system. The reason is that the drive methods for BIPAP ventilators and multivent systems are different. The blower is adopted for air supply in BIPAP ventilators. The output pressure can be easily adjusted by changing the electric motor's input current and is nearly affected by loads like exhaust valves and lungs. Differently, the output pressure of the multivent system is adjusted by changing the effective area of proportional valves. The upstream and downstream loads, like the exhaust valve and lungs, affect the output pressure. Therefore, the airway pressure of the multivent system is more difficultly controlled than that of the BIPAP ventilator. Besides, the proportional valve response is quicker than the blower because of the structural differences. So the pressure rise time for the multivent system is shorter than the BIPAP ventilator.

Although only three lung simulators were used and validated in this study, the multivent system proposed in this study can realize ventilation for more patients depending on the air supply system's capacity. Each patient can be ventilated individually, and ventilation settings can match each patient's needs. Nevertheless, the control performance still needs to be improved. The PID control method, which is based on the error between the set value and the output value, is used in this study. The coefficients like k_p, k_i, and k_d remain constant during the control period, which may result in control error and fluctuation, especially in the EPAP control process. Precise control is necessary when the error between the set and output values tends to be small. Therefore, more advanced algorithms like fuzzy PID control, model reference control (MRC), or active disturbance rejection control (ADRC) are needed to improve the multivent system's performance, which is our future study.

IV. CONCLUSION

This study proposes a novel mechanical ventilation system named Multivent system for non-invasive ventilated patients. The mathematical model of the multivent system is established and validated through experiments. Besides, in order to test the performance of the multivent system, experiments under different IPAP, EPAP, I:E, and BPM in three ventilation circuits have been conducted and analyzed. The experimental results show that the multivent system can realize the BIPAP ventilation mode in non-invasive ventilation. Each ventilation circuit can work individually. The ventilation settings can match the needs of each patient. Finally, the popular Philip BIPAP ventilator is used for the comparative study. The results also demonstrate the excellent performance of the multivent system proposed in this study.

However, the pressure control performance in current research using the PID control method is not good enough. More advanced algorithms like fuzzy PID control, MRC, or ADRC are necessary for precise pressure control of the multivent system, which is our future study. Besides, the performance of the multivent system on different respiratory characteristics needs to be tested. Only the non-invasive ventilation function of this system is presented in this study. At the same time, invasive ventilation experiments are still undergoing now.

Nevertheless, the novel designed multivent system can bring innovation to the current mechanical ventilation system and solve the problem of ventilator shortage for major, new, and emerging respiratory infectious diseases in the future.

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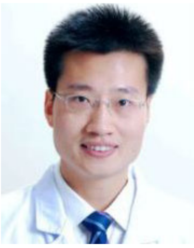

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