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Working characteristics of a new ventilator with automatic secretion clearance function

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Secretions in the airways of ventilated patients must be cleared efficiently and timely. A novel ventilator (SC ventilator) is proposed with an automatic secretion clearance function in order to provide a new approach. A mathematical model of a ventilation system with the SC ventilator is set up to optimize the SC ventilator. Based on the research, conclusion can be reached as follows. First, the experimental results and the mathematical model are proved to be authentic and reliable. Second, the secretion clearance efficiency of the SC ventilator may be higher than that of IL-IE device. Finally, increasing the inspiratory positive airway pressure or decreasing the expiatory positive airway pressure of the SC ventilator can improve the efficiency of the secretion clearance. This paper lays a foundation for the secretion clearance improvement of the SC ventilator.

mechanical ventilation, pneumatic system, secretion clearance, modeling simulation, experimental study

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1 Introduction

Mechanical ventilation is a vital treatment, which is usually adopted to ventilate patients who cannot breathe adequately on their own [1–3]. Due to the establishment of an artificial airway, the physiologic function of the ventilated patient's epiglottis may be weakened or even lost. However, the high pressure of the airway, which is utilized for cough, cannot be generated, which seriously blocks cough [4–6]. Furthermore, an artificial airway may accelerate the secretion of the lung, and restrain cilium movements [7,8]. In addition, because of the use of sedatives and muscle relaxants, expectoration capacity of ventilated patients will be further declined and even lost [9–11].

Deposition of secretion in patients' airway can cause increases in the airway resistance, hypoventilation, and respiratory failure, and aggravate the patients' hypoxia and carbon dioxide retention [12]. Moreover, a secretion blocking airway may easily lead to reproduction of bacteria, which may cause the occurrence or aggravation of pulmonary infection [13–16]. Lastly, effective secretion clearance has a good effect on the prevention of ventilator associated pneumonia (VAP), which is a common complication of mechanical ventilation. The incidence rate of the VAP is up to 68%, and the mortality rate of the VAP is 50%–70% [17–19].

Therefore, in order to prevent pulmonary infection, and save ventilated patients' life, secretions must be cleared efficiently and timely [20,21].

So far, some MIE devices are applied clinically [22,23]. One is CoughAssist, which is rarely used in the ICU. Another MIE device is called IL-IE device. Through clinical application, it was proved that the IL-IE device can clear secretion and reduce the risk of VAP [22]. However, be-

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*Corresponding author (email: niujinglong723@163.com) cause of the lack of communication with the ventilator, the IL-IE device has negative effects on mechanical ventilation treatments and threatens the patient's life [22]. In addition, the efficiency of the IL-IE device is restricted by the tidal volume of patients, which is set during normal mechanical ventilation treatment.

To improve the efficiency and safety of secretion clearance, a new ventilator with automatic secretion clearance function is proposed in this paper. The new ventilator, which is named SC ventilator, can automatically identify the respiratory mechanic characteristics on line, and judge when to clear secretions in the ventilated patient. When secretion should be cleared, the output pressure of the SC ventilator is automatically adjusted to ensure a high efficiency of secretion clearance.

To confirm that the secretion clearance efficiency of the SC ventilator is higher than that of IL-IE device and lay a foundation for the optimization of the SC ventilator, a mathematical model of the SC ventilation system is set up.

Moreover, to verify the mathematical model and avoid injury to real lungs, a prototype SC ventilation system of a lung simulator is proposed. On the basis of experimental and simulation study on the prototype system, its dynamic characteristics can be obtained and analyzed.

Last, the influences of pressure settings of the SC ventilator on the pressure dynamic characteristics are studied.

2 Introduction of the SC ventilation system

2.1 The SC ventilator

As shown in Figure 1, the SC ventilator comprises a controller, an input unit, a monitor, a ventilation unit, a suction unit, an atomization unit, a solenoid valve, a flow sensor and a pressure sensor.

The ventilation unit can be considered as a ventilator, and its working is controlled by the controller. The function of the suction unit is to suck air from patients' lungs (as an IL-IE device), and its working is also controlled by the controller too [24].

The parameters of the SC ventilator can be set by the input unit, and the working states and parameters are displayed on the monitor.

The dynamics of the mechanical ventilation system (including a ventilator, a tube and a patient) is monitored with the pressure sensor and the flow sensor.

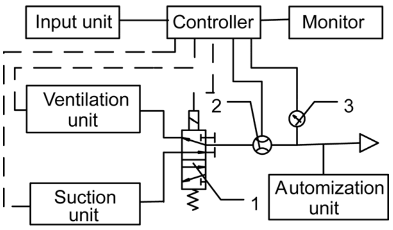

Figure 1 Structure of the SC ventilator. 1, Solenoid valve; 2, flow sensor; 3, pressure sensor.

A special algorithm is used to estimate the time to clear secretions, according to the respiratory mechanic characteristics (such respiratory compliance, resistance).

The working process of the SC ventilator consists of two processes. i.e. secretion clearance process (or called suction process) and mechanical ventilation process. During the mechanical ventilation process, the solenoid valve is controlled to connect the ventilation circuit and break the suction circuit, and the patient is ventilated by the SC ventilator.

When the secretion should be cleared, ipap of the SC ventilator is set higher and/or epap of the SC ventilator is set lower automatically. After a deep inspiration, the ventilation circuit is broken and the suction circuit is connected through the solenoid valve, the air in the patient's lungs is rapidly sucked, and the airflow is controlled by the controller. After the suction process, the suction circuit is broken and the ventilation circuit is connected, and then the patient is sequentially ventilated.

Unlike an IL-IE device, the SC ventilator is controlled by a controller to avoid a negative impact of secretion clearance on the mechanical ventilation and the patient's safety. Therefore, secretion clearance of the SC ventilator may be more efficient than the IL-IE device.

2.2 The SC ventilation system

A simplified mechanical ventilation system, as illustrated in Figure 2(a), consists of a human lung, a respiratory airway, a flexible tube and an SV ventilator. In this study, the atomization unit is neglected.

According to the working principle of the SC ventilator, the ventilation unit and the suction unit can be considered as an air compressor and a vacuum pump, respectively.

In this simplified system, the total respiratory resistance results from friction loss of the flexible tube and the respiratory system (including respiratory airway and lungs). Therefore, the flexible tube and the respiratory system can be equivalent to two combinations of a throttle and a variable volume container, and then the total resistances are represented by the friction losses of the two equivalent throttles.

Because the lengths of the inspiration circuit and the expiration circuit are almost fixed, the structure parameters of the two equivalent throttles, which affect the respiratory resistance, are just their equivalent effective areas (A_t, A_r).

The pressure of ventilation system is set no higher than 40 cm H_2O, and then the compliances of the tube can be neglected [25,26].

Based on the description above, the simplified mechanical ventilation system can be regarded as a pure pneumatic system, as depicted in Figure 2(b). The vacuum pump, the compressor, combination A and combination B represent

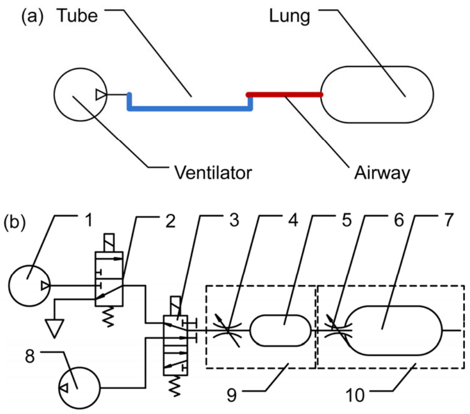

Figure 2 Structures of the SC ventilation system and equivalent pneumatic system. (a) Simplified mechanical ventilation system; (b) equivalent pneumatic system. 1, Compressor; 2, solenoid valve A; 3, solenoid valve B; 4, throttle A; 5, container A; 6, throttle B; 7, container B; 8, vacuum pump; 9, combination A; 10, combination B.

the suction unit, the ventilation unit, the flexible tube and the respiratory system respectively.

3 Simulation and experimental study on the mechanical ventilation system

3.1 Modeling of mechanical ventilation system

3.1.1 Flow equation of lung simulator

According to ISO 6358, mass flow equation of each throttle in the SC ventilation system can be obtained [27–30].

$$q=\frac{n_f A p_u\sqrt{1-b}}{\sqrt{R\theta}}\sqrt{1-\left(\frac{\frac{p_d}{p_u}-b}{1-b}\right)^2}, \tag{1}$$

where n_f is flow coefficient, when air flows into a chamber, it is 1. Inversely, when air exhausts from a chamber, it is −1. A is equivalent effective area. R is gas constant. θ means temperature. b is critical pressure ration. p_u is the pressure of upstream side. p_d is the pressure of the downstream side.

Volume flow of air can be given by the following equation:

$$Q_v=\frac{n_f A p_u\sqrt{1-b}}{\rho_a\sqrt{R\theta}}\sqrt{1-\left(\frac{\frac{p_d}{p_u}-b}{1-b}\right)^2}, \tag{2}$$

where ρ_a is the density of the standard reference atmosphere state.

3.1.2 Pressure equation

The ventilation system can be considered as an open thermodynamic system, and its working can be regarded as an isothermal process. The pressure of containers in the system can be calculated as follows:

$$\frac{\mathrm{d}p}{\mathrm{d}t}=\frac{1}{V}R\theta q-\frac{mR\theta}{V^2}\frac{\mathrm{d}V}{\mathrm{d}t}, \tag{3}$$

$$\frac{\mathrm{d}p}{\mathrm{d}t}=\frac{R\theta qV}{V^2+CmR\theta}, \tag{4}$$

where C is the respiratory compliance, and m is the mass of air.

In this study, the ventilation model is a time-triggered BiPAP. In a normal ventilation cycle, the output pressure of the SC ventilator can be calculated by the following equation:

$$p_v=\begin{cases} p_{\text{epap}}+\dfrac{p_{\text{ipap}}-p_{\text{epap}}}{t_r}t, & t\leqslant t_r;\\ p_{\text{ipap}}, & t_r\leqslant t\leqslant t_i;\\ p_{\text{ipap}}-\dfrac{p_{\text{ipap}}-p_{\text{epap}}}{t_r}(t-t_r), & t_i\leqslant t<(t_i+t_r);\\ p_{\text{epap}}, & t>(t_i+t_r). \end{cases} \tag{5}$$

When the secretion should be cleared, the output pressure of the SC ventilator can be described as

$$p_v=\begin{cases} p_{\text{epap}}+\dfrac{n_i p_{\text{ipap}}-p_{\text{ipap}}}{t_r}t, & t\leqslant t_r;\\ n_i p_{\text{ipap}}, & t_r\leqslant t\leqslant t_i;\\ p_s, & t_i\leqslant t, p_t>p_{\text{epap}};\\ p_{\text{epap}}, & t_i\leqslant t, p_t\leqslant p_{\text{epap}}. \end{cases} \tag{6}$$

where ipap means the inspiratory positive airway pressure, epap means the expiratory positive airway pressure, t_i means the inspiratory time, and t_r means the rise time of pressure.

3.1.3 Volume equation

According to the definition of compliance C, the compliance C of container A and B can be described as [31]

$$C_{\text{A}}=\frac{\mathrm{d}V_{\text{A}}}{\mathrm{d}p_{\text{A}}}, \tag{7}$$

$$C_{\text{B}}=\frac{\mathrm{d}V_{\text{B}}}{\mathrm{d}p_{\text{B}}}. \tag{8}$$

Then, the volume of container A and B can be given as

$$\mathrm{d}V_{\text{A}}=C_{\text{A}}\mathrm{d}p_{\text{A}}, \tag{9}$$

$$\mathrm{d}V_{\text{B}}=C_{\text{B}}\mathrm{d}p_{\text{B}}. \tag{10}$$

3.2 Validation of the mathematical model

When the suction pressure of the suction unit is set the same as the expiatory positive airway pressure, the secretion clearance process is equal to a ventilation process, therefore, the secretion clearance process can be considered as a special ventilation process.

To verify the mathematical model, and avoid injury to real lungs, an experimental ventilation system is proposed, as shown in Figure 3, which consists of a BiPAP ventilator, a tube, an air power meter (combines a flow sensor, a pressure sensor), a lung simulator, a data acquisition card and a computer.

The values of ventilator settings, including inspiratory positive airway pressure (ipap), expiatory positive airway pressure (epap), breaths per minute (BPM), inspiratory time (t_i) and rise time of pressure (t_r), are shown in Table 1.

The diameter of the tube is 22 mm, the inlet diameter of lung simulator is 3.2 mm, therefore, the efficient area of the equivalent throttle A and B is respectively 380 and 8 mm^2.

Through the experiment, it can be calculated that the compliance (C) of the lung simulator is about 10 mL/cmH$_2$O.

The initial values of the parameter in the simulation study are the same as those in the experimental study. The software, matlab/simulink, is used for simulation [32].

The simulation pressure (p_t) of the tube, the experimental pressure (p_t) of the tube and the simulation pressure (p_l) of the lung simulator are shown in Figure 4. The air flows of the respiratory system, which is obtained by experimentation and simulation, are shown in Figure 5.

From Figures 4 and 5, it can be obtained that:

1) The average ipap and epap, in the report of the ventilator, are 21.3 and 3.9 cmH$_2$O, respectively; hence, the measured data has a good consistency with the ventilator report.

2) The simulation results are consistent with the experimental results, and this verifies the mathematical model above.

3) As can be seen, the air pressure in the lung simulator always lags behind the output pressure of the ventilator. The main reason is that the respiratory resistance and compliance blocks the increase or decrease of the air pressure in the lung simulator. This characteristic can be utilized to control the pressure of the ventilated lung during the secretion clearance process.

4) It should be noticed that, if the inspiration time is not long enough, and the respiratory resistance or compliance is big enough, the air pressure in the lung simulator may not reach to ipap.

Therefore, the mathematical model can be adopted in the research on the SC ventilation system, and the pressure hysteretic nature of the ventilated lung should be used to improve the secretion clearance efficiency.

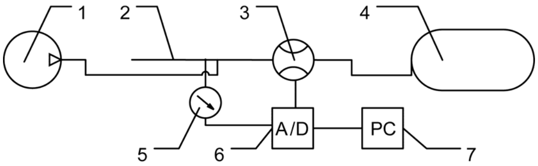

Figure 3 Configuration of experimental apparatus. 1, Ventilator; 2, tube; 3, flow sensor; 4, lung simulator; 5, pressure sensor; 6, data acquisition card; 7, computer.

Table 1 Values of the main ventilator setting

Parameter	ipap (cmH$_2$O)	epap (cmH$_2$O)	BPM	t_i (s)	t_r (s)
Value	22	4	20	1.2	0.3

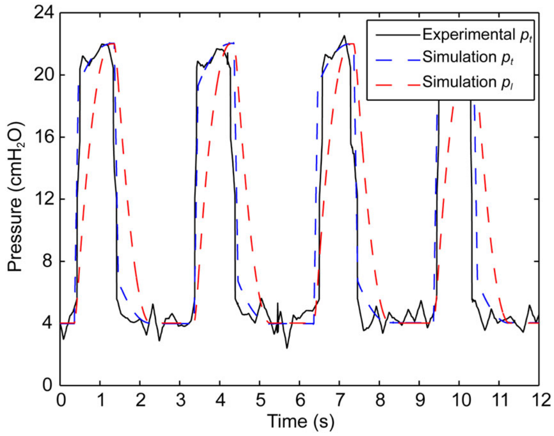

Figure 4 Curve and fitted curve of air pressure in tube

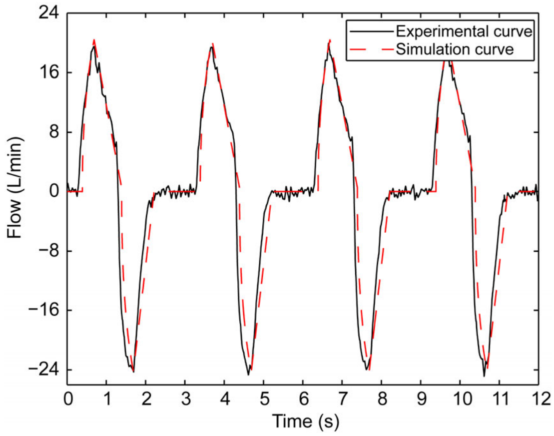

Figure 5 Curve of air flow in the system

4 Working characteristics of the SC ventilation system

4.1 Dynamic characteristics of the system

As the compliance of the ventilated lung is set 50 ml/cmH$_2$O, the inner diameters of the tube and the endotracheal intubation are set 10 and 5 mm. Ipap, epap and suction pressure are set 22, 4 and −22 cmH$_2$O, respectively.

The curves of the output pressure ($p_{\text{v-sc}}$) of the SC ventilator in the ventilation process, the output pressure ($p_{\text{s-sc}}$) of the SC ventilator in the secretion clearance process, the pressure ($p_{\text{v-t}}$) of the tube in the ventilation process, the pressure ($p_{\text{s-t}}$) of the tube in the secretion clearance process, the pressure ($p_{\text{v-l}}$) of the ventilated lung in the ventilation process and the pressure ($p_{\text{s-l}}$) of the ventilated lung in the secretion clearance process are all shown in Figure 6(a). The air flow ($q_{\text{s-l}}$) of the ventilated lung in the secretion clearance process and the air flow ($q_{\text{v-l}}$) of the ventilated lung in the ventilation process are shown in Figure 6(b). Here subscript v means ventilator or ventilation process. Subscript s means suction process. l means lung.

As illustrated in Figure 6, it can be seen that due to the respiratory resistance and the compliance, with a growth or a descent in the pressure of the tube, the pressure of the ventilated lung ascends or declines slowly and accordingly.

In the inspiration process, with an increase in the pressure of the tube, the input air flow of the ventilated lung rises sharply. When the output pressure of the ventilator reaches ipap, the pressure of the tube increases slowly, and the input air flow of the ventilated lung starts to decline. And finally the ventilated lung stops inspiration when the air pressure in lung simulator is the same as the pressure one in the tube.

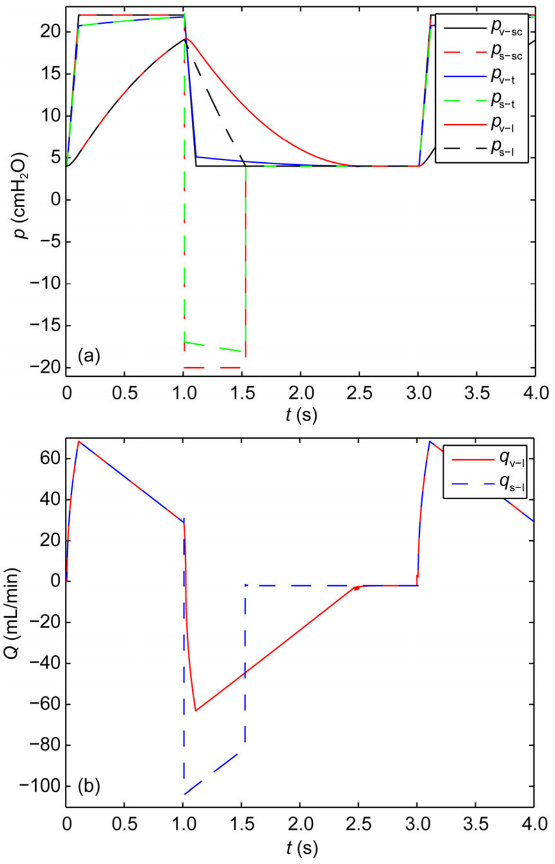

Figure 6 Dynamic of the system. (a) Pressure dynamic characteristics of the system; (b) flow dynamics of the ventilated lung.

In the normal expiration process and the secretion clearance process, the output air flow of the ventilated lung sharply increases with a reduction of the pressure in the tube. Because the pressure of the tube in the normal expiration process is higher than the pressure of the tube in the secretion clearance process, the output air flow in the secretion clearance process is bigger than that in the normal expiration process; however, the duration of the output air flow in the secretion clearance process is shorter than that in the normal expiration process. When the pressure of the ventilated lung tends to be epap, the output air flow of the lung drops to zero and keeps constant.

4.2 Influence of the pressure settings on the working characteristics of the SC ventilation system

The pressure settings of the SC ventilator play an important role in the dynamics of the system. According to refs. [23,24], the efficiency of the secretion clearance increases with a rise in the output air flow of the ventilated lung and the output flow duration. In order to improve the secretion clearance efficiency of the system, the influences of the SC ventilator output pressure settings on the dynamics of the SC ventilation system should be studied.

Through simulation, the influences of ipap, epap and suction pressure on the dynamics are shown in Figures 7–9.

With an increase in ipap, the peak suction flow and suction duration increase accordingly. Therefore, increasing the ipap may improve the output air flow of the ventilated lung, and prolong the suction duration.

The influence of epap on the peak suction flow can be neglected. The relationships between the suction duration and ipap are approximately of linear negative correlation, and decreasing epap can prolong the suction duration.

With a decrease in the suction pressure, the suction duration increases, but the peak flow decreases. Therefore, decreasing suction pressure may accelerate the suction flow of the ventilated lung, but that may shorten the duration of the suction flow.

Therefore, increasing ipap and decreasing epap may definitely improve the efficiency of the secretion clearance. But it is uncertain whether decreasing the suction pressure may improve the efficiency of the secretion clearance, which should be studied clinically.

The ipap and epap of the SC ventilator can be automatically adjusted in the secretion clearance process; however, the IL-IE device by innovent medical solutions cannot control the ipap and epap of the independent ventilator. Therefore, the secretion clearance of the SC ventilation may be more efficient than the IL-IE.

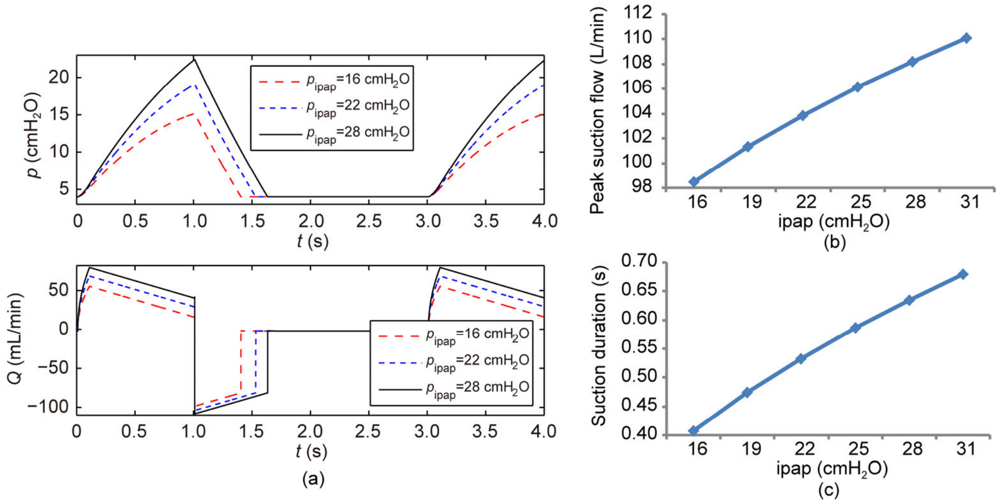

Figure 7 Influences of ipap on the working characteristics. (a) Influences of ipap on the dynamics; (b) relationship between the peak suction flow and ipap; (c) relationship between the suction duration and ipap.

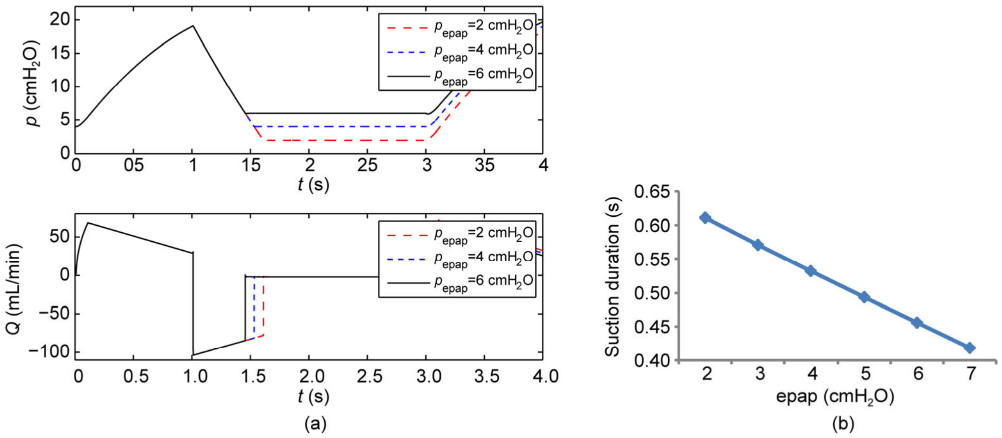

Figure 8 Influences of epap on the working characteristics. (a) influences of the epap on the dynamics; (b) relationship between the suction duration and epap.

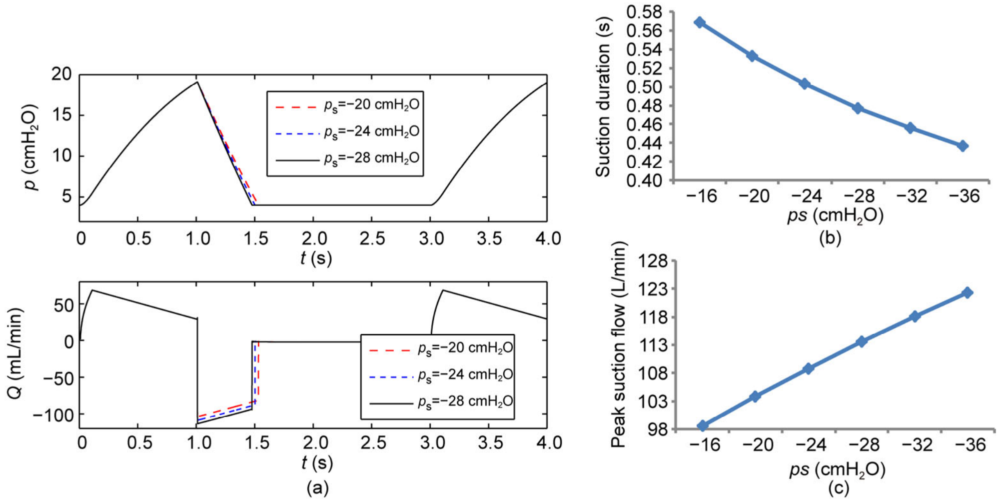

Figure 9 Influences of the suction pressure on the working characteristics. (a) Influences of the suction pressure on the dynamics; (b) relationship between the peak suction flow and the suction pressure; (c) relationship between the suction duration and the suction pressure.

5 Conclusion

In this study, a new ventilator (SC ventilator) with automatic secretion clearance function was proposed with an aim of providing a new approach to clear the secretions of ventilated patients. To confirm that the secretion clearance efficiency of the SC ventilator is higher than that of the IL-IE device and lay a foundation for the optimization of the SC ventilator, a mathematical model of the ventilation system was set up. Through the research on the ventilation system, we come to the following points:

1) The experiment is proved to be authentic and reliable, and the simulation results are consistent with the experimental results, which verify the mathematical model.

2) With an increase in the ipap, the peak suction flow and suction duration increase accordingly. The relationships between the suction duration and ipap are approximately of linear negative correlation. With a decrease in the suction pressure, the suction duration increases, but the peak flow decreases.

3) Increasing ipap and decreasing epap of the SC ventilator can definitely improve the efficiency of the secretion clearance.

4) The secretion clearance efficiency of the SC ventilation may be higher than that of the IL-IE device.

This paper proposes a new method for secretion clearance, lays a foundation for optimizing the secretion clearance efficiency of the SC ventilator. In the future, the authors will further carry out the research and apply the machine designed to clinical trials.

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