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Creation method for bi-level positive airway pressure based on pressure and flow feedback

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Abstract: An airway pressure and flow data acquisition system is developed to investigate the approach to building the bi-level positive airway pressure (BiPAP) in a ventilator. A number of experiments under different breathing situations and states are conducted and the experimental data are recorded. According to the data from these experiments, the variation characteristics of the pressure and flow are analyzed using Matlab. The data analysis results show that the pressure increases while the flow decreases in the expiratory phase; contrarily, the pressure decreases while the flow increases in the inspiratory phase; during the apnea state, both the pressure and the flow remain unchanged. According to the above variation characteristics of breath, a feedback-based method for creating bi-level positive airway pressure is proposed. Experiments are implemented to verify the BiPAP model. Results demonstrate that the proposed method works effectively in following respiration and caters well to most polypnea and apnea events.

Key words: ventilator; bi-level positive airway pressure; pressure; flow

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Obstructive sleep apnea syndrome (OSAS) is a common disorder that occurs in at least 2% to 4% of the adult population[1]. Continuous positive airway pressure (CPAP) is the most safe and effective method in the clinical treatment of OSAS[2−3]. The bi-level positive airway pressure (BiPAP) ventilator meets human natural breathing by supplying the two-level air pressures depending on the patients' exhalation and inhalation, and thus make patients feel more comfortable[4−5]. However, the producers have not revealed the method of building bi-level positive airway pressure, and the technology still stays in its infancy.

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The present study approaches the problem of building bi-level positive airway pressure based on the feedback of pressure and flow. Under meticulous monitoring for detailed data recording, the patient's breathing changes are timely detected and the fans' rotational speed is regulated correspondingly by analyzing the variation of pressure and flow between the expiratory and inspiratory phases.

1 Experiment on Bi-Level Positive Airway Pressure

Fig. 1 shows the block diagram of an experimental BiPAP system which consists of a nasal mask, a tube, a blower with BLDC motor, a 1-4 kPa pressure sensor (MPX5004G), a ± 500 Pa differential pressure sensor (SDP600) and a control circuit board[6]. The experiment was done on six testers under the following three conditions: 1) Wearing no nasal mask with the blower running; 2) Wearing the nasal mask without the blower running; 3) Wearing the nasal mask with the blower running. Data of the changing pressure and flow were collected every 200 ms.

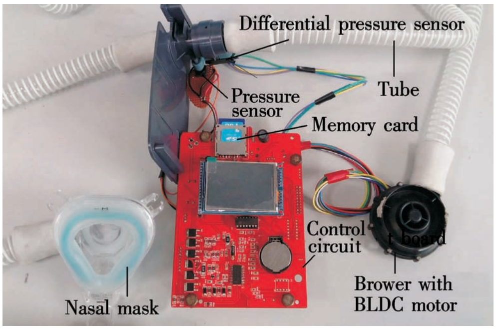

Fig. 1 Experimental BiPAP machine

2 Results and Discussion

2.1 Analysis of pressure changes

Six testers for a total of 18 sets of data from the subjects were collected in the experiment. Similar breathing variation was observed among them, from one of whom the pressure data is shown in Fig. 2.

Fig. 2(a) shows the pressure changes inside the tube under the condition of wearing no nasal mask with the blower running. As illustrated by the diagram, the pressure stays around a constant value with only slight changes. In addition, a sharp increase and decrease at points *a* and b are observed, which may be attributed to the tube shaking and other factors that influence the BiPAP model precision.

Fig. 2(b) demonstrates the pressure changes inside the tube under the condition of wearing the nasal mask without the blower running. As indicated here, the pressure increases or decreases periodically with paced breathing. At a certain time (T_1-T_3), the pressure increases with the increasing expiratory volume and declines by the end of the expiratory phase at exhalation time (T_1-T_2). The pressure goes down as the inhaling deepens, but returns to normal at the end of inhalation time (T_2-T_3). It is notable that the peak pressure and breathing period vary with each breathing circle. Point c has a sharp increase caused by outside interference.

Fig. 2(c) presents the pressure changes inside the tube under the condition of wearing a nasal mask with the blower running. Similar to Fig. 2(b), the pressure varies periodically with the changes in breathing. Due to the effects of the blower, the mean value of pressure remains high.

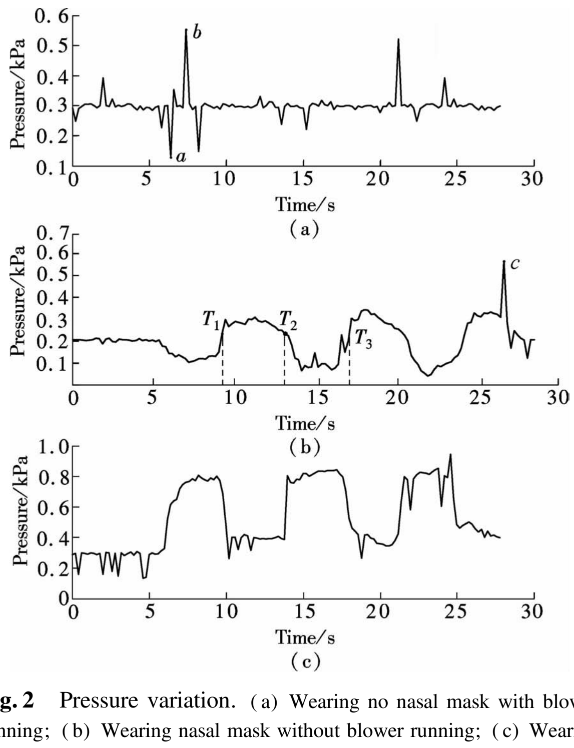

Fig. 2 Pressure variation. (a) Wearing no nasal mask with blower running; (b) Wearing nasal mask without blower running; (c) Wearing nasal mask with blower running

2.2 Analysis of flow changes

Eighteen sets of data from the subjects were also collected in the flow experiments. Fig. 3 gives three sets of the flow data taken from one of the subjects. The positive or negative sign represents the direction of the flow.

Fig. 3(a) illustrates the flow changes inside the tube under the condition of wearing no nasal mask with the blower running. As shown here, the flow in the tube stays around a constant value with only slight changes. However, a conspicuous fluctuation at points d and e is observed, due to the influence of various external factors.

Fig. 3(b) gives the flow changes inside the tube under the condition of wearing the nasal mask without the blower running. At a certain time (T_4-T_6), the flow increases with the increasing expiratory volume and declines by the end of the expiratory phase at exhalation time (T_4-T_5). The flow goes down as the inhaling deepens, but returns to normal at the end of inhalation time (T_5-T_6).

Fig. 3(c) demonstrates the pressure changes inside the tube under the condition of wearing the nasal mask with the blower running. Similar to Fig. 3(b), the flow varies periodically with the changes in breathing.

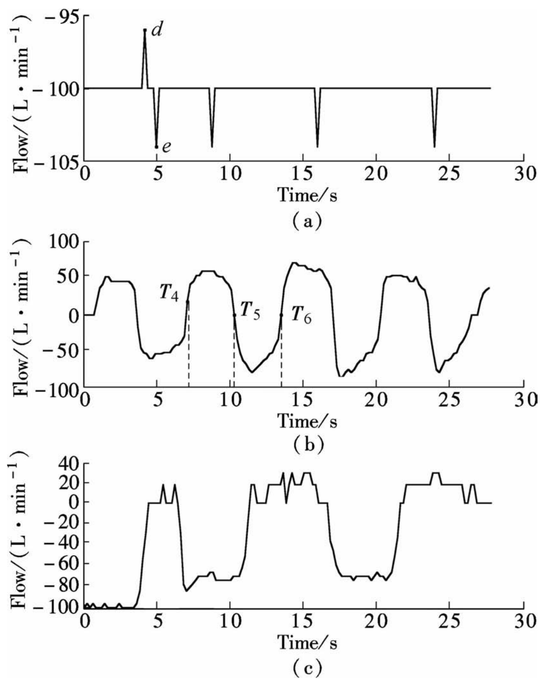

Fig. 3 Flow variation. (a) Wearing no nasal mask with blower running; (b) Wearing nasal mask without blower running; (c) Wearing nasal mask with blower running

3 Methods for Creating BiPAP

3.1 Principle for BiPAP construction

As indicated in Fig. 2 and Fig. 3, the pressure and flow undergo significant changes in the expiratory phase, the inspiratory phase, and the apnea state. It can be seen from the durations (T_1-T_2) and (T_2-T_3) in Fig. 2(b) that the pressure increases in the expiratory phase and decreases in the inspiratory phase. On the other hand, durations (T_4-T_5) and (T_5-T_6) in Fig. 3(b) show that the flow decreases in the expiratory phase and increases in the inspiratory phase, due to the flow blown by the blower and the patient in opposite directions. Set up high and low thresholds for pressure and flow, i. e., high trigger pressure (HTP), low trigger pressure (LTP), high trigger flow (HTF), and low trigger flow (LTF). As notable fluctuations in pressure and flow may be triggered by such external factors as tube shaking and so on.

Then, we can assert that:

1) The patient is in the breathing status of exhalation if the air pressure inside the tube is higher than HTP and the air flow is lower than LTF.

2) The patient is in the breathing status of inhalation if the air pressure inside the tube is lower than LTP and the air flow is higher than HTF.

3) The patient's breathing status holds at the previous state if the situation is not compliant with the terms of the aforementioned.

4) The patient is in the breathing status of apnea if the pressure and flow stay unchanged for a long time, thus prolonging the phase of inhalation.

It is difficult for the BiPAP model to recognize inhalation and exhalation upon acute fluctuations in pressure and flow. For that sake, in this study inhalation and exhalation are identified in terms of the pressure and flow changes observed in real time by the following principles:

1) Each step in the BiPAP model must proceed forward, allowing no leapfrogging or reversing. And it can only be executed when the previous step ends.

2) The circulation of the BiPAP model is set to begin with wearing the nasal mask; otherwise, the system runs in the original state with no BiPAP model present.

3) The circulation of the BiPAP model ends in removing the nasal mask. The system keeps running until the nasal mask is removed.

4) The BiPAP model applies to the patient who can breathe spontaneously.

3.2 Flowchart of BiPAP model

The flowchart of the BiPAP model derived from the present study is given in Fig. 4.

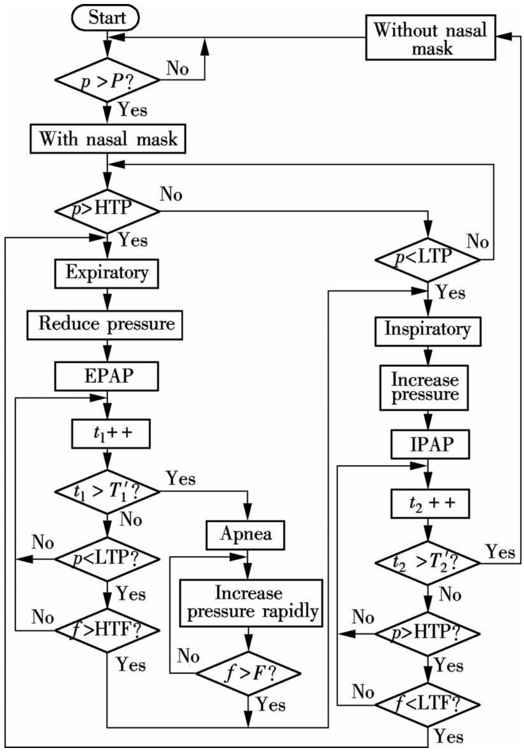

Fig. 4 The flowchart of BiPAP model

Here P is the trigger pressure used to judge whether the tester is wearing the nasal mask or not; T'_1 is the trigger time for apnea determination; T'_2 is the trigger time for judging if the nasal mask is removed; F is the trigger flow for determining whether or not the state of apnea has come to an end; p represents the pressure in the tube; f represents the flow in the tube; t_1 represents the exhalation time; t_2 represents the inhalation time.

To build a BiPAP model by the flowchart, the following points must be noted.

● The detection of the starting and ending points of the model. The model starts with wearing the nasal mask and ends with removing the nasal mask. The BiPAP model is intended for ventilators. Upon the patient's use of the ventilator, there may occur a variety of possible circumstances, which, however, need not necessarily be considered in full. As the model is only applied during a particular period (breathing period), other aspects do not have to be fully addressed except that its starting and ending points must be accurately determined.

● The pressure output of the blower in expiratory and inspiratory phases: The pressure and flow detected by pressure and flow sensors reflect the dual function in the blower and patient. Variations in the pressure and flow are illustrated in Fig. 2, and Fig. 3 serves to verify that the output of pressure and flow by the blower stays constant under all the conditions. So when the patient's breathing switches from exhalation to inhalation, the blower must output a corresponding constant value.

● The thresholds of pressure and flow: As shown in Fig. 4, the thresholds of pressure and flow exert a notable influence on the detection precision, which require the parameters for the BiPAP model to be selected in a proper way.

3.3 Selection of thresholds for pressure and flow

The parameters of HTP, LTP, HTF and LTF are of trigger sensitivity, varying one from another. Setting LTP at a low level and HTF at a high level may make the patient strain to breathe at the beginning of the inspiratory phase. Setting them vice versa can ease the patient's breathing. But the bad news is that there exists a wrong trigger in breathing change caused by a small fluctuation of pressure and flow inside the tube. Setting HTP at a high level and LTF at a low level may make the patient strain to breathe in the expiratory phase. Conversely, the switching will be implemented in advance.

To build an accurate BiPAP model, the parameters of HTP, LTP, HTF and LTF should be tailored to the type of patients. The system is required to record the highest pressure (PH), the lowest pressure (PL), the highest flow (FH) and the lowest flow (FL) inside the tube in each breathing period. Initial values should be given to the parameters, which will be changed according to the previous records in the next breathing period.

3.4 Nasal mask detection

The validity of the BiPAP model largely depends on the accuracy of nasal mask detection. As no sensor is allowed for the detection, what is wanted is an easy but effective approach, which is proposed as follows:

1) An airway pressure threshold of precise mask-wearing detection is set and the nasal mask is considered wearing based on the fact that the airway pressure has a sharp rise upon the patient wearing the nasal mask.

2) A no nasal mask state can be determined by an extended period of lower tube pressure than the set threshold.

3.5 Failure prevention for phase determination

Detecting the expiratory and inspiratory phases may involve the following failure-triggering errors: repetitive trigger, self-trigger, delay switch and advance switch. However, our BiPAP model functions well in minimizing the above possible errors. Developed by the principle proposed in section 3.1, the system allows no repetitive return to the inspiratory phase when it ends. Self-trigger is also well evaded by the model, where the ventilator is switched according to the changes of pressure and flow. And the problem of delay or advance switch can be readily solved by setting the parameters of HTP, LTP, HTF and LTF dynamically according to the pressure and flow feedback.

4 Verification by Experiment

The experimental device shown in Fig. 1 is used to test whether the BiPAP model is effective or not under the conditions of normal breathing, shortness of breath and sleep apnea.

4.1 Tests for normal breathing

Letting the subjects breathe normally wearing the nasal mask in an awakened state can simulate the conditions of normal breathing in sleep. During the tests, the system automatically records the data of pressure and flow as well as the switch points between the expiratory and inspiratory phases. In contrast, experimenters must record the switch points themselves. Finally, whether the BiPAP model is effective or not can be tested under the condition of normal breathing by contrasting the switch points recorded by the system and experimenters.

As indicated by Tab. 1, most of the start and end times of the expiratory and inspiratory phases recorded by the system coincide with the data taken from the subjects. But there are some exceptions: the start time of the expiratory phase recorded by the former turn out to be 0.4 s slower than the latter in the period of 4 s, and 0.2 s slower than the latter in the period of 10.2 s. This result verifies the validity of the BiPAP model for normal breathing.

Tab. 1 Start time of expiratory phase and inspiratory phase in normal breathing s

Start time of inspiratory phase		Start time of expiratory phase	
Record by system	Record by patient	Record by system	Record by patient
0	0	1.8	1.8
2.6	2.6	4.4	4.0
6.0	6.0	7.6	7.6
8.8	8.8	10.4	10.2
11.8	11.8	13.2	13.2

As shown in Fig. 5, at the time of T_1-T_3 the pressure and flow gradually go up with the increase in the blower rotor speed in the inspiratory phase (T_1-T_2), and go down with the declining blower speed in the expiratory phase (T_2-T_3). This tendency meets patient treatment needs [7-8], which confirms the model's efficient control of the pressure.

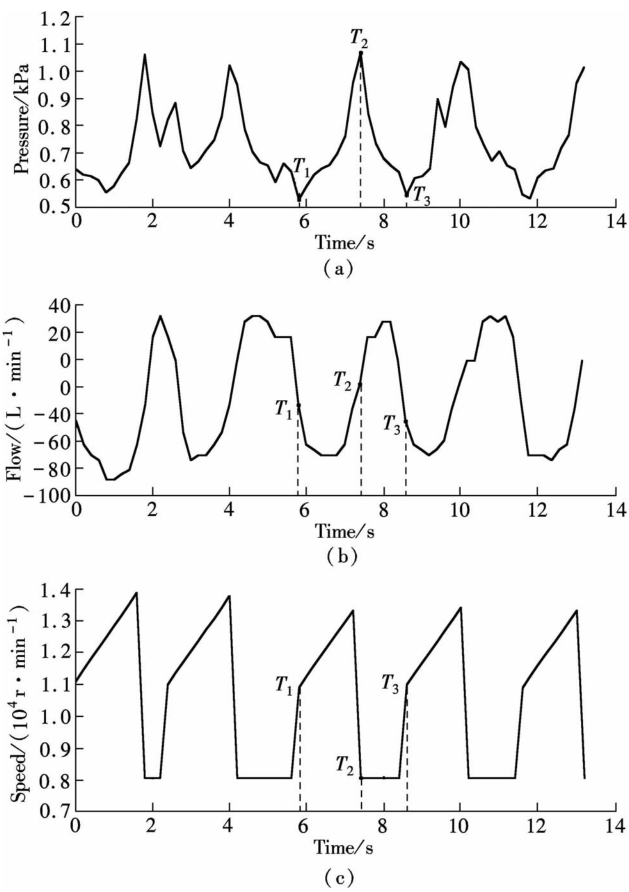

Fig. 5 Normal breathing. (a) Pressure; (b) Flow; (c) Speed

4.2 Tests for insufficient breathing

When using the ventilator, the patient remains in a stable breathing rate most of the time. But short breathing is also observed sometimes. Letting the subjects breathe at high frequency wearing the nasal mask in an awakened state can simulate the condition of breath shortness. During the tests, the system automatically records the switch points between the expiratory and inspiratory phases. In contrast, experimenters must record the switch points themselves. Finally, whether the BiPAP model is effective or not can be tested under the condition of shortness of breath, by contrasting the switch points recorded by the system and experimenters.

As shown in Fig. 6 and Tab. 2, the breathing rate is stable at the beginning of the experiment, and then rises at the time of T_4-T_5 and T_6-T_7. The start time of the inspiratory phase recorded by the system is 0.2 s earlier than that taken from the subjects in the period of 14.2 s, and the start time of the expiratory phase recorded by the system is 0.2 to 0.4 s slower than the latter in the periods of 4.6 and 10.4 s. This suggests that the BiPAP model is helpful for handling the condition of short breathing.

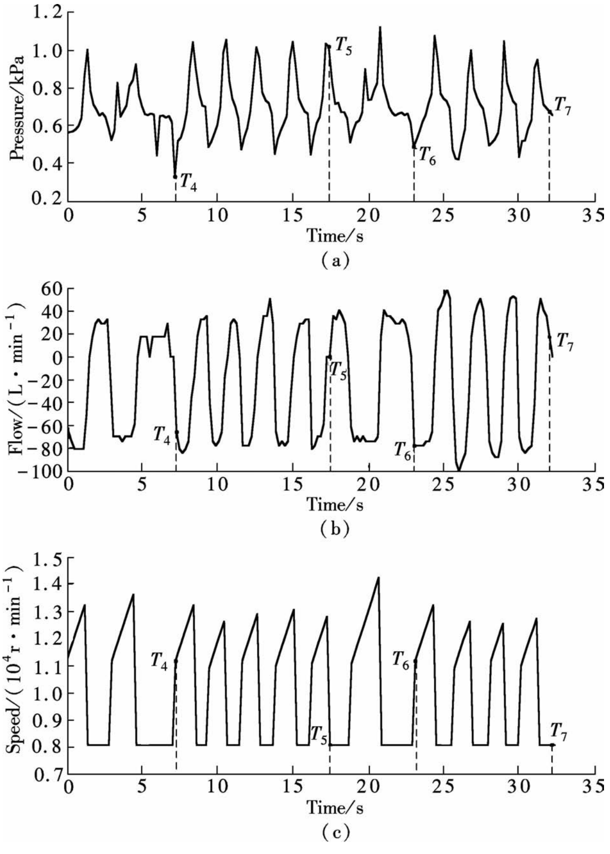

Fig. 6 Shortness of breath. (a) Pressure; (b) Flow; (c) Speed

Tab. 2 Start time of expiratory and inspiratory phases in short breath s

Start time of inspiratory phase		Start time of expiratory phase	
Record by system	Record by patient	Record by system	Record by patient
0	0	1.6	1.6
3.2	3.2	4.8	4.6
7.4	7.4	8.8	8.8
9.6	9.6	10.8	10.4
11.8	11.8	13.0	13.0
14.0	14.2	15.4	15.4
16.4	16.4	17.6	17.6
19.0	19.0	21.0	21.0
23.2	23.2	24.6	24.6
25.8	25.8	27.0	27.0
28.2	28.2	29.2	29.2
30.2	30.2	32.2	32.2

4.3 Tests for sleep apnea

Apnea often occurs in sleep. The system should recognize it and make adjustments in time as required. More specifically, pressure and flow are supposed to stay unchanged at the beginning of apnea, but a while later they will increase rapidly to open the airway. Letting the subjects stop breathing wearing the nasal mask in an awakened state can simulate the condition of sleep apnea.

As demonstrated in Fig. 7, the breathing rate is stable at the beginning of the experiment, and later apnea occurs at the time of T_8-T_9 and T_{10}-T_{11}. The typical symptom of apnea is that the pressure and flow have no conspicuous change. As revealed by the figure, the system manages to recognize the occurrence of apnea within 5 s, during which the pressure and flow have a sharp rise with increasing blower speed, thus opening the patient's airway in a timely way.

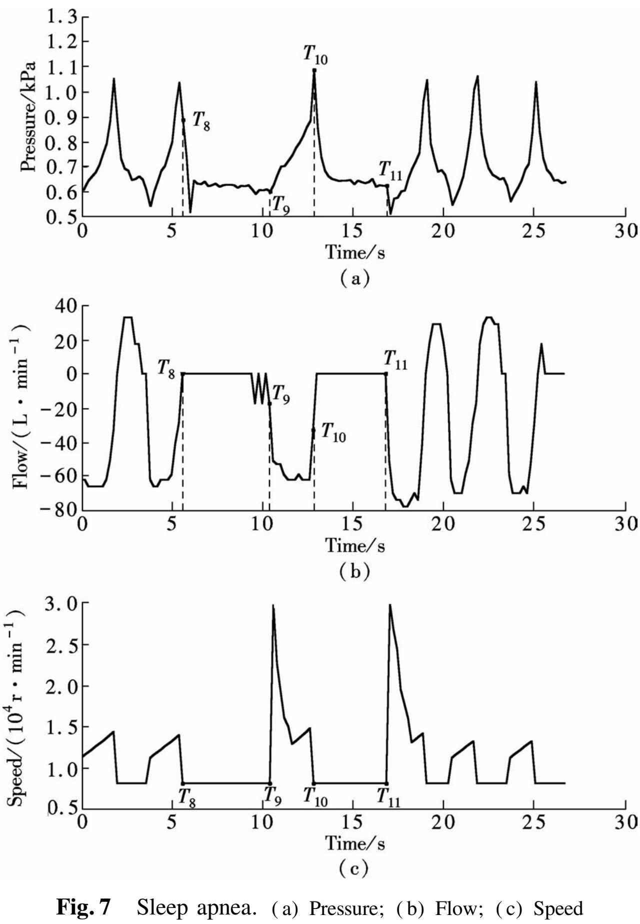

Fig. 7 Sleep apnea. (a) Pressure; (b) Flow; (c) Speed

5 Conclusion

Pressure and flow experiments are conducted to develop and validate the BiPAP model using the feedback-based method. By analyzing the experimental data, this research investigates the variation characteristics of pressure and flow in expiratory and inspiratory phases. The BiPAP model is studied and tested in depth. Experimental results show that the proposed method can follow respiration accurately and respond to respiratory events appropriately.

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基于压力和流量双反馈的双水平气道建立方法

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摘要:为了研究呼吸机中双水平气道的建立方法,搭建了一个呼吸机气道内压力和流量采集系统,对呼吸时气道内压力和流量进行试验并记录试验数据.根据试验数据,运用 Matlab 统计分析了呼吸过程中气道内压力和流量的变化特征.数据分析表明:在呼气相,气道内的压力增加而流量减少;在吸气相,气道内的压力减少而流量增加;在呼吸暂停状态,气道内的压力和流量都保持稳定不变的状态.根据上述呼吸特征提出一种基于压力和流量双反馈的双水平气道建立方法.通过实验对双水平模型进行了验证.研究结果表明,所提出的方法对呼吸相的跟随具有很高的精度,对呼吸急促和呼吸暂停等呼吸事件有很强的适应性.

关键词:呼吸机;双水平气道;压力;流量

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