Research Article

A Novel Method to Evaluate Patient-Ventilator Synchrony during Mechanical Ventilation

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The synchrony of patient-ventilator interaction affects the process of mechanical ventilation which is clinically applied for respiratory support. The occurrence of patient-ventilator asynchrony (PVA) not only increases the risk of ventilator complications but also affects the comfort of patients. To solve the problem of uncertain patient-ventilator interaction in the mechanical ventilation system, a novel method to evaluate patient-ventilator synchrony is proposed in this article. Firstly, a pneumatic model is established to simulate the mechanical ventilation system, which is verified to be accurate by the experiments. Then, the PVA phenomena are classified and detected based on the analysis of the ventilator waveforms. On this basis, a novel synchrony index (SIhao) is established to evaluate the patient-ventilator synchrony. It not only solves the defects of previous evaluation indexes but also can be used as the response parameter in the future research of ventilator control algorithms. The accurate evaluation of patient-ventilator synchrony can be applied to the adjustment of clinical strategies and the pathological analyses of patients. This research can also reduce the burden on clinicians and help to realize the adaptive control of the mechanical ventilation and weaning process in the future.

1. Introduction

Nowadays, respiratory diseases have become some of the deadliest diseases in the world [1, 2]. Sudden global epidemic diseases, such as COVID-19, also bring great threat to people’s life. In order to provide people with the necessary life support, the application and research of mechanical ventilation in clinical treatment are getting more and more attention from experts. Mechanical ventilation is an effective means of clinical treatment for respiratory failure and pneumonia and of respiratory support in critically ill patients. The indications for mechanical ventilation include acute respiratory distress syndrome (ARDS), chronic obstructive pulmonary diseases (COPD), pneumonia, severe acute respiratory syndrome (SARS), middle east respiratory syndrome (MERS), and corona virus disease (COVID-19) [2–6]. In the treatment of the COVID-19 that has swept the world, mechanical ventilation has played an important role. During mechanical ventilation, patient-ventilator asynchrony (PVA) is a common problem [7]. The incidence of severe PVA can be as high as 25% in spontaneously breathing patients with acute respiratory failure during invasive ventilation [8, 9]. During noninvasive ventilation, PVA also maintains a high incidence [10]. Clinically, PVA could result in prolonged time on mechanical ventilation, increased use of sedation, complications of ventilator, and decrease in patient’s comfort accompanied by the physiological and psychological changes [11–15]. For example,
during the treatment of COVID-19, PVA occurs in most patients, which increases the need for sedation and muscle relaxants \[16, 17\]. In addition, the respiratory gland is stimulated, which increases the secretion of sputum and causes sputum stasis, resulting in difficulty in suction \[18–20\]. Therefore, the research and clinical evaluation of patient-ventilator synchrony are vital for the process of mechanical ventilation.

In clinical practice, ventilator waveforms are often used to detect PVAs manually. Nilsestuen and Hargett summarized the method of using ventilator waveforms to identify PVAs \[21\]. The patient’s pulmonary system and the ventilator are described as two pumps. The asynchrony between the two pumps can be identified by comparing the pressure, flow, and volume waveforms. However, they did not propose a standard index to evaluate the degrees of patient-ventilator synchrony. And the detection work is performed manually with lower intelligence degrees and real-time performance. Diaphragm electrical activity (EAdi) waveform can reflect patient’s respiratory effort intuitively. Compared to conventional ventilator waveforms, EAdi can effectively monitor the interaction between the patient and the ventilator \[22, 23\]. However, the acquisition of the EAdi signal requires the placement of an esophageal electrode catheter, which is complicated in clinical practice and may interfere with mechanical ventilation. Therefore, it is not easy to popularize the application of synchrony index using EAdi clinically.

In addition, Sinderby et al. have proposed a neural index to quantify patient-ventilator interaction \[24\]. In their research, the patient-ventilator synchrony was evaluated by comparing ventilator pressure and EAdi waveforms. The two waveforms were analyzed for their timings, and the error between the waveforms was quantified, thus obtaining the synchrony index that is standardized and automated. However, this index still has certain limitations. In addition to the difficulty of measuring EAdi signals, this index lacks the synchrony evaluation on the space of ventilator waveforms. For example, amplitude fluctuations of pressure and flow waveforms caused by insufficient ventilation or over-ventilation cannot be effectively evaluated.

In this article, a novel method to evaluate patient-ventilator synchrony is proposed based on a pneumatic model of the mechanical ventilation system, by comparing changes in ventilator waveforms during the breathing cycles of patients. This method can automatically detect the main asynchrony phenomena considering the feasibility of clinical operation and the effectiveness of the evaluation. Different from the contribution of the research work completed by other scientists, the method proposed in this article does not require invasive operations and can comprehensively evaluate the patient-ventilator synchrony. The PVAs are classified according to different phases of a ventilation cycle. And the accuracy of the model and detection method is verified by a series of simulations. The synchrony index (SIhoa) is established in the form of a vector, and its elements correspond to various aspects of the asynchrony phenomena. This index intuitively reflects the detection and quantification results of the patient-ventilator synchrony. It is significant for the diagnosis of the patient, the prediction of the development of patient’s condition, and the clinical regulation of mechanical ventilation.

### 2. Materials and Methods

#### 2.1. Pneumatic Model of the Mechanical Ventilation System

The patient and the ventilator are driven by two different pneumatic systems. The patient’s spontaneous breathing is driven by respiratory muscle, of which the work of diaphragm accounts for 60%–80% \[25–27\]. The ventilator is driven by an external air source or fan to generate pressure and flow to provide respiratory support to the patient. The interaction between the patient and the ventilator affects the changes of the ventilator waveform. A pneumatic model is established to simulate the process of mechanical ventilation, as shown in Figure 1.

In the pneumatic model, the vacuum pump simulates the generation of negative pressure when the patient inhales. The lungs can be regarded as a variable-volume container, whose elasticity corresponds to pulmonary compliance. The airway resistance is represented by the friction loss of the throttle valve. The brake valve simulates the switching between inspiration and expiration. The ventilator pneumatic system is established based on the working principle of a medical ventilator that can achieve pressure support ventilation (PSV). These two pneumatic systems are connected by the ventilation tube whose compliance and air resistance can be negligible ideally.

The working principle of the pneumatic model corresponds to the physiological principle of the patient’s respiratory system. During a normal breathing cycle, the negative pressure is first generated inside the pleural cavity, to bring a pressure difference between the inside and outside of the human body. Then the air gets into the lungs through the airway. This process can be completed by the vacuum pump and the brake valve in the pneumatic model. When the patient starts exhaling, the chest wall retracts, expelling excess air in the lungs. This process can be completed by the variable-volume container which is elastic. The breathing support of the mechanical ventilation system is provided by the ventilator pneumatic system as shown in Figure 1. When the patient’s compliance changes, the elasticity of the variable-volume container changes accordingly, and their change rules are inversely proportional. When the patient’s airflow resistance changes, the effective sectional area of the throttle valve changes accordingly, and their change rules are proportional. Therefore, the pneumatic model in this article can effectively simulate the changes and effects of respiratory mechanical parameters in the mechanical ventilation system.

#### 2.2. Mathematical Model of the Mechanical Ventilation System

##### 2.2.1. Driving Pressure of Patient’s Spontaneous Breathing

Patient’s spontaneous breathing is driven by the contraction of respiratory muscles. The formula of pressure changes in the lungs produced by respiratory muscles can be fitted from
the pressure curve produced by the lung simulator (ASL5000), and the simulator curve can accurately represent the curve of pressure changes generated by the patient's spontaneous breathing [28–30]. In this article, the value of this pressure changes is denoted as $P_{\text{mus}}$. In previous research, both Vicario and Hao have revealed this law [30, 31], and $P_{\text{mus}}$ can be expressed as a piecewise function, as shown in equation (1). In this formula, $P_{\text{mus,max}}$ represents the maximum value of the pressure change, $t_{\text{dec}}$ is the time for pressure dropping, $t_{\text{inc}}$ is the start of the pressure rising, $t_{\text{ins}}$ is the termination of the pressure rising, and $T_{\text{cycle}}$ is the time for a breathing cycle.

$$P_{\text{mus}} = \begin{cases} -P_{\text{mus,max}} \cdot \sin \left( \frac{\pi t}{2 \cdot t_{\text{dec}}} \right), & 0 \leq t < t_{\text{dec}}, \\ -P_{\text{mus,max}} \cdot \sin \left( \frac{\pi (t + t_{\text{ins}} - 2 \cdot t_{\text{inc}})}{2(t_{\text{ins}} - t_{\text{inc}})} \right), & t_{\text{dec}} \leq t < t_{\text{ins}}, \\ 0, & t_{\text{inc}} \leq t < T_{\text{cycle}}. \end{cases}$$

The pressure curve (see Figure 2) can be simulated according to equation (1). The red dotted line was obtained by the data acquisition of the lung simulator (ASL5000), and the black solid line is the fitted curve based on equation (1).

### 2.2.2. Operating Pressure of the Ventilator

For the PSV mode, the operating pressure of the ventilator can be expressed as a piecewise function, as shown in equation (2) [29–31]. In the formula, $P_V$ is the operating pressure of the ventilator, $P_{\text{trigger}}$ is the trigger pressure, $P_{\text{peak}}$ is the plateau pressure, $P_{\text{PSV}}$ is the maximum support pressure set by the ventilator, $t_{\text{trigger}}$ is the trigger time, $t_{\text{rise}}$ is the rise time from $P_{\text{trigger}}$ to $P_{\text{peak}}$ (the value of $P_{\text{peak}}$ is approximately equal to $(P_{\text{PSV}} + P_{\text{trigger}} + \text{PEEP})$), $t_{\text{ins}}$ is the termination time of inhalation, and $t_{\text{drop}}$ is the drop time from $P_{\text{peak}}$ to PEEP. When the airway pressure drops more than the trigger pressure, the ventilator is triggered and starts working. The value of $t_{\text{rise}}$ is preset by the clinician and $t_{\text{ins}}$ is based on a percentage of peak flow. This percentage is preset or varies...
depending on the algorithm of the ventilator. PEEP means positive end expiratory pressure, which maintains a certain pressure in the airway at the end of expiration.

\[
P_v = \begin{cases} 
(P_{PSV} + P_{trigger}) \cdot \left(1 - e^{-\left(\frac{t_{trigger}}{t_{rise}}\right)}\right) + PEEP, & t_{trigger} \leq t < (t_{trigger} + t_{rise}), \\
P_{peak}, & (t_{trigger} + t_{rise}) \leq t < t_{ter}, \\
P_{peak} - (P_{peak} - PEEP) \cdot \left(\frac{t - t_{ter}}{t_{drop}}\right), & t_{ter} \leq t < (t_{ter} + t_{drop}), \\
PEEP, & (t_{ter} + t_{drop}) \leq t < T_{cycle}.
\end{cases}
\]

(2)

2.2.3. Differential Equations and Transformation Relations of Physical Quantities. During the mechanical ventilation, the pneumatic model can be regarded as an isothermal system [32, 33]. By deforming the ideal gas equation, the differential equation for intrapulmonary pressure can be obtained, as shown in equation (3) [31, 34–36]. In the formula, \( P_{pl} \) means the intrapulmonary pressure (pa), \( \rho \) means the air density (1.293 kg/m\(^3\)), \( R \) means the gas constant (297 J/(kg·K)), \( T \) means the temperature (K), \( Q \) means the volumetric flow rate, \( V \) means the lung volume, \( C \) means the pulmonary compliance, and \( m \) means the air mass.

\[
\frac{dP_{pl}}{dt} = \frac{\rho RTQV}{V^2 + CmRT}. 
\]

(3)

In the pneumatic model, the ratio of downstream pressure (\( P_d \)) to upstream pressure (\( P_u \)) of the throttle valve is bigger than 0.528, which means the airflow is subsonic [31, 34–36]. The equation of volumetric flow rate can be described as follows:

\[
Q = \frac{nA_e P_u \sqrt{1 - r}}{\rho \sqrt{RT}} \cdot \sqrt{1 - \left(\frac{P_{pl}/P_u}{1 - r}\right)^2}, 
\]

(4)

where \( n \) is the flow coefficient (equal to 1 during inhalation; equal to \(-1\) during exhalation), \( A_e \) is the effective sectional area of the throttle valve, and \( r \) is critical pressure ratio (0.528).

According to the definition of respiratory compliance, the differential equation of lung volume can be described as follows [31, 34–36]:

\[
dV = C \cdot dP_{pl}. 
\]

(5)

During the mechanical ventilation, the difference between the operating pressure of the ventilator and the patient’s intrapulmonary pressure produces inspiratory and expiratory airflows. The mathematical model as shown in equations (3)–(5) illustrates the correlation between the pressure and flow in the pneumatic model. During the clinical process, the pressure and flow in the mechanical system are affected by the respiratory mechanical parameters. The compliance and the airflow resistance are regarded as the main respiratory mechanical parameters [31]. The compliance reflects pulmonary ability to deform. The higher compliance results in the greater change in the lung volume at unit pressure, which is described as equation (5). The airflow resistance affects the volumetric flow rate. The
greater resistance results in the smaller volumetric flow rate. In the pneumatic model proposed in this article, the effect of the airflow resistance is equivalent to a throttle valve, as shown in Figure 1. Therefore, the effective sectional area of the throttle valve ($A_e$) is directly proportional to the airflow resistance. In equation (4), the effective sectional area of the throttle valve ($A_e$) is used to describe the effect of airflow resistance on the volumetric flow rate. According to the mathematical model, the simulation calculation can be carried out. In the calculation, the units of each physical quantity are the basic units of the international system of units. In the reports of clinical diagnosis and treatment or the display of parameters on the ventilator, the units of each physical quantity are converted into the units commonly used in the clinic. The corresponding units of each physical quantity are shown in Table 1.

### 2.2.4. Clinical Operation Principle and Simulation Parameter Settings

The clinician needs to make some presets on the ventilator according to the physical condition of the patient before the operation of mechanical ventilation. The clinical operation process of the mechanical ventilation is shown in Figure 3. The ventilator waveforms are affected by the interaction between the patient and the ventilator. Therefore, unreasonable presets, changes in the patient’s physical condition, and changes in the clinical environment can all lead to the occurrence of PVA, thus producing specific changes in the ventilator waveforms.

In this article, the PSV mode is the main ventilation mode for the research of patient-ventilator synchrony. This common ventilation mode has a wide range of applications and is involved in invasive and noninvasive ventilation and in weaning process. Based on the mathematical model of the pneumatic system of the patient and the ventilator, the mechanical ventilation process can be simulated. According to the parameter preset of clinical operation, the settings of simulation parameters are shown in Table 2 [30, 31, 37].

The ventilator waveforms are simulated as shown in Figure 4. The green dotted lines indicate the successful triggering of the breathing cycle. The red dotted lines indicate the termination of the inspiratory phase and the beginning of the expiratory phase.

In order to verify the accuracy of the model, an experimental prototype was established to obtain the experimental data to be compared with the simulation data. The experimental prototype consists of a lung simulator (ASL5000), a ventilator (Philips Respironics BiPAP ST30), and a PC, as shown in Figure 5. The lung simulator can simulate the natural respiratory process of the patients, which has been verified to be accurately fitted in clinical medicine [28–30]. The PC is the control center of the lung simulator, which can adjust the respiratory mechanical parameters to simulate the pathological difference in the patients. The ventilator is connected to the airway of the lung simulator to provide breathing support. By setting the ventilator to the PSV mode, the mechanical ventilation experiments in this article can be performed. The regulation of the ventilator parameters is regarded as the clinician’s operation process. The clinical operation process of the mechanical ventilation is illustrated in Figure 3. The goodness of fit ($R^2$) between the experimental curve and the simulation curve is calculated by equation (6). In the formula, $\bar{d}_i$ means the value of the simulation data, $\bar{d}$ means the average value of the experimental data, $d_i$ means the value of the experimental data, and $n$ means the number of samples. In Figure 4, $R^2$ values of the pressure curve, the flow curve, and the volume curve are 0.9423, 0.9378, and 0.9628. The values of $R^2$ verify the good fitting between the experimental curve and the simulation curve, thus verifying the validity of the pneumatic model and the accuracy of the mathematical model.

### Table 1: The units of basic physical quantity.

<table>
<thead>
<tr>
<th>Physical quantity</th>
<th>Calculation unit</th>
<th>Reported unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time</td>
<td>s</td>
<td>s</td>
</tr>
<tr>
<td>Pressure</td>
<td>Pa</td>
<td>cmH$_2$O</td>
</tr>
<tr>
<td>Volume</td>
<td>m$^3$</td>
<td>cmH$_2$O/L/s</td>
</tr>
<tr>
<td>Compliance</td>
<td>m$^2$/Pa</td>
<td>mL/cmH$_2$O</td>
</tr>
<tr>
<td>Mass</td>
<td>kg</td>
<td>—</td>
</tr>
<tr>
<td>Effective area</td>
<td>m$^2$</td>
<td>mm$^2$</td>
</tr>
</tbody>
</table>

### Table 2: The settings of simulation parameters.

<table>
<thead>
<tr>
<th>Physical quantity</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{PSV}$</td>
<td>17</td>
<td>cmH$_2$O</td>
</tr>
<tr>
<td>$P_{trigger}$</td>
<td>2</td>
<td>cmH$_2$O</td>
</tr>
<tr>
<td>PEEP</td>
<td>5</td>
<td>cmH$_2$O</td>
</tr>
<tr>
<td>$t_{rise}$</td>
<td>0.2</td>
<td>s</td>
</tr>
<tr>
<td>$k_{ter}$</td>
<td>10%</td>
<td>—</td>
</tr>
<tr>
<td>A</td>
<td>15</td>
<td>mm</td>
</tr>
<tr>
<td>C</td>
<td>50</td>
<td>mL/cmH$_2$O</td>
</tr>
<tr>
<td>$P_{mus,max}$</td>
<td>5</td>
<td>cmH$_2$O</td>
</tr>
<tr>
<td>$t_{dec}$</td>
<td>0.5</td>
<td>s</td>
</tr>
<tr>
<td>$t_{inc}$</td>
<td>0.75</td>
<td>s</td>
</tr>
<tr>
<td>$t_{fin}$</td>
<td>1</td>
<td>s</td>
</tr>
<tr>
<td>$T_{cycle}$</td>
<td>3</td>
<td>s</td>
</tr>
</tbody>
</table>

$k_{ter}$ represents the ratio of flow rate to peak flow rate at the end of inspiration, which determines the value of $t_{fin}$.
2.3. Classification and Detection of PVA. Considering the process of a typical breath, PVA usually occurs in four phases of each breathing cycle. According to these four phases, PVA can be divided into triggering asynchrony, inspiration asynchrony, switching asynchrony, and exhalation asynchrony. These phenomena can be detected and classified by observing and comparing pressure and flow waveforms. In this part, several main PVA phenomena in PSV ventilation mode are classified and reproduced through simulation, and the automatic detection method of PVA is described.

2.3.1. Triggering Asynchrony

(1) Ineffective Triggering. During clinical mechanical ventilation, the ventilator is usually triggered by the pressure or flow, which depends on the type of ventilation mode. The effort to breathe results in the variation of the pressure or flow in the airway. When the variation reaches the preset triggering level, the ventilator will be triggered and work. In this article, the ventilator works in PSV mode. Therefore, the triggering pressure is regarded as the trigger signal. The value is set to 2 cmH₂O as shown in Table 2. It is designed according to the general clinical standard in pressure support ventilation [30, 31, 37].

When the effort of patient’s respiratory muscle cannot reach the triggering level, the ventilator fails to be triggered and will not work. This phenomenon is called ineffective triggering. Usually, this phenomenon is caused by the sensitivity setting of the ventilator being too low (the trigger level is set too high) or the patient’s pathological changes (such as excessive airway resistance). As shown in Figure 6, the red arrows point to the occurrence of the ineffective triggering, and the blue dotted line indicates the start of ineffective effort. In the ventilator waveforms, the pressure is slightly reduced into a concave shape, corresponding to the short-term rise of the flow waveform, which constitutes a

\[ R^2 = \frac{\sum_{i=1}^{m} (\hat{d}_i - \bar{d})^2}{\sum_{i=1}^{m} (d_i - \bar{d})^2} \]  

(6)
short-term inspiratory flow. This reflects the patient’s efforts to inhale.

It can be seen from Figure 6 that the ineffective triggering may also occur in the expiratory phase. This is usually caused by the patient’s sudden inspiratory demand or a slight leak in the ventilation system.

(2) **Double Triggering.** When the patient’s breathing demand suddenly increases, the patient produces a second inspiratory effort in the same respiratory cycle and successfully triggers the ventilator, which will produce a double triggering asynchrony. As shown in Figure 7, the red arrows point to the occurrence of double triggering. It can be seen from the curve that when double triggering occurs, the exhalation time is less than half of the inhalation time, which can be regarded as an automatic detection standard. The peak flow of the second triggered cycle is often higher than the average peak flow, as shown by the red dotted line in Figure 7.

In addition, when premature switching occurs, if the patient’s continuous breathing effort is intense, a second respiratory cycle may be triggered, causing the double triggering. A cough may also trigger multiple respiratory cycles within a short period of time, but this is not considered to be double triggering.

(3) **Autotriggering.** In the mechanical ventilation system, there may be leakage in the mask, ventilation pipeline, pipeline interface, etc., which is especially common in noninvasive ventilation. When the leakage reaches the trigger level, the ventilator is triggered to work, causing the autotriggering asynchrony. As shown in Figure 8, the exhalation time of the autotriggering cycle is less than the average value. Different from the double triggering, the peak flow of the second cycle produced by the autotriggering is lower than the average level. This can be regarded as the detection criteria.

2.3.2. **Inspiration Asynchrony.** For the PSV mode, the inspiration asynchrony usually occurs during the pressure rise phase. The pressure rise time \( t_{rise} \) depends on the valve-opening rate of the ventilator. The value of \( t_{rise} \) can be preset by the clinician. If the rise time is too slow, the time to reach the effective ventilation level will be significantly delayed, and the ventilation flow will not reach the average level, resulting in insufficient tidal volume, as shown by the red arrow and red dotted line in Figure 9.

Conversely, if the pressure rise time is too fast, there will be a spike at the initial position of the inspiratory phase of the plateau pressure of the pressure-time waveform. Correspondingly, there will be an overshoot at the initial position of the inspiratory flow. By appropriately reducing the valve-opening rate or increasing the setting value of \( t_{rise} \), this phenomenon can be effectively improved.

2.3.3. **Switching Asynchrony**

(1) **Delayed Switching.** The accurate switching between inhalation and exhalation of mechanical ventilation affects the patient’s comfort and the effect of mechanical ventilation. If the ventilator is still supplying air after the termination of the patient’s inhalation, there will be a confrontation between the patient and the ventilator. When the confrontation occurs, the patient’s expiratory efforts produce changes of the intrapulmonary pressure, which makes the airway pressure suddenly rise at the end of the plateau pressure. Corresponding to the pressure, the patient’s inspiratory flow suddenly drops at the end of the inspiratory phase. In Figure 10, the red dotted line and the red arrow indicate the characteristic performance of the delayed switching.

(2) **Premature Switching.** For PSV ventilation mode, the switching time depends on the percentage of the peak flow, that is, the termination level of the inspiratory phase. If the termination level is set too high, the ventilator supply will be terminated prematurely. At the end of the ventilator supply, the patient has not yet completed the inhalation, and the inspiratory effort causes a brief reversal of the ventilator waveforms. As shown in Figure 11, the beginning of the expiratory phase of the flow waveform suddenly rebounds toward the baseline. Corresponding to the flow waveform, the pressure suddenly drops at the beginning of the expiratory phase and then rises again, showing a concave shape. The red dotted line and the red arrow indicate the characteristic performance of the delayed switching, and the blue dotted line shows the simulated waveform without confrontation. If the premature switching asynchrony is serious, it will cause double triggering.

2.3.4. **Exhalation Asynchrony.** Exhalation asynchrony is usually caused by too short or prolonged exhalation time. Premature switching will cause the prolonged exhalation...
If the exhalation time is too long, it will cause hypoventilation. Usually, prolonged exhalation is of little consequence to the subsequent cycles. However, shorten exhalation usually has the risk of causing endogenous positive end expiratory pressure (PEEPi). The presence of PEEPi often causes ineffective triggering of the subsequent

Figure 7: Ventilator waveforms of double triggering.

Figure 8: Ventilator waveforms of autotriggering.

Figure 9: Ventilator waveforms of inspiration asynchrony.

Figure 10: Ventilator waveforms of delayed switching.
cycles, as the patient has to overcome the additional positive end expiratory pressure to reach the trigger level. The presence of PEEPi can be detected by observing whether the inspiratory flow can return to baseline before the next breathing cycle. As shown in Figure 12, the red dotted line and red arrows point to the performance of the exhalation asynchrony. At the end of the expiratory phase, there is a certain difference between the intrapulmonary pressure and the airway pressure.

In addition, PEEPi is closely related to pathological changes in patients. When patients have pathological changes, such as chronic bronchitis, chronic obstructive pulmonary disease (COPD), and other diseases, which lead to structural destruction of the bronchial wall, thickening of the tube wall, stenosis of the lumen, and significant increase in expiratory resistance, the isobaric point is shifted inward. The expiratory process is not completed, but the bronchial collapse occurs, and positive pressure is formed in the alveoli.

2.4. Definition of Patient-Ventilator Synchrony Index. In the pressure support ventilation mode, the clinical regulation of mechanical ventilation is achieved through the control and adjustment of ventilator pressure. From the classification of PVA, it can be concluded that PVA usually occurs at different phases of each breathing cycle. Therefore, to evaluate patient-ventilator synchrony during mechanical ventilation, each breathing cycle is divided into four phases for analysis: (1) triggering phase; (2) rising phase; (3) inspiratory phase; and (4) expiratory phase. These four phases are determined based on the airway pressure waveform of the ventilator. As shown in Figure 13, point a is the triggering phase, the interval from point a to point b is the rising phase, the interval from point b to point c is the inspiratory phase, and the interval from point c to point d is the expiratory phase. ΔPins represents the difference between the abnormal pressure value and the normal pressure waveform.

Corresponding to the performance of patient-ventilator synchrony at different phases, a novel evaluation index of patient-ventilator synchrony, SI_{haao}, is proposed in this article.

\[
SI_{haao} = (SI_{t}, SI_{t}, SI_{p}, SI_{peep}). \tag{7}
\]

SI_{haao} is a vector, whose elements can be used as indicators for different problems of patient-ventilator synchrony. The set of SI_{t} is \{-1, 0, 1, 2\}. In the case of normal ventilation, the value of SI_{t} is 1. Different values represent different triggering asynchrony phenomena: 0 represents ineffective triggering; 2 represents double triggering; and -1 represents autotriggering. When a triggering problem occurs, the ventilator control parameters must be adjusted in time. Therefore, SI_{t} cannot only evaluate the triggering synchrony over time but also serve as an alarm for triggering asynchrony.

As shown in equation (8), the value of SI_{t} is equal to the ratio of \( t_{effective} \) and \( T_{cycle} \). When the airway pressure rises to 95% of \( P_{PSV} \), it can be considered that the ventilator pressure has reached an effective support level. If the pressure rise time of the ventilator is set too long, or the trigger level is set too high to trigger the ventilator immediately, the value of \( t_{effective} \) will increase significantly, delaying the effective ventilation and increasing the patient’s work of breathing. Therefore, when the value of SI_{t} exceeds the normal threshold value, it may correspond to the inspiration asynchrony caused by the excessively slow rise time, and the peak flow and tidal volume will significantly reduce. At the same time, the change of SI_{t} can also reflect the triggering synchrony, as the increase of SI_{t} reflects the delay of the trigger of the ventilator. Thus, when SI_{t} is abnormal, the trigger sensitivity can be fine-tuned if inspiration asynchrony is not detected.

As shown in Figure 14, \( \Delta P_{ins} \) represents the difference between the abnormal pressure value and the normal pressure waveform. When the delay switching occurs, there will be an overshoot at the end of the plateau pressure, and the value of \( \Delta P_{ins} \) is positive. When the premature switching occurs, there will be a sudden drop during the transition between the inspiratory phase and the expiratory phase, showing a concave shape on the pressure curve, and the value of \( \Delta P_{ins} \) is negative. Therefore, \( \Delta P_{ins} \) can be used as the characteristic quantity for synchrony evaluation.

\[
SI_{a} = \frac{\Delta P_{ins}}{P_{PSV}} \times 100%. \tag{9}
\]

The value of SI_{a}, as shown in equation (9), reflects the patient-ventilator synchrony in amplitude of ventilator waveform. It corresponds to some phenomena of the
inspiration asynchrony and switching asynchrony. When the switching asynchrony occurs, or during the normal ventilation, the value range of SI\textsubscript{a} is \((-1, 1)\). And the closer the value of SI\textsubscript{a} is to zero, the better the synchrony is. However, when the rise time of the pressure is too short, there will be a short-term spike at the beginning of the plateau pressure, as shown in Figure 15. In this case, the value of \(\Delta P_{\text{ins}}\) is also positive. In order to distinguish it from...
delayed switching, when the above phenomenon occurs, the calculation of SI adds 1 to the result of equation (9), and the value range becomes (1, 2).

SI_{peep} corresponds to the phenomenon of exhalation asynchrony, which is mainly manifested as the increase of endogenous positive end expiratory pressure (PEEPi). The value of PEEPi is closely related to pathological changes in patients and PVA caused by improper mechanical ventilation, so continuous monitoring of PEEPi is required during ventilation. However, the measurement of the intrapulmonary pressure imposes high requirements on the equipment and is not easy to achieve. Therefore, the judgement of the occurrence and increase of PEEPi is achieved through the detection of expiratory flow instead of the detection of intrapulmonary pressure. When the PEEP provided by the ventilator cannot offset PEEPi, the expiratory flow cannot return to zero before the next breathing cycle, as shown in Figure 16.

\[
SI_{peep} = \frac{\Delta F_{ex}}{F_{exmax}} \times 100\%.
\] (10)

In equation (10), the value of \(\Delta F_{ex}\) represents the difference between the end expiratory flow and zero, as shown in Figure 16. And the value of \(F_{exmax}\) represents the absolute value of the peak flow during the expiratory phase. Therefore, the higher value of SI_{peep} means the more serious phenomenon of exhalation asynchrony, and the value of PEEP need to be increased to offset the influence of PEEPi. During normal ventilation, the value of SI_{peep} is equal to 0.

3. Results and Discussion

Through the definition of SI_{hao}, it can be concluded that the evaluation index of patient-ventilator synchrony proposed in this paper is a vector index, and its four elements correspond to different aspects of PVA phenomena.

In the past, the asynchrony index was usually used as the evaluation index of patient-ventilator synchrony. The asynchrony index proposed by Thille is defined as follows [8]:

\[
AI_{Thille} = \frac{\text{Number of asynchrony phenomena}}{\text{Total breathing cycles (ventilator cycles + ineffective efforts)}} \times 100\%,
\] (11)

which counts the number of asynchrony phenomena within a certain period, such as 30 breathing cycles. This asynchrony index cannot analyze the synchrony of a single breathing cycle. Besides, Sinderby et al. proposed a neural index to automatically evaluate the patient-ventilator interaction. This index can reflect the timing synchrony and triggering synchrony between the patient’s spontaneous breathing and ventilator ventilation. However, the measurement requirement of EAdi makes it more difficult to obtain this index. Besides, it cannot reflect the PVA caused by the improper rise time of ventilator pressure and the increase of PEEPi, which makes the index have certain defects when evaluating the patient-ventilator synchrony.

Different from the traditional evaluation index, SI_{hao} can realize the single-period judgement, with a better real-time performance. As a vector index, it covers several major...
Figure 16: The effect of PEEP on expiratory flow.

Figure 17: Evaluating patient-ventilator synchrony of the breathing cycles with asynchrony phenomena.
asynchrony phenomena under PSV mode, which makes this index more convincing. Taking several different breathing cycles shown in Figure 17 as examples, the determination of corresponding asynchrony phenomena and SIhao is shown as follows:

(a) Inspiration asynchrony (longer rise time)

\[ t_{\text{effective}} = 0.53 \text{ s} \]

\[ SI_{\text{hao}} = (1, 17.67\%, 0, 0) \]

(b) Inspiration asynchrony (shorter rise time)

\[ t_{\text{effective}} = 0.14 \text{ s} \]

\[ \Delta P_{\text{ins}} = 1.8 \text{ cmH}_2\text{O} \]

\[ SI_{\text{hao}} = (1, 4.67\%, 1.11\%, 0) \]

(c) Switching asynchrony (delayed switching)

\[ t_{\text{effective}} = 0.32 \text{ s} \]

\[ \Delta P_{\text{ins}} = -3 \text{ cmH}_2\text{O} \]

\[ SI_{\text{hao}} = (1, 10.67\%, 17.65\%, 0) \]

(d) Switching asynchrony (premature switching)

\[ t_{\text{effective}} = 0.32 \text{ s} \]

\[ \Delta P_{\text{ins}} = -10 \text{ cmH}_2\text{O} \]

\[ SI_{\text{hao}} = (1, 10.67\%, -58.82\%, 0) \]

(e) Exhalation asynchrony

\[ t_{\text{effective}} = 0.32 \text{ s} \]

\[ k_{\text{ex}} = 20.3 \text{ L/min} \]

\[ SI_{\text{hao}} = (1, 10.67\%, 0, 36.25\%) \]

To define the pros and cons of the patient-ventilator synchrony, it is necessary to set a certain threshold value for SIhao. The setting of the threshold depends on the detection accuracy of each parameter and the normal variation range. According to the clinical experience of physicians [30, 38–40], \( P_{\text{trigger}} \) is usually set to 1 to 2 cmH\text{O}, \( t_{\text{rise}} \) is usually set to 0.1 to 0.3 s, and \( k_{\text{ex}} \) is usually set to 5–10%. The values of \( P_{\text{trigger}} \) and \( t_{\text{rise}} \) influence the variation of \( t_{\text{effective}} \). The value of \( k_{\text{ex}} \) influences the termination of the inspiratory phase and then affects the performance characteristics of switching asynchrony. Therefore, the thresholds of the elements of SIhao are set as shown in Table 3.

The corresponding threshold value also indicates the automatic detection standard of PVA. When the value of SI\( _{\text{tr}} \) is not displayed as 1, it means that the triggering asynchrony has occurred (0 represents ineffective triggering; 2 represents double triggering; and –1 represents autotriggering). When the value of SI\( _{\text{ins}} \) exceeds 15%, it means that the rising time from the triggering to the plateau pressure is too long to provide effective respiratory support in time. This abnormal value usually means the occurrence of inspiration asynchrony (the rising time is set too long) or delayed triggering. When the value of SI\( _{\text{p}} \) falls in (10%, 100%), it means the occurrence of delayed switching asynchrony. Correspondingly, when the value of SI\( _{\text{a}} \) falls in (–100%, –10%), it means the occurrence of premature switching asynchrony. It should be noted that when the value of SI\( _{\text{p}} \) exceeds 1, it means the occurrence of the inspiration asynchrony (the

### Table 3: The thresholds of the evaluation indices.

<table>
<thead>
<tr>
<th>Evaluation index</th>
<th>Normal value/threshold</th>
</tr>
</thead>
<tbody>
<tr>
<td>SI( _{\text{tr}} )</td>
<td>1</td>
</tr>
<tr>
<td>SI( _{\text{ins}} )</td>
<td>&lt;15%</td>
</tr>
<tr>
<td>SI( _{\text{p}} )</td>
<td>(–10%, 10%)</td>
</tr>
<tr>
<td>SI( _{\text{peep}} )</td>
<td>0</td>
</tr>
</tbody>
</table>

In addition, SIhao can also be used as the response parameter of ventilator regulation. If the asynchrony phenomenon occurs, the control parameters of the ventilator can be adjusted according to the corresponding evaluation index. As shown in Figure 18, the ventilator waveform data of each breathing cycle is analyzed to obtain the threshold range of the four elements of the vector, SIhao. After the threshold judgement, the control parameters can be adjusted according to the judgement results. If the value of the synchrony index exceeds the threshold, it will correspond to the specific asynchrony phenomena mentioned above. Then the control parameters could be adjusted according to the corresponding asynchrony phenomena. For example, when premature asynchrony occurs, the value of \( k_{\text{ex}} \) is appropriately lower. The adjustment of control parameters will realize the feedback control of the ventilator through the controller [41–44]. In future research, the control law will be designed to realize the adaptive control of the mechanical ventilation system.

### 4. Conclusion

In this research, a novel pneumatic model of the mechanical ventilation system is established to simulate the mechanical ventilation process, and different PVA phenomena are simulated. An experimental prototype is established to verify the validity of the pneumatic model and the accuracy of the mathematical equations. The goodness of fit between the experimental curve and the simulation curve exceeds 90%.

By analyzing the morphological characteristics of different asynchrony phenomena, the PVA phenomena are divided into four categories, namely, (1) triggering asynchrony; (2) inspiration asynchrony; (3) switching asynchrony; (4) exhalation asynchrony.
asynchrony; and (4) exhalation asynchrony. A method to detect different PVA phenomena by morphology was proposed in this article. Based on this method, almost all the PVA phenomena in pressure support ventilation are analyzed.

A new type of evaluation index, $SI_{hao}$, is established in this study, which completes the evaluation of patient-ventilator synchrony of each breathing cycle during mechanical ventilation in the form of a vector. It reflects the real-time performance of patient-ventilator synchrony with the use of a morphology-based method and gives the index for automatic evaluation. The four elements of the evaluation index correspond ingeniously to different types of PVA, establishing the link between synchrony evaluation and asynchrony detection. Therefore, the evaluation index, $SI_{hao}$, can also be used as a response parameter in the control of ventilator, optimizing the control algorithm, achieving the intelligent adjustment of parameters, and improving the patient-ventilator synchrony.

This work proposes a novel method to evaluate patient-ventilator synchrony during mechanical ventilation at the current stage. It solves certain problems of the existing results in clinical application. The existing asynchrony index cannot evaluate the performance of synchrony, while the synchrony index proposed in this article can comprehensively evaluate the patient-ventilator synchrony. The existing neural index needs to be obtained by the invasive operations, which adds difficulty to clinical promotion. In contrast, the method in this work is noninvasive, which is safer and more convenient.

This research can be used to adjust clinical strategies during mechanical ventilation. And it is helpful for the pathological analysis of patients during the treatment. It aims at reducing the burden on clinicians, optimizing the mechanical ventilation process, effectively reducing the complications caused by PVA, and realizing the adaptive control of the ventilator and weaning process in the future.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Authors’ Contributions

Liming Hao and Shuai Ren contributed equally to this work.

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References
