Synchronized Oxygen Delivery and Its Optimization Method: A Bench Study

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KEYWORDS: Synchronized demand oxygen delivery, Chronic obstructive pulmonary disease, Minimization of discomfort index, Prediction algorithm, Bench model

Long-term oxygen therapy (LTOT) has been widely used to treat patients with chronic obstructive pulmonary disease. The traditional oxygen delivery methods used for LTOT are continuous flow oxygen (CFO) and demand oxygen delivery (DOD). CFO wastes a considerable amount of oxygen, whereas DOD often makes patients feel uncomfortable because it abruptly supplies a large amount of oxygen at the onset of inhalation. Hence, we developed an algorithm for predicting the onset of inhalation, which allowed oxygen to be supplied smoothly before inhalation. Moreover, we minimized the discomfort index (DI) to offer more comfortable oxygen delivery. By integrating the prediction algorithm and the minimization of DI, the previous synchronized demand oxygen delivery (SDOD) method was modified. We constructed a bench model to validate the modified SDOD. The results showed that the proposed algorithm accurately predicted the onset of inhalation. The difference in the real-time measured and predicted values for the beginning of inhalation was less than 0.10 s. Using the proposed minimization technique, the DI was decreased by 50% under 20 breaths per minute when compared with the DI calculated from a previous study. In conclusion, the modified SDOD could supply oxygen more comfortably while synchronizing with patient breathing patterns.

1. Introduction

Recently, there has been an increasing number of patients with respiratory diseases, especially chronic obstructive pulmonary disease (COPD), owing to reasons such as smoking and air pollution.¹ Long-term oxygen therapy (LTOT) has been widely used for COPD patients because it can improve the survival of COPD patients with severe hypoxemia.² There are two typical methods for LTOT, continuous flow oxygen (CFO) and demand oxygen delivery (DOD); both have inherent shortcomings. CFO often restricts patients’ activities because of the large oxygen tank required for continuous delivery of oxygen and considerable waste of oxygen.³ Though current oxygen-conserving devices have adopted DOD, which supplies oxygen during inhalation only, to reduce wasted oxygen, it makes breathing uncomfortable for patients because of the abrupt supply of a preset amount of oxygen (bolus) as inhalation begins. In addition, when rapid changes in pressure or breathing patterns occur, oxygen may not be supplied because of low sensitivity in the pressure sensor used by DOD devices.⁴⁻⁷

A saving ratio (SR) is defined as the ratio between prescription flow rate \(Q_p\) (oxygen flow rate prescribed by clinicians) and supply flow rate \(Q_s\) (oxygen flow rate of oxygen delivery devices when using continuous flow oxygen). CFO does not conserve oxygen because it supplies oxygen continuously to patients at a flow rate as much as up to \(Q_p\). In other words, the SR of CFO is equal to one. On the other hand, DOD’s SR is as high as 3.4⁴ because it was primarily developed to conserve oxygen. Therefore, there is a wide gap between the SRs of CFO and DOD.

To offset the disadvantages of CFO’s and DOD’s approaches, a new oxygen delivery method, synchronized demand oxygen delivery (SDOD), was developed in the previous study.⁸ This method was designed not only to reduce patient discomfort, but also to conserve oxygen through synchronization with patient breathing patterns. SDOD could determine a time-dependent oxygen profile according to the patients’ breathing patterns and the SR. A discomfort index (DI) to quantitatively represent the level of discomfort of oxygen devices was defined and the actual feeling of discomfort among subjects has been shown to be strongly proportional to the logarithmic DI through
experiments. Thus, as the DI of an oxygen delivery device is decreased, a patient would feel more comfortable with the supply oxygen to him or her from the device.

SDOD supplies oxygen before inhalation to improve patient comfort during oxygen therapy. By adopting an S-shaped curve (logistic function), oxygen can be smoothly supplied to patients. In addition, oxygen should be supplied up to \( Q_p \). Thus, the flow rate of discharged oxygen should be raised to \( Q_p \) in accordance with the S-shaped curve, before inhalation. To supply oxygen before inhalation, it is necessary to accurately predict the beginning of patient inhalation accurately, making it possible to supply oxygen through the S-shaped oxygen profile before inhalation. However, one limitation of the previous study stems from the fact that SDOD did not predict the beginning of inhalation. In addition, current DODs, of which there are three types—pulse, demand, and hybrid—supply oxygen at the beginning of inhalation. Another limitation of the previous study stems from the fact that SDOD used only a fixed S-shaped discharge curve before inhalation. Therefore, when considering the fact that the current DODs and SDOD in the previous study cannot predict the onset of inhalation, developing an algorithm to predict the beginning of inhalation is necessary to make SDOD supply oxygen accurately before inhalation. Another limitation of the previous study stems from the fact that SDOD used only a fixed S-shaped curve without considering minimization of DI. To supply oxygen more comfortably, an algorithm to minimize DI is needed. Thus, the purpose of this study were (1) to develop an algorithm to predict the onset of inhalation to synchronize with patients’ breathing patterns, (2) to minimize the DI for more comfortable oxygen supply, and (3) to realize the modified SDOD method under normal breathing patterns using the bench model.

In the present study, the SDOD method was modified with two newly developed algorithms, one for predicting the onset of inhalation and another for minimizing DI. After establishing the SDOD method including these two algorithms, a bench model was realized and the overall performance of the modified SDOD was examined.

2. Materials and Methods

2.1 Algorithm to predict the onset of inhalation

The prediction algorithm for the beginning of inhalation consists of three steps. First, the beginning time of inhalation was predicted by modeling the patient’s breathing pattern. Second, the valve open time was determined. Third, oxygen was supplied in accordance with the S-shaped discharge curve before inhalation using a proportional valve to control the oxygen flow rate.

The parameters that represent the characteristics of breathing patterns were defined. The respiration cycle was divided into three stages: inhalation, exhalation, and a rest period. Inhalation and exhalation were represented as having the positive and negative values of flow rate, respectively. The rest period was assumed when the patient’s flow rate was between -0.5 liters per minute (LPM) and 0.5 LPM. A normal breathing pattern was represented by eight parameters that consisted of either time or flow rate. The names and definitions of the eight parameters are described in Fig. 1 and Table 1.

These breathing pattern parameters were measured from normal breathing in real time, and the breathing model was determined by linearly connecting each parameter. Hence, the breathing prediction model was determined when one breathing cycle was completed. After the breathing prediction model was defined, weighting factors were applied to the breathing parameters from three previous breathing cycles. The most recent breathing cycle was multiplied by a weighting factor of 0.5, the second most recent cycle was weighted by a multiple of 0.3, and the third most recent breathing cycle was multiplied by a 0.2 weighting factor. The initial prediction model was established by calculating the averages of the breathing parameters from three previous breathing cycles. After the initial prediction model was determined, it was corrected by comparing the parameters determined using the breathing prediction model with those from the real-time breathing. The peak point of the inhalation (\( \Delta T_1 \)), the rest period (\( \Delta T_3 \)), and the valley point of the exhalation (\( \Delta T_4 \)) were primarily used as reference points for correction. These parameters were corrected by the difference of \( \Delta T_1 \) between the initial breathing prediction model and the measured breathing in real time. For example, if \( \Delta T_1 \) of the initial breathing prediction model and the real-time breathing were 0.5 s and 0.4 s, respectively, then \( \Delta T_2 + \Delta T_3 \) and \( \Delta T_4 \) of the initial breathing model were each shortened by 0.1 s. A similar technique was applied to \( \Delta T_2 + \Delta T_3 \). The value of \( \Delta T_4 \) was increased or decreased by the difference between \( \Delta T_2 + \Delta T_3 \) from the initial prediction model and that from the real-time breathing. Finally, the value of \( \Delta T_3 \) and \( \Delta T_6 \) were increased or decreased by the difference between \( \Delta T_4 \) from the initial prediction model and that from the real-time breathing. Thus, the

![Fig. 1 Defined parameters for development of a breathing prediction model.](image)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
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<tbody>
<tr>
<td>( \Delta T_1 )</td>
<td>elapsed time from onset of inhalation to the peak point</td>
</tr>
<tr>
<td>( \Delta T_2 )</td>
<td>elapsed time from the peak point to the end of inhalation</td>
</tr>
<tr>
<td>( \Delta T_3 )</td>
<td>rest period (± 0.5 LPM)</td>
</tr>
<tr>
<td>( \Delta T_4 )</td>
<td>elapsed time from the beginning of exhalation to the valley point</td>
</tr>
<tr>
<td>( \Delta T_5 )</td>
<td>elapsed time from the valley point to end of exhalation</td>
</tr>
<tr>
<td>( \Delta T_6 )</td>
<td>rest period (± 0.5 LPM)</td>
</tr>
</tbody>
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