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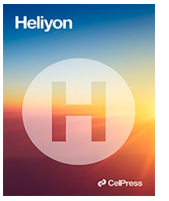

Effect of modified high-flow oxygen therapy on positive end-expiratory pressure and end-expiratory lung volume based on simulated lung platform

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ABSTRACT

Objective: The aim of this study was to assess the effect of modified high-flow oxygen therapy on end-expiratory lung volume (EELV) and positive end-expiratory pressure (PEEP) in tracheotomized patients with normal pulmonary, acute hypoxic respiratory failure (AHRF) or chronic obstructive pulmonary disease (COPD).

Methods: A ventilator and an artificial lung model were used to simulate the normal or strong inspiratory effort state of normal lung, AHRF and COPD patients. The traditional high-flow respiratory humidification therapy device connected with a standard interface (group A), and the modified therapy device added two types of resistance valves (group B, inner diameter 7.7 mm, length 24.0 mm; group C, inner diameter 7.7 mm, length 34.0 mm) to the exhalation end of the standard interface. The changes of end-expiratory lung volume (ΔEELV) and PEEP with the increase of flow rate (10 L/min, 20 L/min, 30 L/min, 40 L/min, 50 L/min, 60 L/min) in the three groups was recorded.

Results: Under simulated conditions of normal lung, AHRF and COPD, as the flow rate increased by using the modified therapy device, the PEEP values in all groups showed an exponential increasing trend, and the ΔEELV also increased accordingly. In addition, under the same flow rate level, the PEEP values of the two modified high-flow oxygen therapies (Group B and Group C) were significantly higher than those of the standard high-flow oxygen therapy (Group A) ($p < 0.05$). In the normal lung model with normal or strong inspiratory effort, and in the AHRF or COPD model with strong inspiratory effort, when the flow rate was higher than 30 L/min, the PEEP levels of Group B were significantly lower than those of Group C ($p < 0.05$). In the AHRF model with normal inspiratory effort, when the flow rate was between 10 L/min and 60 L/min, the PEEP levels of Group B were significantly lower than those of Group C ($p < 0.05$). Moreover, in the COPD model with normal inspiratory effort, the PEEP levels of Group B were significantly lower than that of Group C only when the flow rate was 60 L/min ($p < 0.05$).

Conclusion: The addition of different types of resistance valves to the high-flow exhalation end may be a feasible solution to improve the clinical efficacy of tracheotomized high-flow oxygen therapy.

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1. Introduction

High-flow oxygen therapy refers to the effective respiratory support provided to patients by delivering a high flow of accurately concentrated, heated, and humidified oxygen-air mixture [1]. Compared with conventional oxygen administration strategy, high-flow oxygen therapy has gradually become the mainstream choice in clinical practice due to its ability to produce positive pressure ventilation when delivering high-speed oxygen, as well as its non-invasive nature, ability to flush out ineffective anatomical spaces in the mouth and nose, and good tolerance [2,3]. Multiple studies have shown that high-flow nasal oxygen therapy could increase lung volume by producing flow-dependent positive end-expiratory pressure (PEEP), and was the main factor of high-flow oxygen therapy being more effective than traditional oxygen therapy in improving oxygenation [4,5]. Natalini et al. [6] found that compared with high-flow nasal oxygen therapy, high-flow oxygen therapy through a tracheostomy tube at a gas flow rate of 50 L/min resulted in significantly lower maximum expiratory pressure and PEEP. Additional studies have reported that high-flow oxygen therapy did not reduce respiratory effort or respiratory rate in tracheostomized patients, and their results suggested that the physiological effects of high-flow oxygen therapy through a tracheostomy might differ from those through nasal delivery [7]. However, it worth noting that neither of these studies have investigated the effect of expiratory resistance on the PEEP effect in tracheostomized patients under high-flow oxygen therapy.

In view of this, by using the in vitro pulmonary model, our research group undertook an attempt to improve the standard interface of tracheotomy high-flow oxygen therapy by adding a 5-cm H_2O/L/s resistance valve at the expiratory end and examined multiple spontaneous breathing parameters under different combinations of compliance and inspiratory drive (normal lung model and acute hypoxic respiratory failure (AHRF) model). Our findings suggested that when delivering 10–60 L/min of flow rate through the standard and improved interface, the PEEP levels of the modified interface group was significantly higher than that of the conventional interface group [8]. Nevertheless, it is noteworthy that there is still one unresolved problem in the application of this resistance valve, that is, the mismatch between this resistance valve and the standard interface. In addition, chronic obstructive pulmonary disease (COPD), as one of the most common and difficult to control respiratory diseases, has received increasing attention from clinicians. One study by Pilcher et al. [9] showed that high-flow oxygen therapy could reduce arterial partial pressure of carbon dioxide and respiratory effort in COPD patients, but its effects on COPD patients' respiratory mechanical load was unclear. Therefore, it is necessary to increase PEEP related studies on the use of high-flow oxygen therapy in COPD patients [10].

On the basis of the above background, we developed different types of resistance valves that could be detached from the expiratory end of a high-flow respiratory humidification device according to the treatment demands. Meanwhile, the second aim of this study is to further investigate the effect of this modified high-flow oxygen therapy interface on end-expiratory lung volume (EELV) and PEEP in different disease models, and providing experimental evidence for the promotion of resistance valve-optimized high-flow oxygen therapy.

2. Materials and methods

2.1. Modified high-flow respiratory humidification therapy device

The traditional high-flow respiratory humidification therapy device consists of an oxygen mixer, an active heating and humidification unit, and a heating loop, which is connected to the patient through a nasal cannula, mask, or standard interface. The standard interface is similar to a T-tube, with one end connected to the high-flow respiratory humidification therapy device and the other end having two ports, one of which is connected to the patient and the other to the atmosphere as the patient's exhaled gas end. The modified high-flow respiratory humidification therapy device adds a homemade resistance valve to the exhaled gas end of the traditional high-flow respiratory humidification therapy device (900PT501, Fisher & Paykel Healthcare, Auchland, New Zealand) to

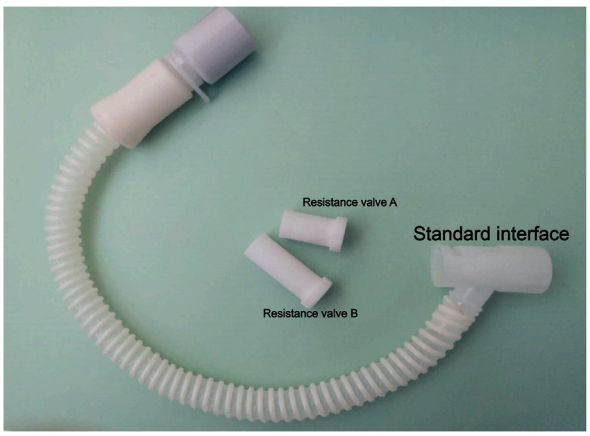

Fig. 1. Standard interface, resistance valve A and resistance valve B.

increase expiratory resistance. There are two types of resistance valves: resistance valve A, with an inner diameter of 7.7 mm and a length of 24.0 mm; resistance valve B, with an inner diameter of 7.7 mm and a length of 34.0 mm (Fig. 1). The self-made resistance valve is hollow cylindrical in shape. The inner diameter of this resistance valve is consistent with that of the standard high-flow interface, and it has a slot for attachment. In future applications, it can be connected to the interface end for continued use.

2.2. Spontaneous breathing model

We used an airtight dual-chamber lung simulator (Dual Adult Training Test Lung, Model 5600i, Michigan Instruments, Grand Rapids, MI, USA) and a ventilator (Puritan BennettTM 840, Covidien Co., Ltd., Tyco Healthcare International Trading, Shanghai, China) as the driving force to simulate spontaneous breathing. The two chambers of the simulator lung are connected by a rigid metal bridge. One chamber is connected to the driving ventilator as the driving lung, and the other chamber simulates spontaneous breathing under the action of the driving lung, i.e., the spontaneous breathing simulator lung.

2.3. Experimental grouping

Group A: High-flow humidification therapy device with a standard interface.
Group B: High-flow humidification therapy device with a standard interface and a resistance valve A.
Group C: High-flow humidification therapy device with a standard interface and a resistance valve B.

2.4. Parameter setting of different lung model

Normal lung model: airway resistance = 5 $cmH_2O/L/s$, lung compliance = 60 ml/cmH_2O
AHRF model: airway resistance = 5 $cmH_2O/L/s$, lung compliance = 30 ml/cmH_2O
COPD model: airway resistance = 20 $cmH_2O/L/s$, lung compliance = 60 ml/cmH_2O [8,11].

2.5. Parameter setting of inspiratory efforts

Normal inspiratory effort set the driving ventilator parameters as follows: volume-controlled ventilation mode, decelerating type, tidal volume (VT) = 600 mL, respiratory rate (RR) = 15 breaths/min, peak inspiratory flow rate of 50 L/min, and inspiratory-expiratory ratio of 1:2.

Strong inspiratory effort set the driving ventilator parameters as follows: volume-controlled ventilation mode, decelerating type, VT = 900 mL, RR = 15 breaths/min, peak inspiratory flow rate of 75 L/min, and inspiratory-expiratory ratio of 1:2.

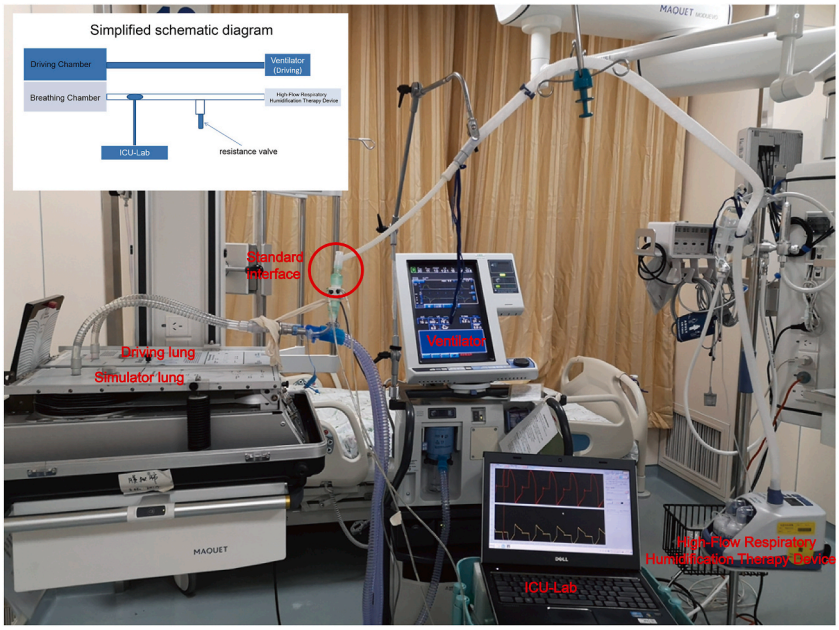

Fig. 2. Experimental platform.

2.6. Research procedure and observation indicators

After self-check and calibration experiments of each module in the experimental platform, the model was connected as shown in Fig. 2. The high-flow respiratory humidification therapy device was connected to the simulated lung via a 7.5-sized tracheal tube (Smiths Medical International Ltd, Kent, UK). The parameters of the driving ventilator and simulated lung were set. Under the same conditions, the high-flow respiratory humidification therapy device was set to a temperature of 37 °C, oxygen concentration of 21%, and flow rate gradually increased from 10 L/min to 60 L/min in increments of 10 L/min (10 L/min, 20 L/min, 30 L/min, 40 L/min, 50 L/min, 60 L/min). After a stable period of 10 min at each flow rate level, the connection between the high-flow humidified respiratory therapy device and the simulated lung was disconnected. Then, relevant data were monitored and recorded.

During the entire experiment, the ICU-lab (KleisTEK Engineering, Bari, Italy) was used to monitor and record the waveform of intrapulmonary pressure and time, as well as the waveform of airway pressure and time in the spontaneous breathing simulator lung. Meanwhile, the change of end-expiratory lung volume (ΔEELV) in the spontaneous breathing simulator lung was recorded when the high-flow respiratory humidification therapy device was disconnected from the simulated lung.

2.7. Statistical analysis

Statistical analysis was performed using SPSS 21.0 software. All continuous variables were firstly tested for normal distribution by using Kolmogorov-Smirnov test. Numerical variables satisfying normality were expressed as mean ± standard deviation (Mean ± SD). One-way ANOVA was used for comparison between three groups. And if the variance and normal distribution were consistent, the LSD method was used for pairwise comparisons, otherwise, the SNK-q test was used. The p value with less than 0.05 was taken as statistically significant.

3. Results

In normal lung model, AHRF model, and COPD model, both standard and modified high-flow oxygen therapies were tested under conditions of normal or strong inspiratory effort. The PEEP values increased exponentially with flow rate during both standard and modified high-flow oxygen therapies. Among all the different combinations, with the increase of flow rate, PEEP values exhibited an exponential growth trend. Meanwhile, as shown in Fig. 3, ΔEELV significantly increased in the modified high-flow oxygen therapy as flow rates increased, whereas no significant change in ΔEELV was observed with the standard high-flow oxygen therapy.

Comparisons of PEEP values under different conditions among the three groups were summarized. As can be seen from Fig. 4A–F, under the same flow rate level, the PEEP values of the two modified high-flow oxygen therapies (Group B and Group C) were higher than those of the standard high-flow oxygen therapy (Group A), and the differences were statistically significant ($p < 0.05$).

In the normal lung model with normal or strong inspiratory effort, when the flow rates were 10 or 20 L/min, there was no statistical difference between Group B and Group C about the PEEP levels ($p > 0.05$). While when the flow rate was higher than 20 L/min including 30 L/min, 40 L/min, 50 L/min, and 60 L/min, the PEEP levels of Group B were significantly lower than those of Group C ($p < 0.05$). In addition, among all different flow rates, the PEEP values in Group B and Group C were significantly higher than Group A ($p < 0.05$) (Table 1 and Table 2). In the AHRF model with strong inspiratory effort, when the flow rate was higher than 20 L/min, the PEEP levels of Group B were significantly lower than those of Group C ($p < 0.05$) (Table 3). In the AHRF model with normal inspiratory effort, when the flow rate was between 10 L/min and 60 L/min, the PEEP levels of Group B were significantly lower than those of Group C ($p < 0.05$), and the PEEP values in Group B and Group C were significantly higher than Group A ($p < 0.05$) (Table 4). In addition, in the COPD model with strong inspiratory effort, when the flow rate was in 20 L/min or more than 30 L/min including 40 L/

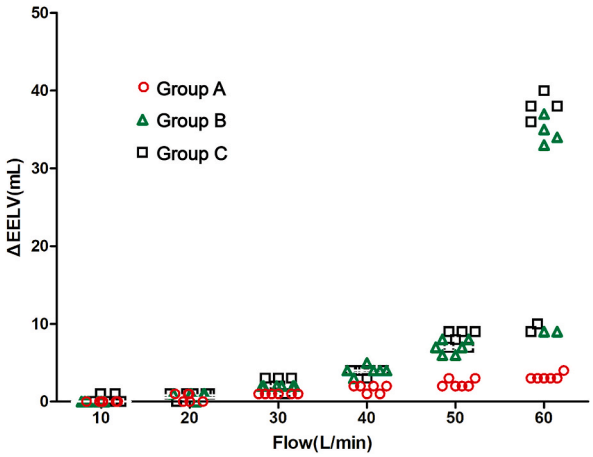

Fig. 3. Changes of ΔEELV with different flow rate in the three models.

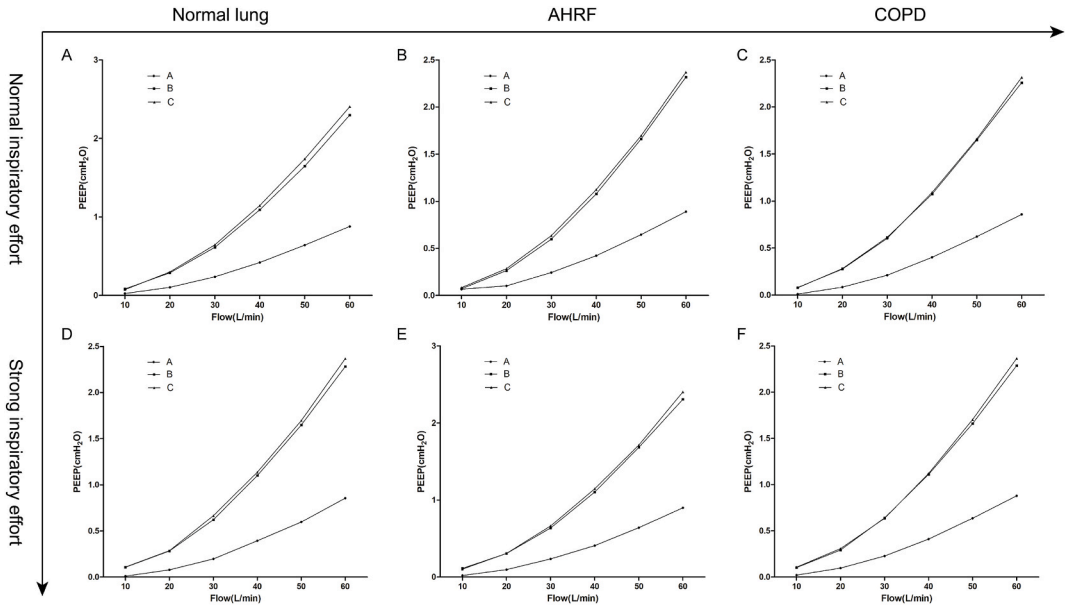

Fig. 4. Comparisons of PEEP values under different conditions among three groups. (A) Normal lung under normal inspiratory effort; (B) AHRF under normal inspiratory effort; (C) COPD under normal inspiratory effort; (D) Normal lung under strong inspiratory effort; (E) AHRF under strong inspiratory effort; (F) COPD under strong inspiratory effort.

min, 50 L/min, and 60 L/min, the PEEP levels of Group B were significantly lower than those of Group C ($p < 0.05$) (Table 5). And in the COPD model with normal inspiratory effort, the PEEP levels of Group B were significantly lower than that of Group C only when the flow rate was 60 L/min ($p < 0.05$) (Table 6).

4. Discussion

Tracheostomy is an important emergency rescue measure for critically ill patients and has been widely used in clinical practice. High-flow oxygen therapy has become a common oxygen therapy method after tracheostomy due to its good comfort and tolerance, sufficient heating and humidification, stable oxygen concentration, and flushing of ineffective anatomical cavities [2,10]. A previous meta-analysis including 2781 patients showed that compared with traditional oxygen therapy and noninvasive mechanical ventilation, high-flow oxygen therapy was more helpful in improving patient's prognosis, and could significantly reduce the re-intubation rate and complications [12]. Several studies on nasal high-flow oxygen therapy suggested that the increase of end-expiratory lung volume caused by PEEP effect might be the core determinant of improving patients' respiratory mechanics and oxygenation [13,14]. Some scholars have proposed that the production of PEEP effect during nasal high-flow oxygen therapy was mainly related to the increase of expiratory resistance caused by high-flow gas encountering the nasal airway [15,16]. However, many previous studies reported that PEEP effect was significantly weakened in patients undergoing tracheostomized high-flow oxygen therapy. It is hypothesized that the reduction of expiratory resistance due to the bypass of the larynx and upper airway by the high-flow gas may be an important reason for the limited PEEP effect in tracheostomized patients [17,18].

In view of this, our research group have designed a resistance valve device to artificially increase expiratory resistance. An in vitro artificial lung model study conducted by our group found that the resistance valve could significantly increase EELV and PEEP in both normal lung and AHRF models, and all the above parameters were within the acceptable physiological range for patients [6]. In present study, we further optimized the resistance valve device based on the previous experiment. Two types of resistance valves that matched the high-flow standard interface for exhalation were designed, thereby, further improving the high-flow respiratory

Table 1
Comparison of PEEP values among the three normal groups at different flow rates under strong inspiratory effort (cmH_2O).

	Flow(L/min)					
	10	20	30	40	50	60
Group A	0.011 ± 0.008	0.078 ± 0.010	0.197 ± 0.009	0.393 ± 0.006	0.597 ± 0.019	0.856 ± 0.022
Group B	0.107 ± 0.007※	0.283 ± 0.010※	0.622 ± 0.011※	1.100 ± 0.008※	1.648 ± 0.013※	2.282 ± 0.026※
Group C	0.109 ± 0.012※	0.286 ± 0.017※	0.666 ± 0.013※*	1.137 ± 0.013※*	1.696 ± 0.021※*	2.368 ± 0.012※*
F-value	232.580	529.413	3430.982	12414.293	7025.689	10082.571
p-value	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001

※Compared with Group A, $p < 0.05$; *Compared with Group B, $p < 0.05$.

Table 2
Comparison of PEEP values among the three normal groups at different flow rates under normal inspiratory effort (cmH_2O).

	Flow(L/min)					
	10	20	30	40	50	60
Group A	0.025 ± 0.005	0.104 ± 0.007	0.237 ± 0.012	0.420 ± 0.011	0.641 ± 0.016	0.879 ± 0.009
Group B	0.083 ± 0.014※	0.289 ± 0.013※	0.613 ± 0.013※	1.092 ± 0.008※	1.647 ± 0.007※	2.298 ± 0.021※
Group C	0.075 ± 0.007※	0.299 ± 0.010※	0.645 ± 0.011※*	1.147 ± 0.009※*	1.739 ± 0.017※*	2.404 ± 0.027※*
F-value	67.286	703.657	2129.811	10969.723	10907.417	10609.309
p-value	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001

※Compared with Group A, $p < 0.05$; *Compared with Group B, $p < 0.05$.

Table 3
Comparison of PEEP values among the three AHRF groups at different flow rates under strong inspiratory effort (cmH_2O).

	Flow(L/min)					
	10	20	30	40	50	60
Group A	0.020 ± 0.007	0.096 ± 0.008	0.235 ± 0.007	0.408 ± 0.010	0.641 ± 0.013	0.900 ± 0.012
Group B	0.113 ± 0.007※	0.305 ± 0.010※	0.636 ± 0.008※	1.104 ± 0.016※	1.683 ± 0.019※	2.307 ± 0.013※
Group C	0.103 ± 0.006※*	0.307 ± 0.005※	0.663 ± 0.014※*	1.147 ± 0.019※*	1.714 ± 0.015※*	2.403 ± 0.015※*
F-value	331.722	1276.882	3223.049	4392.972	8716.114	24476.686
p-value	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001

※Compared with Group A, $p < 0.05$; *Compared with Group B, $p < 0.05$.

Table 4
Comparison of PEEP values among the three AHRF groups at different flow rates under normal inspiratory effort (cmH_2O).

	Flow(L/min)					
	10	20	30	40	50	60
Group A	0.067 ± 0.010	0.102 ± 0.008	0.244 ± 0.007	0.422 ± 0.009	0.646 ± 0.007	0.890 ± 0.020
Group B	0.071 ± 0.006※	0.264 ± 0.006※	0.597 ± 0.011※	1.078 ± 0.012※	1.661 ± 0.023※	2.318 ± 0.009※
Group C	0.084 ± 0.011※*	0.284 ± 0.011※*	0.634 ± 0.007※*	1.123 ± 0.015※*	1.696 ± 0.006※*	2.370 ± 0.011※*
F-value	5.640	848.089	3678.785	6250.540	10727.669	21717.864
p-value	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001

※Compared with Group A, $p < 0.05$; *Compared with Group B, $p < 0.05$.

Table 5
Comparison of PEEP values among the three COPD groups at different flow rates under strong inspiratory effort (cmH_2O).

	Flow(L/min)					
	10	20	30	40	50	60
Group A	0.021 ± 0.008	0.097 ± 0.004	0.227 ± 0.007	0.411 ± 0.010	0.636 ± 0.013	0.879 ± 0.009
Group B	0.103 ± 0.009※	0.292 ± 0.006※	0.640 ± 0.015※	1.111 ± 0.016※	1.660 ± 0.016※	2.288 ± 0.009※
Group C	0.107 ± 0.011※	0.307 ± 0.008※*	0.635 ± 0.009※	1.121 ± 0.010※*	1.704 ± 0.016※*	2.365 ± 0.014※*
F-value	157.463	2097.545	2745.090	6227.709	9385.996	35788.946
p-value	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001

※Compared with Group A, $p < 0.05$; *Compared with Group B, $p < 0.05$.

Table 6
Comparison of PEEP values among the three COPD groups at different flow rates under normal inspiratory effort (cmH_2O).

组别	Flow(L/min)					
	10	20	30	40	50	60
Group A	0.011 ± 0.004	0.085 ± 0.007	0.211 ± 0.010	0.401 ± 0.006	0.621 ± 0.010	0.858 ± 0.011
Group B	0.077 ± 0.008※	0.281 ± 0.007※	0.614 ± 0.007※	1.074 ± 0.019※	1.648 ± 0.015※	2.259 ± 0.007※
Group C	0.080 ± 0.010※	0.276 ± 0.007※	0.603 ± 0.004※*	1.091 ± 0.017※	1.660 ± 0.018※	2.314 ± 0.010※*
F-value	145.095	1500.859	5485.706	4199.548	10039.150	43221.517
p-value	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001

※Compared with Group A, $p < 0.05$; *Compared with Group B, $p < 0.05$.

humidification therapy device. Meanwhile, previous studies have shown that high-flow oxygen therapy was beneficial for increasing tidal volume and reducing respiratory frequency in COPD patients, thus reducing respiratory effort [19–21]. However, unlike AHRF, COPD patients themselves have the characteristic of obvious difficulty in exhalation. Therefore, the addition of a resistance valve to these patient's exhalation end may have a potential disadvantage to their ventilation. Considering this, the present study added a COPD model in addition to the normal lung and AHRF models. Overall, this study further verified the effect of modified high-flow oxygen therapy on EELV and PEEP in normal lungs, AHRF, and COPD models under three physiological states based on an in vitro lung platform. And also preliminarily verified the efficacy of using two types of resistance valves, providing a theoretical basis for further optimizing the design of resistance valves.

Consistent with our prior results, this study also found that modified high-flow oxygen therapy could increase PEEP and EELV levels in simulated normal lung and AHRF models [8]. Nevertheless, we further confirmed a significant increase of PEEP and EELV in COPD models with the use of modified high-flow oxygen therapy. Among the three simulated models, modified high-flow oxygen therapy significantly increased PEEP levels compared to standard high-flow oxygen therapy. However, standard high-flow oxygen therapy did not increase PEEP levels to clinically relevant levels. Furthermore, with modified high-flow oxygen therapy, increasing PEEP levels significantly increased ΔEELV, while with standard high-flow oxygen therapy, PEEP levels only slightly increased with increasing flow rate, resulting in smaller changes in lung volume. All the above findings confirm that adding a resistance valve at the expiratory end of high-flow oxygen therapy is able to increase PEEP levels in tracheotomized patients, thereby increasing EELV. The increase in PEEP levels in these patients is related to expiratory resistance and flow rate. These findings suggest that for tracheotomized patients, if traditional oxygen therapy is ineffective, high-flow oxygen therapy can be used to adjust flow rate and increase expiratory resistance within an acceptable range to improve patient oxygenation.

In the normal lung model with normal or strong inspiratory efforts, as well as in the AHRF model with intense inspiratory efforts, the mean PEEP level in group B was significantly lower than that in group C when the flow rate exceeded 30 L/min. In the AHRF model with normal inspiratory efforts, the mean PEEP level in group B was significantly lower than that in group C when the high flow rate ranged from 10 L/min to 60 L/min. These results could be explained by Poiseuille's law, which states that the fluid resistance in a horizontal cylindrical tube under laminar flow is mainly determined by the radius, length, and viscosity of the fluid [22]. The two types of resistance valves have the same inner diameter (7.7 mm), whereas the main difference lies in the length, with a 10 mm longer length for resistance valve B than resistance valve A. As a result, the resistance valve B could produce a higher expiratory resistance effect, leading to a higher PEEP. In contrast to the above two models, patients with COPD have poor lung compliance and high airway resistance. The difference between group B and group C is statistically significant only when the flow rate reached 60 L/min during normal inspiratory efforts. However, during strong inspiratory efforts, the difference between group B and group C was statistically significant when the flow rate exceeded 30 L/min. These results suggest that strong inspiratory efforts may be more beneficial for improving oxygenation in COPD patients by flushing and ventilating the airflow. However, it should be noted that due to the high expiratory resistance in COPD patients, the effect of PEEP caused by the length changes of the two types of resistance valves is limited. Therefore, there was no statistically significant difference in the PEEP level between group B and group C at lower flow rates and during normal inspiratory effort. Moreover, in clinical use, we tend to start with a flow rate of 30–40 L/min and adjust the FiO2 to achieve the desired peripheral oxygen saturation. If symptoms do not improve, we may subsequently increase the flow rate by 5–10 L/min. In the balance between flow rate and FiO2 adjustments, we tend to prefer higher flow rates to ensure that the FiO2 remains $\leq$60%. When the patient's flow rate is $\leq$ 20 L/min and FiO2 $\leq$50%, switching to traditional low-flow oxygen therapy, such as nasal cannula, could be considered. In this study, the difference between group C and group B was statistically significant only when the flow rate of the AHRF group was $\leq$30 L/min. Therefore, this modification may not provide significant benefits for patients requiring lower levels of high-flow support.

5. Limitations

Due to the limitations of technology and experimental conditions, this study still has some shortcomings. Firstly, our study is mainly based on an in vitro simulation platform, although different physiological conditions are simulated, the human body is a complex system and there are individual differences. Therefore, the parameters set in the study may could not fully reflect the real clinical model. Secondly, although consistent with previous research findings, that is higher flow levels were associated with higher EELV values [8]. However, in the bench model, the measured ΔEELV was found to be lower than the theoretical volume change. This discrepancy could be attributed to the fact that the system is an open circuit. In our experiment, we did not occlude the tracheostomy tube, but only performed end-expiratory occlusion in the driving ventilator and disconnected the high-flow tracheal oxygen interface. As a result, the measured tracheal PEEP resembled a dynamic PEEP, comprising resistance-related components and compliance. The impact of high-flow tracheal oxygen on EELV also requires further investigation, which is acknowledged as a limitation of this study. Thirdly, regarding the setting of strong inspiratory effort, this condition simulates the tidal volume pattern under the circumstance of intense inspiratory effort in patients. Based on relevant literature and combined with clinical experience, we chose to set the tidal volume at 900 ml to simulate the state of strong inspiratory effort. It is important to note that this setting is not a parameter used in clinical ventilator management for patients. Moreover, multiple mechanisms may contribute to the clinical benefits of high-flow oxygen, including more reliable delivery of high fractions of inspired oxygen, flushing of dead space in the upper airway, and provision of adequate humidification and PEEP effects [23]. In this study, we only focused on the effects of high-frequency ventilation on PEEP and lung volumes. The results for statistically different PEEP levels at lower flow levels also do not confirm that increased flow levels are not clinically beneficial. The feasibility and safety of modified transtracheal high flow requires further animal studies. Additionally, although this study designed resistance valves of different lengths, there was still a lack of setting for resistance valves

with different inner diameters, which will be the focus of our research team's optimization in the future.

6. Conclusion

In the autonomous breathing platform, the modified high-flow oxygen therapy with a resistance valve could increase clinically relevant levels of PEEP and EELV. The length of the resistance valve has a certain effect on the change of PEEP level. Therefore, addition of different types of resistance valves to the high-flow exhalation end may be a feasible solution to improve the clinical efficacy of tracheotomized high-flow oxygen therapy. And also, the clinical feasibility and safety of this approach need to be further investigated.

Author contribution statement

Kunming Cheng: Performed the experiments; Contributed reagents, materials, analysis tools or data; Wrote the paper. Wanqing Li: Yanqiu Lu: Analyzed and interpreted the data. Haiyang Wu: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper. Jianxin Zhou: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data.

Data availability statement

Data will be made available on request.

Additional information

No additional information is available for this paper.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] S.D. Levy, J.W. Alladina, K.A. Hibbert, et al., High-flow oxygen therapy and other inhaled therapies in intensive care units, Lancet 387 (10030) (2016) 1867–1878.
[2] M. Nishimura, High-flow nasal cannula oxygen therapy in adults: physiological benefits, indication, clinical benefits, and adverse effects[J], Respir. Care 61 (4) (2016) 529–541.
[3] Y.N. Ni, J. Luo, H. Yu, et al., Can high-flow nasal cannula reduce the rate of endotracheal intubation in adult patients with acute respiratory failure compared with conventional oxygen therapy and noninvasive positive pressure ventilation?: a systematic review and meta-analysis[J], Chest 151 (4) (2017) 764–775.
[4] J.C. Luo, M.S. Lu, Z.H. Zhao, et al., Positive end-expiratory pressure effect of 3 high-flow nasal cannula devices[J], Respir. Care 62 (7) (2017) 888–895.
[5] F. Vargas, M. Saint-Leger, A. Boyer, et al., Physiologic effects of high-flow nasal cannula oxygen in critical care subjects[J], Respir. Care 60 (10) (2015) 1369–1376.
[6] D. Natalini, D.L. Grieco, M.T. Santantonio, et al., Physiological effects of high-flow oxygen in tracheostomized patients[J], Ann. Intensive Care 9 (1) (2019) 114.
[7] T. Stripoli, S. Spadaro, R. Di Mussi, et al., High-flow oxygen therapy in tracheostomized patients at high risk of weaning failure[J], Ann. Intensive Care 9 (1) (2019) 4.
[8] G.Q. Chen, X.M. Sun, Y.M. Wang, et al., Additional expiratory resistance elevates airway pressure and lung volume during high-flow tracheal oxygen via tracheostomy[J], Sci. Rep. 9 (1) (2019), 14542.
[9] J. Pilcher, L. Eastlake, M. Richards, et al., Physiological effects of titrated oxygen via nasal high-flow cannulae in COPD exacerbations: a randomized controlled cross-over trial[J], Respirology 22 (6) (2017) 1149–1155.
[10] L. Spicuzza, M. Schisano, High-flow nasal cannula oxygen therapy as an emerging option for respiratory failure: the present and the future[J], Ther Adv Chronic Dis 11 (2020), 1754211882.
[11] A. Lyazidi, A.W. Thille, G. Carteaux, et al., Bench test evaluation of volume delivered by modern ICU ventilators during volume-controlled ventilation, Intensive Care Med. 36 (12) (2010) 2074–2080.
[12] H.W. Huang, X.M. Sun, Z.H. Shi, et al., Effect of high-flow nasal cannula oxygen therapy versus conventional oxygen therapy and noninvasive ventilation on reintubation rate in adult patients after extubation: a systematic review and meta-analysis of randomized controlled trials[J], J. Intensive Care Med. 33 (11) (2018) 609–623.
[13] A. Corley, L.R. Caruana, A.G. Barnett, et al., Oxygen delivery through high-flow nasal cannulae increase end-expiratory lung volume and reduce respiratory rate in post-cardiac surgical patients[J], Br. J. Anaesth. 107 (6) (2011) 998–1004.
[14] T. Mauri, C. Turrini, N. Eronia, et al., Physiologic effects of high-flow nasal cannula in acute hypoxemic respiratory failure[J], Am. J. Respir. Crit. Care Med. 195 (9) (2017) 1207–1215.
[15] H. Kumar, C.J. Spence, M.H. Tawhai, Modeling the pharyngeal pressure during adult nasal high flow therapy[J], Respir. Physiol. Neurobiol. 219 (2015) 51–57.
[16] T. Mundel, S. Feng, S. Tatkov, et al., Mechanisms of nasal high flow on ventilation during wakefulness and sleep[J], J. Appl. Physiol. 114 (8) (1985) 1058–1065, 2013.
[17] K. Chadda, B. Louis, L. Benaissa, et al., Physiological effects of decannulation in tracheostomized patients[J], Intensive Care Med. 28 (12) (2002) 1761–1767.

[18] S.K. Epstein, Anatomy and physiology of tracheostomy[J], Respir. Care 50 (4) (2005) 476–482.
[19] C.C. Lee, D. Mankodi, S. Shaharyar, et al., High flow nasal cannula versus conventional oxygen therapy and non-invasive ventilation in adults with acute hypoxemic respiratory failure: a systematic review[J], Respir. Med. 121 (2016) 100–108.
[20] J. Sun, Y. Li, B. Ling, et al., High flow nasal cannula oxygen therapy versus non-invasive ventilation for chronic obstructive pulmonary disease with acute-moderate hypercapnic respiratory failure: an observational cohort study[J], Int. J. Chronic Obstr. Pulm. Dis. 14 (2019) 1229–1237.
[21] S. Kageyama, N. Takeishi, H. Taenaka, et al., Fluid dynamic assessment of positive end-expiratory pressure in a tracheostomy tube connector during respiration, Med. Biol. Eng. Comput. 60 (10) (2022) 2981–2993.
[22] J.K. Marr, L.G. Yamamoto, Gas flow rates through transtracheal ventilation catheters, Am. J. Emerg. Med. 22 (4) (2004) 264–266.
[23] T. Mauri, L. Alban, C. Turrini, et al., Optimum support by high-flow nasal cannula in acute hypoxemic respiratory failure: effects of increasing flow rates, Intensive Care Med. 43 (10) (2017) 1453–1463.