Oxygen Therapy Delivery and Body Position Effects Measured With Electrical Impedance Tomography

Zhiyong Yuan, Xiaoning Han, Lisha Wang, Ping Xue, Yunbo Sun, Inéz Frerichs, Knut Möller, Jinyan Xing, and Zhanqi Zhao

BACKGROUND: The aim of this prospective randomized crossover study was to compare the short-term effects of high-flow nasal cannula (HFNC) therapy and a 45° head-up tilt to the short-term effects of conventional oxygen (O_2) therapy in post-abdominal surgery patients. METHODS: A total of 18 subjects who were successfully weaned from ventilator support after abdominal surgery were included in the study. The subjects were randomly assigned to 2 groups: conventional O_2 was applied in group A for 15 min, and HFNC (60 L/min) was applied in group B for 15 min. A 15-min washout period with conventional O_2 was performed before the interventions were switched in both groups. Heart rate, blood pressure, breathing frequency, ratio of arterial partial pressure of oxygen to the fraction of inspired oxygen (P_{aO_2}/F_{IO_2}), and subject-reported comfort scores were recorded. Changes in end-expiratory lung impedance (EELI) were calculated with electrical impedance tomography. RESULTS: Results are presented as the percent change in lung volume compared to baseline during volume-controlled continuous mandatory ventilation before extubation. HFNC improved EELI in both the ventral (conventional O_2 vs HFNC, −48.2% ± 41.0 vs −30.0% ± 40.3, $P < .001$) and the dorsal (conventional O_2 vs HFNC, −37.0% ± 75.9 vs −26.5% ± 68.4, $P = .02$) regions of the lungs. Subjective subject-reported scores indicated that HFNC was more comfortable than conventional O_2 (conventional O_2 vs HFNC, 5.8 ± 1.5 vs 6.9 ± 1.9, $P = .02$). No differences were found in the other examined parameters. A head-up tilt position with conventional O_2 improved EELI in the dorsal regions (55.9% ± 100.1, $P < .001$) but not in the ventral regions (−37.9% ± 43.1%, $P = .38$) of the lungs compared to HFNC or conventional O_2 alone. CONCLUSIONS: In post-abdominal surgery subjects who had been extubated, HFNC improved lung volume and patient comfort. A head-up tilt position introduced a heterogeneous increase in EELI in the dorsal regions of the lungs. HFNC therapy may be beneficial in this patient group. (ChiCTR1900020886, http://chictr.org.cn) *Key words: high-flow nasal cannula; 45-degree head-up tilt; end-expiratory lung impedance; abdominal surgery.* [Respir Care 2020;65(3):281–287. © 2020 Daedalus Enterprises]

Introduction

Postoperative pulmonary complications contribute to an increased length of hospital stay and higher mortality rates after surgery.[1] Studies indicate that 5–10% of all surgical patients and 9–40% of those undergoing abdominal surgery experience postoperative pulmonary complications.[2]

Drs Yuan, Han, Xue, Sun, and Xing are affiliated with the Department of Critical Care Medicine, and Ms Wang are affiliated with the Department of Oncology, Affiliated Hospital of Qingdao University, Qingdao, Shandong, China. Dr Frerichs is affiliated with the Department of Anaesthesiology and Intensive Care Medicine, University Medical Centre of Schleswig-Holstein Campus Kiel, Germany. Drs Möller and Zhao are affiliated with the Institute of Technical Medicine, Furtwangen University, Villingen-Schwenningen, Germany. Dr Zhao is also affiliated with the Department of Biomedical Engineering, Fourth Military Medical University, Xi'an, China.

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Atelectasis is one of the possible major causes of these complications. When patients are under general anesthesia and in the supine position, functional residual capacity (ie, the volume remaining in the lungs after passive expiration) may be reduced by up to 1.5 L.[3] Atelectasis may develop in the most dependent lung regions after intubation in up to 90% of patients with normal lungs.[4] After disconnection from mechanical ventilation, further alveolar de-recruitment occurs, especially in the gravity-dependent lung regions. Atelectasis changes the mechanics of regional lung aeration, which may predispose patients to pneumonia and hypoxemia with prolonged oxygen and antibiotic therapies.[5,6]

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High-flow nasal cannula (HFNC) therapy might provide an alternative option to conventional O_2 therapy and noninvasive ventilation. In HFNC therapy, heated and humidified air is delivered via nasal prongs with a flow up to 60 L/min and with the prescribed F_{IO_2}. The principle underlying HFNC therapy guarantees certain positive physiological effects, including the generation of flow-dependent CPAP and reduction of dead space.[7,8] The use of HFNC therapy in the ICU has increased in the past few years due to its proven benefits, such as reduced re-intubation rate,[10] in certain clinical contexts (eg, acute respiratory failure).[9] HFNC therapy could have potential therapeutic advantages over conventional O_2 therapy regarding postoperative alveolar collapse and pulmonary atelectasis after extubation; however, the evidence is still controversial. A study in subjects who underwent cardiac surgery showed that HFNC therapy reduced further respiratory interventions.[11] Another study indicated that no significant differences were found in the prevention of respiratory complications after abdominal surgery compared with conventional O_2 therapy.[12] The reasons for this discrepancy require further study.

Electrical impedance tomography (EIT) is a noninvasive, radiation-free imaging technique that monitors ventilation distribution in real time.[13] It has been demonstrated that an adequate correlation exists between end-expiratory lung volume and end-expiratory lung impedance (EELI).[14] Previous studies in healthy and postcardiac surgical subjects found that HFNC therapy increases EELI compared with conventional O_2 therapy,[15,16] which may explain the beneficial effects of HFNC therapy. Until now, the effects of HFNC therapy on patients after abdominal surgery have not been studied.

QUICK LOOK

Current knowledge

High-flow nasal cannula (HFNC) increases end-expiratory lung impedance (EELI) compared to conventional O_2 therapy in healthy subjects and postcardiac surgical patients. The effects of HFNC therapy on patients after abdominal surgery have not been studied.

What this paper contributes to our knowledge

HFNC therapy improved EELI in both the ventral and dorsal regions of the lungs. Subjective subject-reported scores indicated that HFNC therapy might provide more comfort than conventional O_2 therapy. A head-up tilt with conventional O_2 therapy improved EELI in the dorsal but not in the ventral regions of the lungs compared to HFNC therapy or conventional O_2 therapy alone.

We performed a prospective randomized crossover study to assess the short-term physiological effects of HFNC therapy in subjects after abdominal surgery. The primary aim of this study was to analyze the changes in EELI between HFNC therapy and conventional O_2 therapy. The secondary aims of the study were to investigate changes in breathing frequency, subject-reported comfort level, and the ratio of arterial partial pressure of oxygen to the fraction of inspired oxygen (P_{aO_2}/F_{IO_2}) between these 2 therapies. Further, the changes in EELI introduced by HFNC therapy were compared to a 45° head-up tilt position with conventional O_2 therapy.

Methods

The study was approved by the institutional Human Research and Ethics Committee of the Affiliated Hospital of Qingdao University. The study was registered online (ChiCTR1900020886). Written informed consent was obtained from all patients prior to the study.

Patients scheduled for abdominal surgery were included prospectively. They were mechanically ventilated for approximately 24 h in the ICU after abdominal surgery secondary to a variety of factors including advanced age, underlying disease, prolonged operation time, and scope of the operation. Subjects were ready for weaning from mechanical ventilation prior to inclusion in the study. The exclusion criteria included age < 18 y, presence of a nasogastric tube, and other contraindications for EIT usage

Correspondence: Jinyan Xing MD, Department of Critical Care Medicine, the Affiliated Hospital of Qingdao University, No. 16, Jiangsu Rd, Shinan District, Qingdao, Shandong, China. E-mail: xingjy@qduhospital.cn.

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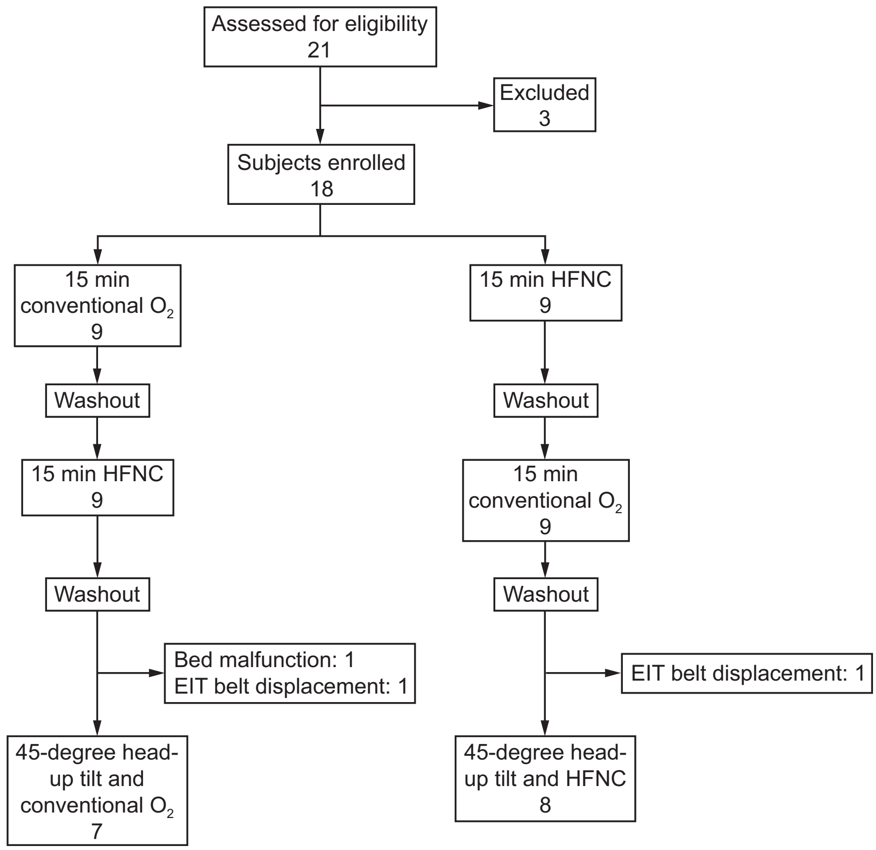

Fig. 1. Flow chart. HFNC = high-flow nasal cannula, EIT = electrical impedance tomography.

(eg, pacemaker, automatic implantable cardioverter defibrillator, implantable pumps).

All subjects were sedated and ventilated under volume-controlled continuous mandatory ventilation in line with standard postoperative ventilator settings in our ICU (Draeger Evita XL, Dräger Medical, Lübeck, Germany; breathing frequency 15 breaths/min, PEEP 4 cm H_2O, and tidal volume 8 mL/kg). Pain intensity was assessed with an 11-point numerical rating scale, and analgesia was administered to keep the score < 4 to ensure breathing without discomfort or restriction. After weaning and extubation, the subjects were in the supine position and received conventional O_2 therapy for 15 min (Xinji Kangye Medical, Hebei, China). The oxygen flow was titrated individually, ranging from 2 to 5 L/min to maintain $S_{pO_2} \geq 95\%$. In this crossover study, subjects were randomly assigned to 2 groups at this point (Fig. 1): subjects in group A continued to receive conventional O_2 therapy for 15 min, an subjects in group B were switched to HFNC therapy with a humidifier (Optiflow system, MR850 heated humidifier, RT202 delivery tubing and RT050/051 nasal cannulae, Fisher and Paykel Healthcare, Auckland, New Zealand). The F_{IO_2} level was titrated to maintain $S_{pO_2} \geq 95\%$, and the flow was set to 60 L/min. A 15-min washout period with conventional O_2 therapy was subsequently performed before the interventions in both groups were switched for an additional 15 min. A second washout period was performed, and subjects in both groups were tilted in a head-up position to 45° with the use of an electric bed.

An EIT electrode belt, which carries 16 electrodes with a width of 40 mm, was placed around the thorax in the fifth intercostal space, and one reference electrode was placed at the subjects' abdomen while avoiding the wound (PulmoVista 500, Dräger Medical). EIT images were continuously recorded at 40 Hz and stored. EIT data were reconstructed with the baseline value set to the lowest impedance value measured during volume-controlled continuous mandatory ventilation in the supine position. Data were filtered using a fourth-degree low-pass Butterworth filter with a cut-off frequency of 50/min to eliminate impedance changes synchronous with the heart rate. The last minute of the EIT data at every phase was analyzed.

Data Collection and Statistical Analysis

At the end of each phase (Fig. 1), collection of the following data was performed in all subjects: heart rate, blood pressure, and breathing frequency rate (IntelliVue MP60, Philips, Boeblingen, Germany); P_{aO_2}/F_{IO_2} (ABL90 FLEX, Radiometer Medica ASP, Denmark); and subject-

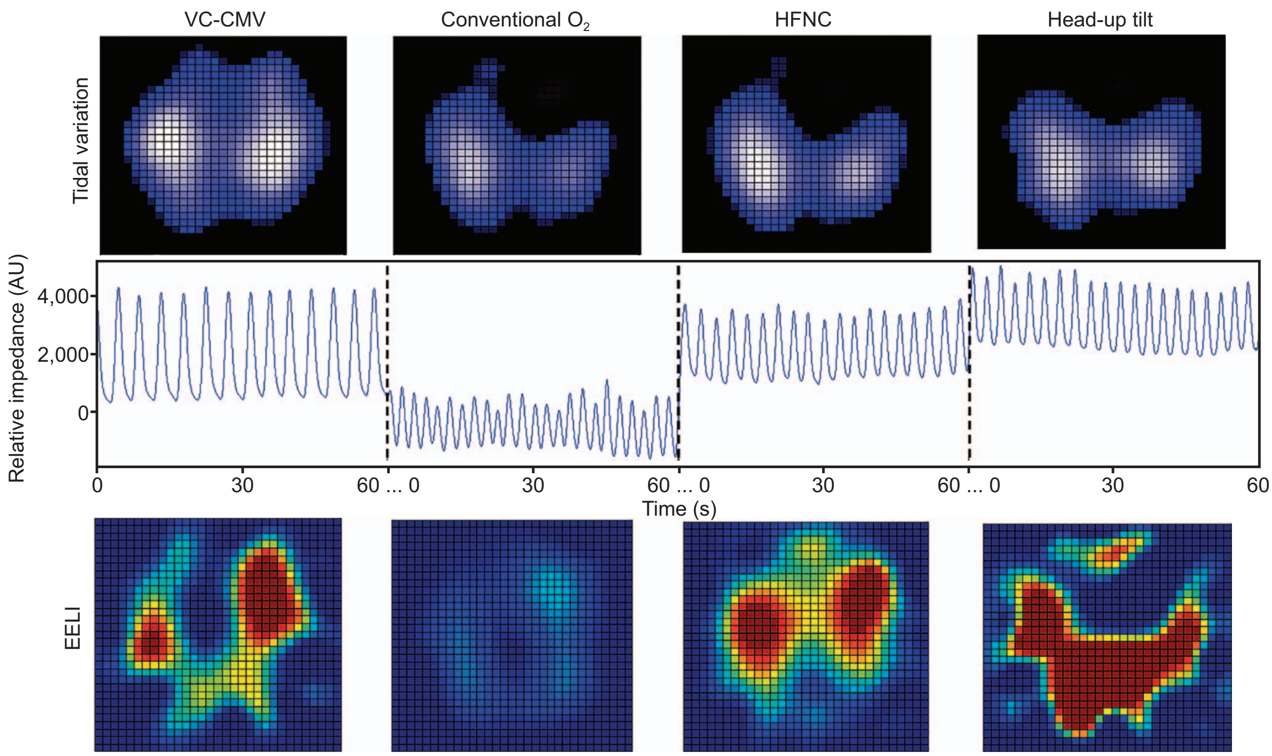

Fig. 2. Ventilation distribution at different study phases. The last minute of EIT data from each phase is presented. In the tidal variation images, highly ventilated regions are coded in light blue. Pixel values are relative impedance in arbitrary units, and the same scale is applied to all 4 panels. In the end-expiratory lung impedance images, regions with high end-expiratory lung volume are coded in red. Pixel values are relative impedance in arbitrary units, and the same scale is applied to all 4 panels. VC-CMV = volume-controlled continuous mandatory ventilation; HFNC = high-flow nasal cannula; head-up tilt = 45° head-up tilt with conventional O_2; AU = arbitrary units; EIT = electrical impedance tomography.

reported subjective comfort scores (ranging from 0 to 10, with 0 indicating extreme discomfort). Tidal variation was defined as the impedance differences between end-inspiration and end-expiration. The change in EELI was calculated relative to the average EELI at baseline, normalized to tidal variation at baseline, and reported as a percentage.

Data analysis was performed using MATLAB 7.2 (MathWorks, Natick, Massachusetts). The normal distribution of the data was confirmed with a Lilliefors test. Results are expressed as the mean ± SD in the case of a normal distribution. A paired *t* test was used to evaluate differences in the parameters collected during conventional O_2 therapy and HFNC therapy. Changes in EELI between conventional O_2 therapy and HFNC therapy were also compared to those during the 45° head-up tilt using a *t* test. $P < .05$ was considered statistically significant. Significance levels were corrected where applicable for multiple comparisons using Holm's sequential Bonferroni method.

Results

In total, 21 subjects were screened, and 3 were excluded due to unstable vital signs. Eighteen subjects were randomized to group A or group B (age 65.0 ± 9.4 y; male:female ratio 9:9; height 163.4 ± 7.4 cm; weight 61.9 ± 11.2 kg; body mass index 23.1 ± 3.0 kg/m^2). The types of surgery included partial hepatectomy, radical operation for colon tumor, and radical surgery for gastric cancer. Example EIT measurement results from a typical patient are shown in Figure 2. During conventional O_2 therapy and HFNC therapy, the tidal volume was smaller compared to that observed during volume-controlled continuous mandatory ventilation, and ventilation was mainly distributed into dorsal regions of the lungs. EELI during conventional O_2 therapy was generally lower than that in the other phases. The increase in EELI during the 45° head-up tilt mainly occurred in the dorsal regions of the lungs.

Table 1 summarizes the parameters evaluated in this study comparing the effects of conventional O_2 therapy and HFNC therapy on circulation and respiration. P_{aO_2}/F_{IO_2}, subject-reported comfort score, and global and regional EELI were significantly higher during HFNC therapy than during conventional O_2 therapy.

Comparing the EELI changes during phase 3 (45° head-up tilt with conventional O_2 therapy) to either conventional O_2 therapy alone or HFNC therapy, EELI during

Table 1. Effects of Conventional O_2 Therapy and HFNC Therapy on Circulation and Respiration

Evaluated Parameters	Conventional O_2 Therapy	HFNC Therapy	*P*
Heart rate, beats/min	88.6 ± 17.0	82.7 ± 22.2	.21
Blood pressure, mm Hg			
Systolic	138.1 ± 19.4	137.0 ± 19.9	.45
Diastolic	67.4 ± 10.6	66.3 ± 12.9	.35
Breathing frequency, breaths/min	19.7 ± 3.2	19.0 ± 3.0	.18
P_{aO_2}/F_{IO_2}, mm Hg	286.7 ± 88.1	320.2 ± 50.9	.053
Subject-reported comfort scores	5.8 ± 1.5	6.9 ± 1.9	.02
Change in EELI from baseline (% of tidal variation)			
Global	−86.6 ± 101.6	−56.2 ± 92.6	.003
Ventral regions	−48.2 ± 41.0	−30.0 ± 40.3	< .001
Dorsal regions	−37.0 ± 75.9	−26.5 ± 68.4	.02

n = 18 subjects in each group.
HFNC = high-flow nasal cannula
P_{aO_2}/F_{IO_2} = ratio of arterial partial pressure of oxygen to the fraction of inspired oxygen
EELI = end-expiratory lung impedance

phase 3 was significantly higher than in both other therapies (18.1 ± 124.8 vs −86.6 ± 101.6 and −56.2 ± 92.6 compared to conventional O_2 therapy and HFNC therapy, respectively; both $P < .001$). The EELI changes in the dorsal regions of the lungs during phase 3 were significantly higher as well (55.9 ± 100.1 vs −37.0 ± 75.9 and −26.5 ± 68.4 compared to conventional O_2 therapy and HFNC therapy, respectively; both $P < .001$; Fig. 3). The EELI changes in the ventral regions of the lungs were not different during conventional O_2 therapy and HFNC therapy (−37.9 ± 43.1 vs −48.2 ± 41.0 compared to conventional O_2 therapy, $P = .38$; vs −30.0 ± 40.3 compared to HFNC therapy, $P = .17$).

Discussion

In this study, 18 subjects were studied after abdominal surgery and successful weaning from mechanical ventilation. We noted that HFNC therapy improved EELI in both the ventral and dorsal regions of the lungs. Subjective subject-reported scores indicated that HFNC therapy might be more comfortable. Head-up tilt with conventional O_2 therapy improved EELI in the dorsal but not in the ventral region of the lungs compared to HFNC therapy and conventional O_2 therapy alone.

It is well known that general anesthesia is associated with a reduction in functional residual capacity.[17] Mechanical ventilation contributes additionally to heterogeneous ventilation distribution.[18] Spontaneous breathing leads to ventilation redistribution toward dorsal regions,[19] which may be beneficial to reduce atelectasis introduced by anesthesia and mechanical ventilation. However, after extubation, especially with insufficient end-expiratory positive pressure support, lung volume may fall significantly.[20] The use of HFNC therapy has been indicated to increase lung volume in different patient groups, such as infants with bronchiolitis,[21] patients with acute hypoxemic respiratory failure,[22] and postcardiac surgical patients.[16] In this study of post-abdominal surgery patients, HFNC therapy improved EELI in both the ventral and dorsal regions of the lungs.

Plotnikow et al[15] studied the influence of body position and HFNC therapy on lung volume and breathing frequency in healthy volunteers. They found that changing the body position to semi-upright introduced an EELI increase in both the ventral and dorsal regions of the lungs

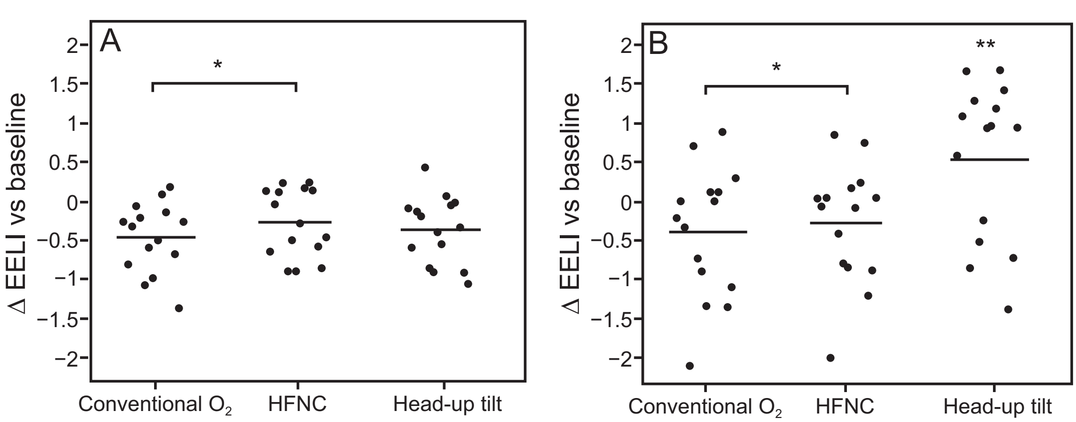

Fig. 3. Comparison of EELI during conventional O_2 therapy, HFNC therapy, and 45° head-up tilt in the ventral (A) and dorsal regions (B) of the lungs. Horizontal lines show the mean EELI in the corresponding phase. * $P < .05$ between conventional O_2 and HFNC therapy; ** $P < .001$ between conventional O_2 and head-up tilt and between HFNC therapy and head-up tilt. EELI = end-expiratory lung impedance; HFNC = high-flow nasal cannula.

compared to the supine position. Their findings coincided with those from a previous study in which leaning forward was compared with upright position.[23] Further, Vogt et al[23] determined that the changes in EELI in the ventral and dorsal regions of the lungs were diverse in subjects with obstructive lung disease who exhibit EELI increases in ventral regions and decreases in dorsal regions of the lungs when leaning forward compared to when they were upright. Spooner et al[24] studied the effect of the body position with a head-up tilt up to 30° on EELI in postcardiac surgery subjects. They found improvement in EELI in the dorsal but not in the ventral regions of the lungs. Similar results were found in our study, in which a 45° head-up tilt increased EELI only in the dorsal regions of the lungs (Fig. 3). A critique of the technical aspects of the article by Spooner et al[24] was that they compared the relative impedance values of different subjects directly, which were in fact not comparable due to varying baseline values.[13] In addition, the authors speculated that the dorsal regions of the lungs became less dependent when the head of the bed was elevated, whereby ventilation was redistributed from the ventral to the dorsal regions. However, a redistribution of ventilation during a head-up tilt position was not observed in our subjects (eg, Fig. 2, first row). We suspect that the diaphragm of the subjects may be shifted further toward the abdomen in the head-up tilt position, which introduced improvement in EELI in the dorsal regions of the lungs. Due to dissimilar diaphragmatic activities among the subjects, the variation in EELI changes in the dorsal regions was higher than that in ventral regions (Fig. 3). Another potential reason for our finding is that the 45° head-up tilt position may reduce intra-abdominal pressure, which might cause dependent atelectasis.

Improved oxygenation with HFNC therapy was observed compared to conventional O_2 therapy, but the difference was not statistically significant (Table 1). Subjects generally felt more comfortable with HFNC therapy. These findings were in agreement with previous studies on HFNC therapy in other patient groups.[25] In a previous randomized study, no improvement of postoperative hypoxemia was observed with HFNC therapy compared to conventional O_2 therapy. We suspect that the surgical subjects studied by Futier et al[12] were ventilated with a lung-protective ventilation strategy and were directly extubated after surgery. Given the low incidence and severity of postoperative atelectasis, no improvement in oxygenation with HFNC therapy was demonstrated. On the other hand, subjects in our study were first treated in the ICU on mechanical ventilation for numerous reasons. Subjects were exposed to higher risks of atelectasis and hypoxemia. The superiority of HFNC therapy over conventional O_2 therapy may only become manifest in such patient groups and requires further investigation. The subject-reported comfort score is subjective and might be influenced by various factors. The procedures in our study were not blinded, which might have impacted the score. Because we did not instruct subjects on the differences between HFNC therapy and conventional O_2 therapy, the bias might not be one-sided. The small number of subjects and lack of a control cohort were considered limitations of this study. Information on other outcome parameters, such as re-intubation rate and length of hospital stay, may add further knowledge to help understand the efficacy of HFNC therapy. Nevertheless, in this preliminary crossover study, we were able to demonstrate the effectiveness of HFNC therapy and a head-up tilt position on lung volume, which inspires further investigation.

Conclusions

In subjects who have been extubated after abdominal surgery, HFNC therapy in the ICU improved lung volume and subject comfort. A head-up tilt position introduced a heterogeneous increase in EELI in the dorsal regions of the lungs. HFNC therapy may be beneficial in this patient group.

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