

Removal of a catheter mount and heat-and-moisture exchanger improves hypercapnia in patients with acute respiratory distress syndrome

A retrospective observational study

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Abstract

To avoid ventilator-associated lung injury in acute respiratory distress syndrome (ARDS) treatment, respiratory management should be performed at a low tidal volume of 6 to 8 mL/kg and plateau pressure of ≤ 30 cmH₂O. However, such lung-protective ventilation often results in hypercapnia, which is a risk factor for poor outcomes. The purpose of this study was to retrospectively evaluate the effectiveness and safety of the removal of a catheter mount (CM) and using heated humidifiers (HH) instead of a heat-and-moisture exchanger (HME) for reducing the mechanical dead space created by the CM and HME, which may improve hypercapnia in patients with ARDS.

This retrospective observational study included adult patients with ARDS, who developed hypercapnia (PaCO₂ > 45 mm Hg) during mechanical ventilation, with target tidal volumes between 6 and 8 mL/kg and a plateau pressure of ≤ 30 cmH₂O, and underwent stepwise removal of CM and HME (replaced with HH). The PaCO₂ values were measured at 3 points: ventilator circuit with CM and HME (CM + HME) use, with HME (HME), and with HH (HH), and the overall number of accidental extubations was evaluated. Ventilator values (tidal volume, respiratory rate, minutes volume) were evaluated at the same points.

A total of 21 patients with mild-to-moderate ARDS who were treated under deep sedation were included. The values of PaCO₂ at HME (52.7 ± 7.4 mm Hg, $P < .0001$) and HH (46.3 ± 6.8 mm Hg, $P < .0001$) were significantly lower than those at CM + HME (55.9 ± 7.9 mm Hg). Measured ventilator values were similar at CM + HME, HME, and HH. There were no cases of reintubation due to accidental extubation after the removal of CM.

The removal of CM and HME reduced PaCO₂ values without changing the ventilator settings in deeply sedated patients with mild-to-moderate ARDS on lung-protective ventilation. Caution should be exercised, as the removal of a CM may result in circuit disconnection or accidental extubation. Nevertheless, this intervention may improve hypercapnia and promote lung-protective ventilation.

Abbreviations: ARDS = acute respiratory distress syndrome, CM = catheter mount, HH = heated humidifiers, HME = heat-and-moisture exchanger, ICU = intensive care unit, PBW = predicted body weight, PEEP = positive end-expiratory pressure, SC = suction catheter, VC = ventilator circuit.

Keywords: acute respiratory distress syndrome, dead space, heat-and-moisture exchanger, carbon dioxide, permissive hypercapnia, ventilation

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SS was responsible to statistical analysis.

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The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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1. Introduction

To avoid ventilator-associated lung injury in acute respiratory distress syndrome (ARDS) treatment, respiratory management should be performed with tidal volumes between 6 and 8 mL/kg and a plateau pressure of ≤ 30 cmH₂O.^[1] However, this lung-protective approach to ventilation often results in hypercapnia. Previously, hypercapnia during lung-protective ventilation was accepted (permissive hypercapnia).^[2]

However, recently, it has become clear that hypercapnia is associated with adverse outcomes.^[3] This association is due to pulmonary hypertension and pulmonary vascular dysfunction caused by hypercapnia.^[4] As a result, it has been proposed that PaCO₂ levels should remain < 48 to 50 mm Hg to protect the right ventricular function.^[5,6] Concurrently, a high respiratory rate to improve hypercapnia may cause dynamic hyperinflation, which may drastically impair right heart function.^[7] In addition, recent studies have examined the increase in in-hospital mortality rates associated with an increase in mechanical power,^[8] which is derived from tidal volume, driving pressure, flow rate, positive end-expiratory pressure (PEEP), and respiratory rate values.^[9] In addition to limiting the tidal volume, plateau, and driving pressure values, a high respiratory rate must be avoided. Extracorporeal CO₂ removal may improve hypercapnia^[10]; however, this approach requires special equipment, and the number of facilities that performs it is limited. A simple intervention to improve hypercapnia is required.

Using heated humidifiers (HH) instead of a heat-and-moisture exchanger (HME) and reducing the mechanical dead space created by HME may improve hypercapnia.^[11–16] Although a catheter mount (CM) (or extension tube, flexible tubing) is a tubing system commonly inserted between the breathing circuit and endotracheal tube to create a flexible connection and prevent circuit disconnection and accidental extubation, it may create a mechanical dead space for the patients. It has been reported that its removal in addition to HME removal may improve hypercapnia.^[17] However, previous studies involved relatively few patients with ARDS; moreover, no previous study has evaluated the effectiveness and safety of CM and HME removal in daily clinical practice.

The aim of this study was to retrospectively evaluate the effectiveness and safety of a CM and HME removal (replaced with HH) at reducing mechanical dead space during lung-

protective ventilation and improving hypercapnia in patients with ARDS.

2. Methods

This retrospective observational study was conducted at an 8-bed general intensive care unit (ICU) at the Nagasaki University Hospital (Nagasaki, Japan). This study protocol adhered to the Declaration of Helsinki, and the ethical approval was provided by the Institutional Review Board of the Nagasaki University Hospital (No. 20072007-2). The informed consent requirement was waived due to the retrospective nature of the study.

2.1. Study population

This study included adult (age > 18 years) patients with ARDS, who developed hypercapnia (PaCO₂ level > 45 mm Hg) during mechanical ventilation targeting tidal volumes between 6 and 8 mL/kg and a plateau pressure of ≤ 30 cmH₂O with a CM and an HME, while under deep sedation at our institution's ICU between November 2018 and November 2020. The patients underwent stepwise removal of CM and HME (replaced with HH) for mechanical dead space reduction. The diagnosis of ARDS was based on the Berlin definition.^[18] Patients were excluded from the present study if they met the following criteria: lack of data on blood gas analysis performed before or after each step, > 90 minutes required for blood gas analysis before and after the removal of CM and HME, changes to ventilator settings or dose of sedatives, required fluid resuscitation or cardiovascular agonists dose adjustment owing to cardiovascular instability during the observation period, underwent bronchoscopy or repositioning during the observation period.

2.2. Data collection

The primary endpoints were PaCO₂ values at 3 points: the use of a ventilator circuit (VC) with a CM and an HME (CM + HME) (Fig. 1A), an HME (Fig. 1B), and an HH (Fig. 1C). These data were extracted from the ICU information system (Prescient ICU; FUJIFILM Medical Co., Ltd., Tokyo, Japan). The values of tidal volume, tidal volume/predicted body weight (PBW), respiratory rate, minute volume, and blood gas analysis data (pH, PaO₂, and

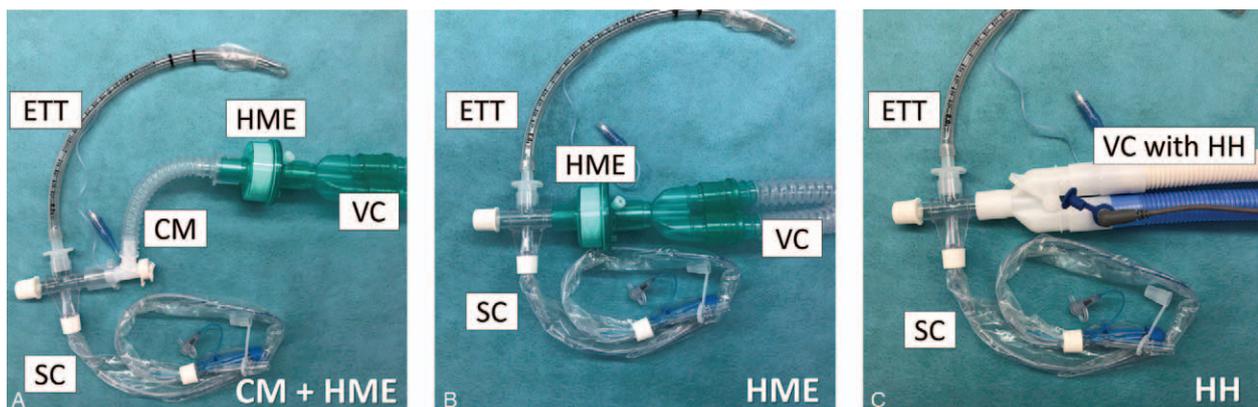


Figure 1. Configuration of the catheter mount and heat-and-moisture exchanger ventilator circuit, heat-and-moisture exchanger ventilator circuit, and head humidifiers. (A): Suction catheter (SC) connected endotracheal tube (ETT), catheter mount (CM), heat-and-moisture exchanger (HME), and ventilator circuit (VC). (B): SC, connected HME and VC. (C): SC and VC connected with heated humidifiers (HH).

base excess values) at CM + HME, HME, and HH, and the time interval between CM + HME and HH were also extracted. The secondary endpoint in the present study was the overall number of accidental extubations after the removal of CM during ICU stay.

Patients' baseline characteristics collected on the day of CM and HME removal were extracted from the electronic medical records system (MegaOakHR; NEC Corp., Tokyo, Japan) and the ICU information system and included the following variables: age, sex, body mass index, PBW, etiology of ARDS, history of chronic obstructive pulmonary disease, sequential organ failure assessment score,^[19] vasoactive-inotropic score (calculated in this study as dopamine dose [$\mu\text{g}/\text{kg}/\text{min}$] + dobutamine dose [$\mu\text{g}/\text{kg}/\text{min}$] + $100 \times$ epinephrine dose [$\mu\text{g}/\text{kg}/\text{min}$] + $25 \times$ olprinone dose [$\mu\text{g}/\text{kg}/\text{min}$] + $10,000 \times$ vasopressin dose [units/kg/min] + $100 \times$ norepinephrine dose [$\mu\text{g}/\text{kg}/\text{min}$]),^[20] neuromuscular blocker use, continuous renal replacement therapy (CRRT), Richmond Agitation-Sedation Scale score,^[21] in-hospital mortality rate, mode of ventilator, levels of FiO_2 , PEEP, driving pressure (calculated as the difference between plateau pressure and total PEEP values), inspiratory time, and respiratory rate.

2.3. Clinical management

In our institution, the initial circuit during ventilation is HME with CM. At the discretion of the attending ICU physician, removal of CM and HME was occasionally performed for patients presenting with hypercapnia; however, it was not a routine practice before October 2018. Since November 2018, it has been routinely performed in all patients presenting with hypercapnia. First the CM is removed, followed by the HME, after preparing the HH.

The Puritan Bennett 840 and 980 ventilators (Medtronic plc., Dublin, Ireland) were used for mechanical ventilation. The initial VC was configured as follows: closed ventilation suction catheter (SC) with a T connector (SuctionPro72, Smiths Medical International Ltd., Kent, UK), 15-cm CM (DAR PVC Catheter Mounts with Double Swivel Elbow Connector; Medtronic plc., Dublin, Ireland), an HME (DAR Adult-Pediatric Electrostatic Filter HME Small, Medtronic plc., Dublin, Ireland), and a VC (DAR Adult Polyvinyl Chloride-Smoothbore Breathing Systems, 150 cm, detachable Y-piece; Medtronic plc., Dublin, Ireland) (CM + HME) (Fig. 1A). When CM was removed to improve hypercapnia, the SC, and HME were connected directly (HME) (Fig. 1B). The VC for use with the HH to further improve hypercapnia was configured as follows: closed ventilation SC with a T connector (SuctionPro72, Smiths Medical International Ltd., Kent, UK) and VC with the HH (EVAQUA 2, Fisher&Paykel Healthcare KK, Auckland, New Zealand) (HH) (Fig. 1C). The dead space values provided in the manufacturer's manual were 36 and 45 mL for CM and HME, respectively.

Ventilator settings were adjusted according to the ARDS clinical practice guidelines.^[1] The selected mode of the ventilator was assist/control (A/C)-pressure control ventilation. Whenever possible, the driving pressure was adjusted so that the tidal volume was 6 to 8 mL/PBW and the plateau pressure was ≤ 30 cmH_2O . PEEP was adjusted according to the FiO_2 value.^[22] The respiratory rate and inspiratory time were determined at the discretion of the attending ICU physician. Inspiratory time was as long as possible, aiming to prevent the induction of intrinsic PEEP and patient-ventilator asynchrony and improve hypercapnia.^[23] Blood samples for blood gas analysis were collected using the

arterial catheter after at least 10 minutes of dead space removal according to our routine practice. Blood gases were analyzed using the ABL800 FLEX system (Radiometer Medical, Copenhagen, Denmark) available within the ICU.

To prevent metabolic acidosis under hypercapnia, trometamol, a buffer that does not create additional CO_2 , was administered through a continuous intravenous infusion to maintain the $\text{pH} > 7.2$.^[24]

Sedation was induced by a combination of propofol and dexmedetomidine, and with fentanyl, as required; it was adjusted to achieve deep sedation and suppress spontaneous breathing and patient-ventilator asynchrony. The neuromuscular blocking agent, rocuronium, was used for lung protection, as required.^[25]

Circulatory management was performed by the attending ICU physicians. In case of complications such as septic shock, interventions were administered, according to clinical practice guidelines.^[26] In the case of renal dysfunction, continuous renal replacement therapy was performed at the discretion of the attending ICU physicians.

2.4. Statistical analysis

Patients' baseline demographic and clinical characteristics, severity and sedation scores, and intervention types are presented as medians and interquartile ranges or means \pm standard deviations (SD) for quantitative variables, and as frequencies and percentages for categorical variables.

PaCO_2 values, ventilator values, and blood gas data at CM + HME, HME, and HH were compared using the paired *t* test.

All tests were 2-sided, and *P*-values $< .05$ were considered indicative of a statistically significant finding. Statistical analyses were conducted using JMP pro 15 (SAS Institute Inc., Cary, NC) and R version 4.0.2 (R Foundation for Statistical Computing, Vienna, Austria).

3. Results

During the study period, 973 patients were admitted to our ICU; among them, 876 patients required mechanical ventilation. Twenty-five of these patients met the present inclusion criteria; moreover, 4 patients were excluded, as they required > 90 minutes for blood gas measurements before and after the removal of CM and HME. Finally, data of 21 patients were included in the analysis.

Patients' baseline characteristics are presented in Table 1. Sepsis was the most common cause of ARDS. Nine (43%) and 12 (57%) patients were diagnosed with moderate and mild ARDS, respectively. The patients' sequential organ failure assessment scores were relatively high; most patients presented with organ dysfunction in systems other than the respiratory system. Most patients presented with septic shock and a high vasoactive-inotropic score. A neuromuscular blocker was used in more than one-third of patients, and all patients were under deep sedation. Ventilator settings observed during the study period are presented in Table 2. In all patients, the plateau pressure was < 30 cmH_2O .

3.1. PaCO_2 levels after the removal of CM and HME

PaCO_2 values at HME (52.7 ± 7.4 mm Hg, $P < .0001$) and HH (46.3 ± 6.8 mm Hg, $P < .0001$) were significantly lower than those at CM + HME (55.9 ± 7.9 mm Hg). The PaCO_2 value at

Table 1
Participants' baseline characteristics.

Characteristic	Value
Age, y	69.7 ± 8.2
Men, n (%)	12 (57.1)
Body mass index, kg/m ²	21.5 ± 4.3
Predicted body weight, kg	56.4 ± 8.0
Etiology of ARDS	
Sepsis, n (%)	10 (47.6)
Pneumonia, n (%)	8 (38.1)
Aspiration, n (%)	3 (14.3)
COPD, n (%)	5 (23.8)
SOFA score	11 (7–15)
Vasoactive-inotropic score*	17.3 (8.1–34.6)
Neuromuscular blocker, n (%)	8 (38.1)
CRRT, n (%)	13 (61.9)
RASS	-5 (-5 to -4)
In-hospital mortality, n (%)	6 (28.6)

Data are presented as means ± standard deviations or median (interquartile range) or count (%). ARDS = acute respiratory distress syndrome, COPD = chronic obstructive pulmonary disease, CRRT = continuous renal replacement therapy, RASS = Richmond Agitation-Sedation Scale, SOFA = sequential organ failure assessment.
* Vasoactive-inotropic score was calculated in this study as dopamine dose (μg/kg/min) + dobutamine dose (μg/kg/min) + 100 × epinephrine dose (μg/kg/min) + 25 × olprinone dose (μg/kg/min) + 10,000 × vasopressin dose (units/kg/min) + 100 × norepinephrine dose (μg/kg/min).

HH was also significantly lower than that at HME ($P < .0001$) (Fig. 2). The values of tidal volume, tidal volume/PBW, respiratory rate, minute volume, and blood gas analysis at CM + HME, HME, and HH are presented in Table 3. Ventilator values were similar during the study period and, in most patients, ventilation was performed with tidal volumes between 6 and

Table 2
Ventilator settings during the study period.

Characteristic	Value
Assist/control (PCV) mode, n (%)	21 (100)
FiO ₂	0.45 (0.33–0.6)
PEEP, mmH ₂ O	10 (8–10)
Driving pressure, mmH ₂ O	13 (12–17.5)
Inspiratory time, sec	1.5 (1.3–1.5)
Respiratory rate, bpm	18 (15–20)

Data are presented as median (interquartile range) or count (%). bpm = breaths per minute, PCV = pressure control ventilation, PEEP = positive end-expiratory pressure.

8 mL/kg. All patients presented with respiratory acidosis, and trometamol was administered to 8 patients during the study period. The time required to measure the PaCO₂ levels in the interval between CM + HME and HH was 44.5 (37–56) minutes.

3.2. Adverse events after the removal of CM

There were no cases of reintubation due to accidental extubation. CM was reinstalled for all patients who no longer required strict lung-protective ventilation and had improved hypercapnia.

4. Discussion

In this retrospective study, we found that the removal of CM and HME could reduce PaCO₂ levels in patients with mild-to-moderate ARDS and hypercapnia. This approach may enhance lung-protective ventilation and improve hypercapnia, which may

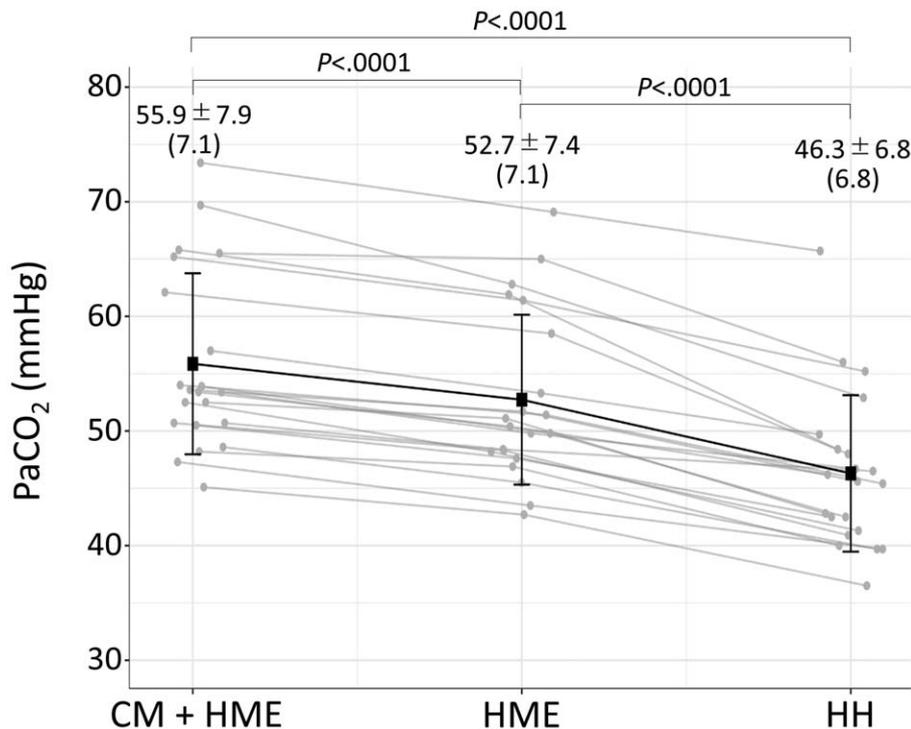


Figure 2. Changes in PaCO₂ levels at 3 time points. PaCO₂ levels decreased significantly at HME and HH compared with those at CM + HME ($P < .0001$), and the PaCO₂ level at HH was also significantly lower than that at HME ($P < .0001$). All statistical analysis was performed using a paired *t* test. Data are presented as means ± standard deviations (effect size). CM + HME = ventilator circuit with catheter mount and heat-and-moisture exchanger, HH = heated humidifier.

Table 3
Ventilator and blood gas analysis data at CM + HME, HME, HH.

Characteristics	CM + HME	HME	HH
Tidal volume, mL	377 ± 54	374 ± 63	366 ± 63
Tidal volume/PBW, mL/kg	6.8 ± 1.2	6.7 ± 1.3	6.6 ± 1.3
Respiratory rate, bpm	17.2 ± 2.3	17.2 ± 2.3	17.2 ± 2.3
Minutes volume, L/min	6.4 ± 1.0	6.4 ± 1.1	6.3 ± 1.1
pH	7.28 ± 0.07	7.30 ± 0.07*	7.35 ± 0.06***
PaCO ₂ , mm Hg	55.9 ± 7.9	52.7 ± 7.4*	46.3 ± 6.8***
PaO ₂ , mm Hg	87.0 ± 17.7	88.0 ± 20.3	86.5 ± 25.1
Base excess, mmol/L	-1.3 ± 3.9	-1.0 ± 4.0*	0.7 ± 3.8***

Data are presented as means ± standard deviations.

Significant differences ($P < .05$) between each point were identified with the paired *t* test.

bpm = breaths per minute, CM = catheter mount, HH = heated humidifies, HME = heat-and-moisture exchanger, PBW = predicted body weight.

* $P < .05$ versus CM + HME.

*** $P < .05$ versus HME.

be harmful. The removal of CM and HME to reduce the mechanical dead space is straightforward to perform and unlikely to cause adverse events in patients under deep sedation.

In a prospective observational study of 11 ARDS patients with hypercapnia, the removal of HME (dead space of 100 mL) reduced PaCO₂ levels by 11 ± 5 mm Hg.^[7] Subsequently, a prospective study of a small number of ARDS patients reported that the removal of HME significantly improved hypercapnia, confirming the usefulness of this intervention.^[12–14] Moreover, in some of these studies, it was possible to achieve lung-protective ventilation by improving hypercapnia.^[13,14] In contrast, one prospective study examined the effect of removing CM in addition to removing HME on improving hypercapnia in 7 ARDS patients; the removal of CM and HME (total dead space of 115 mL) reduced PaCO₂ levels by 11 mm Hg.^[17] Consistent with that study, in the present study, the removal of CM and HME (total dead space of 81 mL) resulted in 9.6 ± 3.2 mmHg reduction in PaCO₂ levels in 21 patients with mild-to-moderate ARDS.

As the effect of PaCO₂ value reduction is associated with dead space capacity,^[27] active apparatus dead space reduction by the removal of HME and CM may be effective at improving hypercapnia. The relief of hypercapnia may improve patient prognosis independently and by reducing the tidal volume, driving pressure values, and respiratory rate. Following the report of a negative impact of hypercapnia on the prognosis of patients with ARDS, the removal of the mechanical dead space was recommended in recent reviews and guidelines^[28,29]; however, it may still be an intervention that is not commonly implemented. The removal of CM in addition to HME is another straightforward procedure that may safely and effectively improve hypercapnia in deeply sedated ARDS patients without increasing the risk of accidental extubation.

The present study has several limitations. First, this was a small, retrospective observational study. The number of patients with ARDS and hypercapnia treated at a single ICU facility tends to be small; in fact, previous studies included approximately 10 patients. However, the present study has demonstrated the effectiveness and safety of this intervention in daily clinical practice. Second, the preintervention PaCO₂ values in the present study were relatively low (55.9 ± 7.9 mm Hg). In the present study, patients had mild-to-moderate ARDS, which may be one of the causes of this condition. Moreover, the prolonged inspiratory time may have improved hypercapnia. In the A/C-pressure control ventilation mode, the inspiratory time tends to

be within the range of 0.7 to 1.0 seconds.^[30] However, in the present study, the median inspiratory time was 1.5 (1.3–1.5) seconds. In a recent study of ARDS patients, the end-inspiratory pause prolongation was reported to induce a significant decrease in the levels of PaCO₂.^[23] This intervention may be another reason why the observed PaCO₂ levels were relatively low. Although end-inspiratory pause prolongation may trigger intrinsic PEEP and patient-ventilator asynchrony, it is straightforward to perform and may have a greater effect when used in combination with the interventions presented in this study. Large prospective studies are required to verify the efficacy of these simultaneous interventions.

5. Conclusions

In this retrospective observational study, the removal of CM and HME reduced PaCO₂ values without changing ventilator settings in deeply sedated patients with mild-to-moderate ARDS on lung-protective ventilation. Although the removal of CM may result in circuit disconnection or accidental extubation, and thus, must be performed with caution, this simple intervention may improve hypercapnia and promote further lung-protective ventilation in this patient group.

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