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Heat and moisture exchangers and heated humidifiers in acute lung injury/acute respiratory distress syndrome patients. Effects on respiratory mechanics and gas exchange

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Abstract *Objective:* To compare, in acute lung injury/acute respiratory distress syndrome (ALI/ARDS) patients, the short-term effects of heat and moisture exchangers (HME) and heated humidifiers (HH) on gas exchange, and also on respiratory system mechanics when isocapnic conditions are met. *Design:* Prospective open clinical study. *Setting:* Intensive Care Service. *Patients:* Seventeen invasively ventilated ALI/ARDS patients. *Intervention:* The study was performed in three phases: (1) determinations were made during basal ventilatory settings with HME; (2) basal ventilatory settings were maintained and HME was replaced by an HH; (3) using the same HH, tidal volume (Vt) was decreased until basal $PaCO_2$ levels were reached. FiO_2, respiratory rate and PEEP were kept unchanged. *Measurements and results:* Respiratory mechanics, Vd_{phys}, gas exchange and hemodynamic parameters were obtained at each phase. By using HH instead of HME and without changing Vt, $PaCO_2$ decreased from 46 ± 9 to 40 ± 8 mmHg ($p < 0.001$) and Vd_{phys} decreased from 352 ± 63 to 310 ± 74 ml ($p < 0.001$). Comparing the first phase with the third, Vt decreased from 521 ± 106 to 440 ± 118 ml ($p < 0.001$) without significant changes in $PaCO_2$, Vd/Vt decreased from 0.69 ± 0.11 to 0.62 ± 0.12 ($p < 0.001$), plateau airway pressure decreased from 25 ± 6 to 21 ± 6 cmH_2O ($p < 0.001$) and respiratory system compliance improved from 35 ± 12 to 42 ± 15 ml/cmH_2O ($p < 0.001$). PaO_2 remained unchanged in the three phases. *Conclusions:* Reducing dead space with the use of HH decreases $PaCO_2$ and more importantly, if isocapnic conditions are maintained by reducing Vt, this strategy improves respiratory system compliance and reduces plateau airway pressure

Keywords ARDS · ALI · Dead space · Heat and moisture exchanger · Heated humidifier

Introduction

Humidification and warming of inspired gases during mechanical ventilation is a crucial issue. Two types of humidifiers are commonly used in clinical practice: heat and moisture exchangers (HME) and heated humidifiers (HH) [1]. Inadequate gas humidification can provoke airway mucosa dysfunction and endotracheal tube occlusion [2]. Management decisions and reduced costs may account for the recent more generalized use of HME [3]. When mechanical ventilation is used, ventilator equipment adds additional dead space (Vd) due to the endotracheal tube, humidification devices and connectors. This instrumental dead space is considered part of the airway Vd (Vd_{aw}) (instrumental and anatomic dead space). Physiologic dead space (Vd_{phys}) is comprised of Vd_{aw} and alveolar Vd (Vd_{alv}) and is the portion of tidal volume (Vt) that does not participate in gas exchange [4]. Therefore, humidification devices might play an important role in pulmonary gas exchange and lung

Table 1 Patients' clinical characteristics at inclusion

	Sex	Age (years)	PaO_2 (mmHg)	$PaCO_2$ (mmHg)	FiO_2	PEEPtot (cmH_2O)	Main diagnosis on admission	APACHE II
1	M	65	80	37	0.6	7	Viral pneumonia	31
2	F	39	129	43	0.5	12	Bacterial pneumonia	22
3	F	69	116	42	0.4	12	Aspiration pneumonia	36
4	F	62	94	59	0.75	11	Bacterial pneumonia	20
5	M	25	83	43	0.55	9	Thoracic trauma	11
6	F	54	95	36	0.35	8	Upper airway obstruction (po)	16
7	M	81	114	38	0.4	10	Aspiration pneumonia	24
8	M	76	82	72	0.7	14	Lung hemorrhage	23
9	F	74	66	52	0.6	10	Peritonitis (po)	18
10	M	49	155	39	0.6	8	Dissecting aortic aneurysm (po)	17
11	M	52	93	41	0.4	6	Benzodiazepine overdose	9
12	M	77	84	45	0.5	10	Dissecting aortic aneurysm (po)	20
13	M	67	88	43	0.4	6	Bacterial pneumonia	23
14	F	75	103	42	0.4	6	Multiple trauma	15
15	F	62	99	56	0.9	9	Bacterial pneumonia	28
16	M	70	69	50	0.3	6	Bacterial pneumonia	22
17	M	63	85	49	0.4	10	Cerebral hemorrhage	8
Mean ± SD		62 ± 15	96 ± 22	46 ± 9	0.5 ± 0.2	9 ± 2.5		20.2 ± 7.4

Abbreviations: PaO_2, partial pressure of oxygen in arterial blood; $PaCO_2$, partial pressure of carbon dioxide in arterial blood; FiO_2, fraction of inspired oxygen; PEEPtot, total positive end-expiratory pressure; APACHE II, Acute Physiology and Chronic Health Evaluation on admission; po, postoperative status

mechanics. In acute lung injury/acute respiratory distress syndrome (ALI/ARDS) patients, respiratory acidosis and high airway plateau pressures are a serious limitation to mechanical ventilation adjustment.

Richecoeur et al. [5] have demonstrated that optimization of mechanical ventilation associated with a reduction in instrumental dead space is a useful combination method to reduce $PaCO_2$ in severe ARDS patients with hypercapnia. Other investigators have confirmed these data [6]. Recently, Wald and coworkers [7], using a preterm infant's test lung, showed that mean CO_2 elimination time was decreased when instrumental dead space was reduced and suggested that such an approach might decrease volutrauma.

Two previous studies performed in ALI/ARDS patients have focused on the effects of instrumental dead space removal in $PaCO_2$ [8, 9]. Our investigation aimed at accruing new knowledge into this issue not only on gas exchange parameters, but mainly to analyze the impact of such strategy on respiratory system mechanics in ALI/ARDS patients. Indeed, the novelty of our study is to analyze the effects of minimizing instrumental dead space on alveolar distension, respiratory system compliance and end-inspiratory plateau pressure while keeping $PaCO_2$ unchanged. Preliminary data of this study have been presented [10].

Materials and methods

The study was performed in the Intensive Care Service of the Hospital de la Santa Creu i Sant Pau, Barcelona (Spain). Given the nature of measurements to be performed and the routine use of humidification in mechanical ventilation, the requirement for informed consent was waived by the institutional ethics committee after approval of the protocol.

Patients

The study involved 17 patients (10 men and 7 women) with a mean age of 62 ± 15 years (range 25–81 years) from the Intensive Care Service. The patients' demographic and clinical characteristics are listed in Table 1. ALI/ARDS was diagnosed based on the American-European Consensus Conference criteria [11]. All patients were intubated and mechanically ventilated. Sedation was achieved with titrated intravenous infusion of propofol, midazolam and opiates, alone or in combination regimens, to ensure that the patient did not trigger the ventilator. Neuromuscular blockade was used in seven patients. Exclusion criteria were age under 18 years, severe hemodynamic instability, previous barotrauma, intracranial hypertension and uncontrolled fever. Patients were excluded from the protocol if body temperature varied by 0.5°C or more during the study [12].

Protocol

Basal mechanical ventilation used was volume assist-controlled ventilation with a constant flow, low tidal volume (Vt) and moderate positive end-expiratory pres-

Table 2 Lung mechanics and gas exchange (mean ± SD) during the study period ($n = 17$ patients unless otherwise specified)

	HME (phase 1)	HH (phase 2)	HH-lowVt (phase 3)	Overall *p* Value	Intergroup differences
Ppeak (cmH_2O)	36 ± 8	34 ± 7	29 ± 8	< 0.001	a, b, c
Pplat (cmH_2O)	25 ± 6	25 ± 6	21 ± 6	< 0.001	a, b
PEEPtot (cmH_2O)	9 ± 2.5	9 ± 2.5	9 ± 2.5	1	
Vt (ml)	521 ± 106	521 ± 106	440 ± 118	< 0.001	a, b
Vt (ml/kg[1])	7.3 ± 1.1	7.3 ± 1.1	6.1 ± 1.3	< 0.001	a, b
Vt (ml/kg[2]) ($n = 12$)	8.3 ± 1.6	8.3 ± 1.6	6.9 ± 1.8	< 0.001	a, b
Vd_{phys} (ml)	352 ± 63	310 ± 74	269 ± 80	< 0.001	a, b, c
Vd/Vt	0.69 ± 0.11	0.60 ± 0.13	0.62 ± 0.12	< 0.001	a, b, c
RR (breaths/min)	20 ± 6	20 ± 6	20 ± 6	1	
Crs (ml/cmH_2O)	35 ± 12	35 ± 12	42 ± 15	= 0.001	a, b
pH	7.34 ± 0.10	7.39 ± 0.11	7.33 ± 0.10	< 0.001	b, c
PaO_2 (mmHg)	96 ± 22	99 ± 29	91 ± 19	= 0.28	
$PaCO_2$ (mmHg)	46 ± 9	40 ± 8	45 ± 9	< 0.001	b, c
FiO_2	0.5 ± 0.2	0.5 ± 0.2	0.5 ± 0.2	1	
Vc (ml)	53 ± 29	52 ± 28	43 ± 25	< 0.001	a, b
Vt_{Vc} (ml)	468 ± 110	469 ± 109	397 ± 117	< 0.001	a, b
$Vd_{phys-Vc}$ (ml)	316 ± 66	279 ± 74	243 ± 79	< 0.001	a, b, c
Crs_{Vc} (ml/cmH_2O)	32 ± 12	32 ± 12	38 ± 15	= 0.002	a, b

Abbreviations: Ppeak, peak airway pressure; Pplat, airway plateau pressure; PEEPtot, total positive end-expiratory pressure; Vt, tidal volume; [1] Weight measured at admission; [2] Predicted body weight; Vd_{phys}, physiologic dead space; RR, respiratory rate; Crs, respiratory system compliance; pH, arterial pH; PaO_2, partial pressure of oxygen in arterial blood; $PaCO_2$, partial pressure of carbon dioxide in arterial blood; FiO_2, fraction of inspired oxygen; Vc, compressible volume; Vt_{Vc}, $Vd_{phys-Vc}$, Crs_{Vc} , tidal volume, physiologic dead space and respiratory system compliance taking into account compressible volume, respectively.
Intergroup differences: a, phase 1 vs phase 3; b, phase 2 vs phase 3; c, phase 1 vs phase 2

sure (PEEP) to keep plateau airway pressure (Pplat) ≤ 35 cmH_2O, as established by the responsible physician. The inspired oxygen fraction (FiO_2) and PEEP were kept constant during the study. Vd_{phys} was calculated using the Enghoff modification of the Bohr equation [13]; $Vd/Vt = (PaCO_2 – PeCO_2)/PaCO_2$, where Vd is the physiologic dead space, Vt is tidal volume, $PaCO_2$ is the partial pressure of carbon dioxide in arterial blood and $PeCO_2$ is the partial pressure of carbon dioxide in mixed expired gas. Expired gases were collected over 3 min using a Douglas bag (P-341–60; Warren E. Collins Inc., Boston, MA, USA) attached to the expiratory port of the ventilator. Arterial blood gases were obtained during the 3rd min of expired gas collection. Expired and arterial gases were measured using an automated analyzer (ABL 520; Radiometer A/S, Copenhagen, Denmark). Fourteen patients were ventilated with 900 C Servo ventilators (Siemens-Elema, Solna, Sweden) and three patients were ventilated with Evita 4 ventilators (Dräger, Lübeck, Germany). Only the Evita 4 ventilators have a compressible volume compensation system. One ventilator per patient was used and maintained throughout the protocol sequence to avoid intra-patient variability.

Ventilatory parameters were recorded directly from the ventilator monitoring system. PEEPtot was measured by performing end-expiratory occlusions with the appropriate buttons built into the ventilators. Respiratory system compliance (Crs) was calculated as Vt/(Pplat – PEEPtot); where Pplat is the plateau airway pressure and PEEPtot is the sum of external PEEP and intrinsic PEEP, if any.

Respiratory system mechanics, gas exchange, physiologic dead space and hemodynamics were measured at each phase of the protocol. Cardiac output (CO), mean pulmonary artery pressure (MPAP) and pulmonary capillary wedge pressure (PCWP) were obtained if a Swan–Ganz catheter was in place.

Patients' body weight was measured at admission in 15 patients with a calibrated balance (Maximove™, Arjo Ltd., Gloucester, UK). In the other two patients (patients 10 and 12 in Table 1) we did not measure their actual body weight because severe hemodynamic instability at ICU admission. In these two patients, the weight was estimated from the previous operating room records. The predicted body weight (PBW) was calculated as described [14]: for male patients as equal to 50+0.91(centimeters of height–152.4), and for female patients as equal to 45.5+0.91(centimeters of height–152.4).

The study was divided into three phases. In phase 1 (basal conditions), an HME (Edit Flex; Datex Engstrom®, Helsinki, Finland; Vd of 90 ml, including integrated flexible tube and a filter, and "in vitro" resistive pressure drop of 0.5 and 1.4 cmH_2O at constant flows of 30 and 60 l/min respectively) was placed distally to the Y piece of the circuit if not already in use. Mechanical ventilation at clinically established parameters was maintained for 45 min and all study data were then collected. The stabilization

period during the different phases of the study was based on a previous study on the dynamics of CO_2 elimination after ventilator resetting [15]. In phase 2, a HH (Fisher & Paykel; MR 290 chamber, MR 850 ALU electric heater; Panmure, New Zealand; internal volume 280 ml and a resistive pressure drop of 2 cmH_2O at 40/l/min airflow) was placed in the inspiratory limb of the circuit in accordance with the manufacturer's recommendations. Data were collected after 45 min of stable mechanical ventilation with the same ventilatory settings as in the first phase. In phase 3, tidal volume was decreased by 20–30 ml each 30 min. The same data were collected at each step until a $PaCO_2$ value equal to that of phase 1 was reached. We did not use a recruitment maneuver after ventilator disconnection to change humidification devices.

Statistical analysis

The results were analyzed using one-way analysis of variance for repeated measures (ANOVA). If significance was achieved, then Student–Newman–Keuls analysis was used for comparison between the study phases. A p value less than 0.05 was considered statistically significant. Data are expressed as means ± standard deviation. The SPSS (v 11.5) statistical software was used for statistical analysis.

Results

Respiratory data obtained in the three phases of the study are shown in Table 2. The change in the humidification system (from phase 1 using HME to phase 2 using HH) was responsible for a significant decrease in $PaCO_2$ (from 46 ± 9 mmHg to 40 ± 8 mmHg, $p < 0.001$), and a significant increase in pH (from 7.34 ± 0.10 to 7.39 ± 0.11, $p < 0.001$). Individual changes in $PaCO_2$ are shown in Fig. 1. The $PaCO_2$ decrease was correlated ($r = 0.59$; $p = 0.016$) with the initial $PaCO_2$ level. The effect of removing HME was not more pronounced in patients with higher Vt. Correlation between the Vt (expressed as ml/kg of body weight measured at admission) in our 17 patients and the decrease of $PaCO_2$ comparing phase 1 (HME, basal Vt) and phase 2 (HH, basal Vt) did not achieve statistically significant differences ($r = –0.07$; $p = 0.78$). Furthermore, if the same correlation was performed using ml/kg of PBW ($n = 12$) the statistical analysis was not significant ($r = –0.2$; $p = 0.52$). The decrease in $PaCO_2$ levels due to the humidification device switch did not differ significantly ($p = 0.48$) between hypercapnic ($n = 6$) and non-hypercapnic ($n = 11$) patients.

With respect to basal conditions, the use of HH induced a significant reduction in Vd/Vt (from 0.69 ± 0.11 to 0.60 ± 0.13, $p < 0.001$) and a significant decrease in Vd_{phys} (from 352 ± 63 to 310 ± 74 ml, $p < 0.001$). Vd/Vt was statistically different between hypercapnic and non-hypercapnic groups in the phase 1 (0.76 ± 0.09 vs 0.65 ± 0.11 respectively; $p = 0.036$).

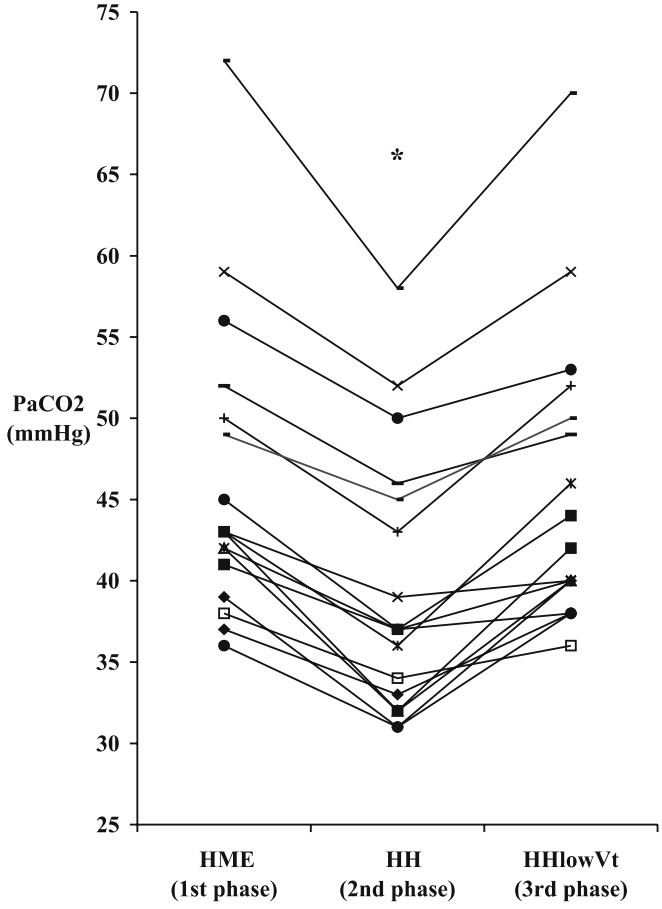

Fig. 1 Individual values for $PaCO_2$ in the three phases of the study. The *asterisk* denotes statistically significant differences ($p < 0.001$) between phase 2 and the other phases

No significant difference was noted in total PEEP, Pplat or Crs between phase 1 (HME, basal Vt) and phase 2 (HH, basal Vt). Peak airway pressure (Ppeak) showed a significant decrease (from 36 ± 8 to 34 ± 7 cmH_2O, $p < 0.01$) and total airway resistance decreased significantly between the same phases (from 12.8 ± 5.4 cmH_2O/l/seg to 11.7 ± 4.2 cmH_2O/l/seg, $p = 0.049$).

In phase 3 (HH, low Vt) arterial blood gases showed no significant difference with phase 1 (HME, basal Vt) and Vt was decreased from 521 ± 106 to 440 ± 118 ml, $p < 0.001$ (7.3 ± 1.1 to 6.1 ± 1.3 ml/kg of weight measured at admission and 8.3 ± 1.6 to 6.9 ± 1.8 of PBW, $p < 0.001$ in both). Ppeak and Pplat decreased from 34 ± 7 to 29 ± 8 and from 25 ± 6 to 21 ± 6 cmH_2O, respectively (both $p < 0.001$). Crs increased from 35 ± 12 to 42 ± 15 ml/cmH_2O, ($p = 0.003$; see Table 2). Vd_{phys} decreased significantly during the different phases of the study, as shown in Table 2. Individual changes in Vd_{phys} are shown in Fig. 2. Vd/Vt ratio differed significantly

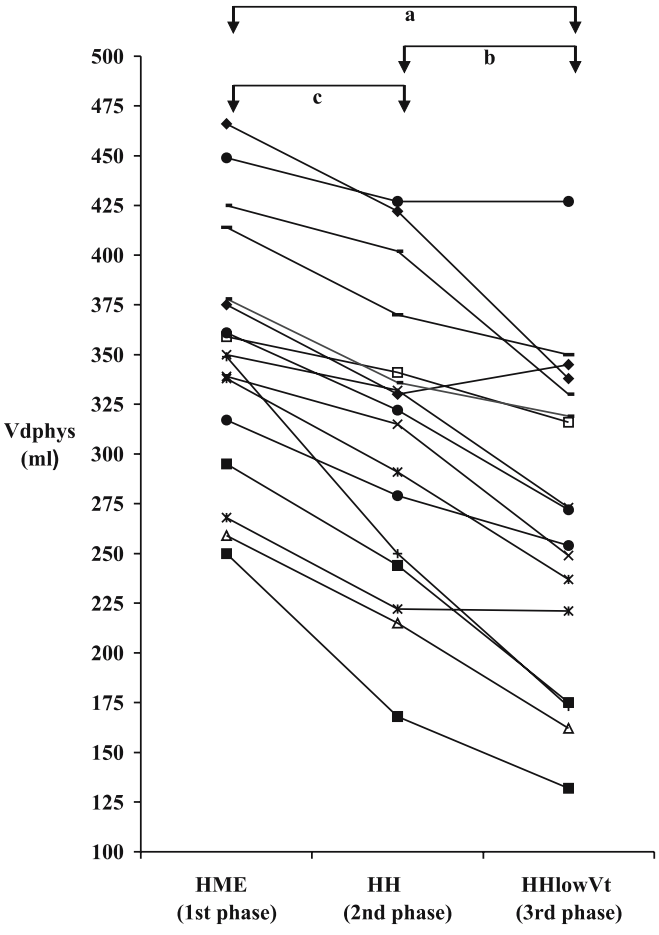

Fig. 2 Individual values for Vd_{phys} during the three phases of the study. There were statistically significant differences among the groups: a, b, c, all $p < 0.001$

among the three phases (Table 2). The decrease in Vt between phase 2 (HH, basal Vt) and the phase 3 (HH, low Vt) was also correlated with an improvement in Crs ($r = 0.52$, $p = 0.031$). Changes in Vt and Vd_{phys} between the same phases of the study strongly correlated ($r = 0.78$; $p < 0.001$), as shown in Fig. 3. The decrease in Pplat between phase 1 (HME, basal Vt) and phase 3 (HH, low

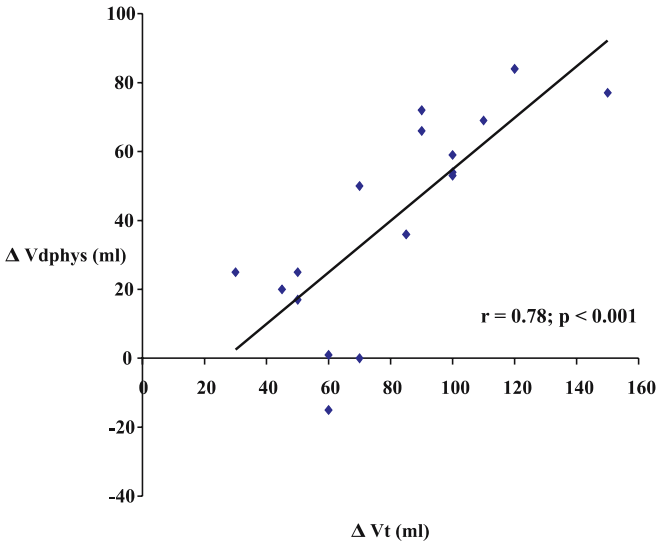

Fig. 3 Relationship between the decrease in Vt (ΔVt) between phase 2 and phase 3, and the decrease in Vd_{phys} (ΔVd_{phys}) between the same phases. The linear correlation was highly significant

Vt) did not correlate with the Pplat level in the phase 1 of the study ($r = 0.34$; $p = 0.12$). Additionally, the drop in Vd_{phys} at the end of the study did not correlate with the initial Vd_{phys} level ($r = 0.18$; $p = 0.5$). However, Vt and Vd_{phys} levels in basal conditions strongly correlated ($r = 0.60$; $p = 0.011$), and the decrease in Pplat between phase 1 and phase 3 had a good correlation with the decrease in Vd_{phys} between the same phases ($r = 0.59$; $p = 0.013$).

All hemodynamic parameters remained unchanged during the study (see Table 3). No patient needed to be excluded from the protocol because of temperature variations.

Discussion

The main findings in this study were: (1) The reduction in instrumental dead space in ALI/ARDS patients by means of HH significantly decreased $PaCO_2$ levels. (2) At iso-

Table 3 Hemodynamic parameters (mean ± SD) during the study period ($n = 17$ patients unless otherwise specified)

	HME (phase 1)	HH (phase 2)	HH-lowVt (phase 3)	Overall *p* Value
HR (beats/min)	91 ± 18	92 ± 18	95 ± 18	0.11
MAP (mmHg)	76 ± 11	77 ± 14	79 ± 12	0.45
CVP (mmHg)	12 ± 4	12 ± 4	12 ± 4	0.56
MPAP (mmHg) ($n = 7$)	26 ± 2	26 ± 3	28 ± 2	0.14
CO (l/min) ($n = 6$)	6.2 ± 2.7	6.0 ± 2.4	6.5 ± 2.2	0.24
PCWP (mmHg) ($n = 7$)	14 ± 2	14 ± 3	14 ± 2	0.68

Abbreviations: *n*, number of patients evaluated; HR, heart rate; MAP, mean arterial pressure; CVP, central venous pressure; MPAP, mean pulmonary artery pressure; CO, cardiac output; PCWP, pulmonary capillary wedge pressure

capnic conditions, HH permitted the use of lower tidal volumes, which led to a significant decrease in Vd_{phys} and Pplat. (3) Tidal volume reduction significantly improved respiratory system compliance in our patients.

Several studies carried out in ALI/ARDS patients have demonstrated significant changes in $PaCO_2$ and/or Vd/Vt values using different humidification devices. Campbell and colleagues [6] showed significant Vd/Vt and $PaCO_2$ increments when exchanging a HH for a HME. In a similar study that evaluated gas humidification devices, Prin and co-workers [9] observed a significant decrease in $PaCO_2$ using HH instead of HME. In a more recent study performed in ten hypercapnic ARDS patients, Prat et al. [8] demonstrated that a progressive reduction in the artificial airway dead space led to a proportional $PaCO_2$ decrease at each device switch. Our data are consistent with this observation. The decrease in Vt in phase 3 of our study was correlated with an improvement in Crs. Our strategy of HH and low Vt further decreased Vd_{phys}. Such change in Vd_{phys} correlated with an improvement in Crs. This suggests that a certain degree of overdistension occurred when ventilating our patients with baseline Vt, since compliance increased when Vt was reduced in phase 3 of the study, and this Vt reduction was also accompanied by a decrease in Vd_{phys}. Our results suggest that, all else unchanged, the effects of exchanging HME for HH would help to minimize potentially injurious ventilation. Interestingly, we found that the amount of decrease in Vd_{phys} at the end of the protocol (HH, low Vt) was not confined to only those patients who had the highest Vd_{phys} at baseline (HME, basal Vt).

A recent study performed in early ARDS patients has demonstrated that an increased dead space fraction was an independent risk factor for death [16]. The authors did not mention which kind of humidifier was used. However, it seems clinically reasonable to assume that in those individuals in whom a high Vd_{phys} was measured, this reflected a worse lung status rather than the effects of different humidifying devices. Our data showing that a reduction in Vt is correlated with a Vd_{phys} decrease, together with the finding of an increased Crs when isocapnic conditions were met when using a HH with low Vt, suggest that this intervention can help minimize potentially harmful ventilation.

The "in vitro" HME volume of the new and unused devices (90 ml) decreased "in vivo", especially due to the condensate accumulation in the filter and in the flexible tube. We occasionally measured the "in vivo" HME internal volume immediately after HME replacement and it averaged 50–60 ml. In our study the decrease in Vd_{phys} observed between phase 1 and phase 2 was approximately 40 ml (from 352 ± 63 to 310 ± 74 ml); this drop is attributed directly to a humidification device switch. Similar data were found by Richecoeur et al. [5], who removed the 15-cm-long tubing connecting the Y piece to the endotracheal tube and obtained a reduction in the total dead space of 40 ml during optimized mechanical ventilation.

Ventilation with low tidal volumes may induce hypercapnia and increases in both cardiac output and pulmonary artery pressure, which could be deleterious and/or contraindicated in some patients [17]. Hypercapnic acidosis may also impair right ventricular function by inducing pulmonary hypertension [18, 19]. In addition, respiratory acidosis has been reported to be significantly and independently involved in acute cor pulmonale development in ARDS patients [20]. We found, however, that the hemodynamic differences were not statistically significant, probably because the magnitude of $PaCO_2$ changes was moderate (from 46 to 40 mmHg between phase 1 and phase 2) in our study. Nevertheless, the small number of patients in whom these determinations were performed precludes drawing definitive conclusions. In this scenario, increasing respiratory rate can be used to counterbalance minute ventilation decrease and prevent respiratory hypercapnia. An increase in respiratory rate, however, may enhance ventilator-induced lung injury, as demonstrated in experimental models [21, 22]. The clinical relevance of these findings is unknown. Investigators have also demonstrated that increasing respiratory rate to avoid Vt reduction-induced hypercapnia may, in turn, induce substantial gas trapping and generate auto-PEEP in ALI/ARDS patients [23, 24, 25]. Vieillard-Baron et al. showed that the increasing respiratory rate might not only produce dynamic hyperinflation but also impair right ventricular function without any decrease in $PaCO_2$ [24]. The strategy implemented in our study facilitated tidal volume reduction in ALI/ARDS patients without changing respiratory rate. In our study, the decrease in $PaCO_2$ due to the humidification device switch was similar in hypercapnic and non-hypercapnic patients. Nevertheless, Vd/Vt was statistically different between the two groups, suggesting greater lung damage in hypercapnic patients. These data were supported by a larger improvement in Crs in hypercapnic than in non-hypercapnic patients; this did not reach statistical significance, probably because of the small number of patients studied (Crs increased by $11 \pm 8 ml/cmH_2O$ in hypercapnic and by 5 ± 7 ml/cmH_2O in non-hypercapnic patients; $p = 0.17$).

Other factors which might change Vd_{phys}, such as PEEP levels and inspiratory pause, were kept constant in our study [26, 27, 28, 29]. High PEEP levels increase ventilation to high ventilation/perfusion areas and may worsen the Vd/Vt ratio [30]. In the current study, a progressive decrease in Vd_{phys} values was observed during reduced Vt ventilation phase after HH implementation, without changes in arterial oxygenation. This finding may be attributed to alveolar overdistension before Vt reduction, and could also explain the improvement observed in respiratory system compliance after Vt was decreased. We did not observe any total PEEP change in our patients, in accordance with previous results [8, 9]. The differences in Ppeak between phase 1 and phase 2 may be explained by a decrease in a total airway resistance

due to changes in humidification devices between these study periods.

Other mechanical ventilation adjuncts to reduce dead space and hypercapnia have been proposed, such as aspiration of dead space during expiration or tracheal gas insufflation [31, 32, 33, 34]. These methods, however, are not of common use and further devices must be applied to the mechanical ventilation apparatus. This may complicate their clinical feasibility. Reducing instrumental airway dead space with the use of HH instead of HME seems to be a simple maneuver to limit undesired hypercapnia when low tidal volume ventilation is used in ALI/ARDS patients. Alternatively, if $PaCO_2$ is of no concern, our results show new physiological and eventual clinical implications of this intervention (i.e. reducing instrumental dead space) since can help to reduce a potentially harmful Vt.

We did not observe any episodes of endotracheal tube occlusion during our study, but our protocol was performed only to evaluate the short-term effects of humidification devices on gas exchange and lung mechanics. In a recent multicenter randomized study evaluating the incidence of ventilator-associated pneumonia and comparing HH and HME in 369 patients, the endotracheal tube became occluded and required emergency reintubation on six occasions, five times with HH and once with HME [35]. These findings did not reach statistical significance and may be explained by poor humidification of inspired gas with some HH, especially when ambient air temperature, minute ventilation and ventilator output gas temperature were high [36]. This situation did not occur in our intensive care service since the ambient temperature is kept at a constant 21°C and we did not use turbine-based ventilators. Nevertheless, Jaber and colleagues demonstrated that the accumulation of mucous secretions in an endotracheal tube caused by prolonged use of humidification devices is higher with HME than with HH [37]. The risk of endotracheal tube occlusion may be diminished using automatic compensation systems for HH or using an HME that provides at least 30 mgH_2O/l of absolute humidity [36]. Besides, Ricard and coworkers demonstrated the absence of statistical significance on clinical parameters and hygrometric measurements and did not observed any episode of endotracheal tube occlusion changing the HME only once a week [38].

In conclusion, reducing artificial airway dead space due to a change in humidification devices appears to be a useful and simple maneuver to control $PaCO_2$ levels. In addition, if moderate hypercapnia is not an issue, using HH instead of HME allows further reduction in Vt, which is accompanied by a diminished mechanical load. In our patients, this intervention entailed an improvement in respiratory system compliance (Crs), a decrease in plateau airway pressure (Pplat) and a decrease in physiologic dead space (Vd_{phys}), suggesting less overdistension.

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