Effect of humidifying devices on the measurement of tidal volume by mechanical ventilators

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Abstract

Purpose. We hypothesized that expiratory tidal volume was underestimated, because a heat-moisture exchanger traps the expired vapor. We, therefore, designed patient and bench studies to investigate the accuracy of tidal volume monitoring.
Methods. In a patient study, applying two humidifying systems (a heat-moisture exchanger and a heated humidifier) and two tidal volumes (12 and 6ml·kg^{-1}) with a Servo ventilator 300, we recorded the displayed expiratory tidal volume and thoracic volume displacement, measured by respiratory inductive plethysmography. Temperature, relative humidity, and absolute humidity were measured at the airway opening and at the end of the expiratory limb. Using a model lung, we also tested three different ventilators (Puritan-Bennett 7200ae, Evita 4, and Servo ventilator 300) to investigate whether the effects of the heat-moisture exchanger and the heated humidifier on monitored tidal volume varied according to the brand of ventilator.
Results. With the use of the heat-moisture exchanger, the displayed expiratory tidal volume was significantly smaller, by 12%–14%, than that with the heated humidifier, although thoracic volume displacement was identical in the two systems. The temperature and absolute humidity at the end of the expiratory limb were significantly lower with the heat-moisture exchanger than with the heated humidifier. In the model lung study, we investigated the effects of different brands of ventilator on the expiratory tidal volume. A similar degree (8%–14%) of underestimation of tidal volume was observed with the heat-moisture exchanger, regardless of ventilator brand.
Conclusion. Monitored expiratory tidal volume was underestimated by approximately 10%, when using a heat-moisture exchanger.

Key words Heat-moisture exchanger · Heated humidifier · Absolute humidity · Temperature

Introduction

The ARDS Network has provided solid evidence that low tidal volume (V_T) ventilation is important to avoid exacerbating the lung injury of patients with acute lung injury/acute respiratory distress syndrome (ALI/ARDS) [1]. Consequently, V_T monitoring accuracy is an important aspect of lung-protective strategies.

During mechanical ventilation, heating and humidification of the inspired gas is mandatory [2–5]. Because a humidifying device increases temperature and adds vapor to the dry and cool gas delivered from a ventilator, the patient's lungs are inflated with a greater volume than that delivered from the ventilator. From this point of view, the monitored V_T of expired gas is more important than the delivered V_T. Recently, heat-moisture exchangers (HMEs), which reuse heat and vapor in the expired gas, have gained popularity for humidifying [6–8]. An HME with good performance can trap most of the expired vapor. This trapping cools and dries out the gas that reaches the expiratory flow-sensor of the ventilator, and the decreased volume of gas with less vapor may lead to underestimation of the expired V_T. In the present study, for mechanically ventilated patients, we investigated whether the displayed expiratory V_T was affected by the type of humidifying system. We also performed a bench study to investigate whether the accuracy of monitored V_T varied according to the type of flow-sensor incorporated in a ventilator.

Patients, and methods

The study was approved by the ethics committee of the National Cardiovascular Center (Osaka, Japan), and written informed consent was obtained from each patient.

Patient protocol

Ten mechanically ventilated patients who had undergone cardiovascular surgery at the National Cardiovascular Center were enrolled in the study. After waiting 1–2h for hemodynamics to stabilize, we started the measurement protocol. Throughout the protocol, patients were sedated and paralyzed by the intravenous injection of propofol ($2\,mg\cdot kg^{-1}\cdot h^{-1}$), and vecuronium bromide (4–8mg). For ventilation we used a Servo ventilator 300 (Siemens, Elema, Sweden) and a reusable low-compliant circuit with a double heating wire for both inspiratory and expiratory limbs (compliance, $1.99\,ml\cdot cmH_2O^{-1}$). The ventilator settings were: intermittent mandatory ventilation (IMV), volume control ventilation (VCV) with square inspiratory flow, and positive end-expiratory pressure (PEEP), $6\,cmH_2O$. In random order, we applied different V_T with the same duration of ventilation (in min): large V_T ($12\,ml\cdot kg^{-1}$) at a rate of ten breaths·min^{-1}; and small V_T ($6\,ml\cdot kg^{-1}$) at 20 breaths·min^{-1}. The fraction of inspired oxygen ($F_{I_{O_2}}$) was adjusted by attending physicians to maintain Pa_{O_2} greater than 100mmHg and was kept constant throughout the protocol. We compared the results obtained using two different humidifying devices: an HME (DAR Hygrobac S; Mallinckrodt, Mirandola, Italy) and a heated humidifier (HH; MR290 Autofeed Humidification Chamber and MR730 Humidification System; Fisher & Paykel Healthcare, Auckland, New Zealand). We placed the HME at the airway opening, turned off the HH and the double heating wire, and ensured that the water chamber was empty. To measure temperature, relative humidity (RH) and absolute humidity (AH), two humidity–temperature sensors (Moiscope; S.K.I. Net, Tokyo, Japan) were placed, one at the airway opening and one at the end of the expiratory limb. To monitor lung volume, using respiratory inductive plethysmography (RIP; Respitrace PT; Non-Invasive Monitoring Systems, Miami, FL, USA), two RespiBands (SensorMedics; Yorba Linda, CA, USA) were placed around the rib cage at the nipple line and around the abdomen above the navel. RIP recorded rib-cage motion (RC), abdominal motion (AB), and the algebraic sum (SUM) of the signals. We defined the thoracic volume displacement as the absolute value produced by subtracting the minimum value of SUM from

the maximum. At each setting, for sequences of ten breaths, we recorded both the expiratory V_T data that were displayed on the ventilator monitor and the thoracic volume displacement calculated from the RIP signals. When we changed the V_T setting, we allowed at least 5min for the Moiscope signals to stabilize. The signals for SUM, RC, and AB from the RIP, and airway opening pressure and flow from the Servo ventilator 300 were led to an analog–digital converter (DI-220; Dataq Instruments, Akron, OH, USA). Similarly, the temperature, and signals for RH and AH at the airway opening and at the end of the expiratory limb were also led to the converter. Using data acquisition software (Windaq; Dataq Instruments), all signals were digitized and recorded at 50Hz per channel on a computer. Subsequent data analysis was performed with dedicated software (Windaq playback; Dataq Instruments). In each ventilatory mode, blood gas was analyzed with a calibrated blood gas analyzer (ABL505; Radiometer, Copenhagen, Denmark).

After we completed the measurements with the HME, we poured 100ml water into the water chamber, turned on the power for the HH and the double heating wire, and removed the HME. Before starting the measurement for the HH, we allowed approximately 30min for the temperature and humidity to stabilize. We repeated the same sets of measurements for the different V_T settings. We conducted the measurement protocol with the HME before the HH, because the humidity measurements of the HME were likely to be affected by wetting of the ventilatory circuit.

Model lung protocol

To investigate whether the effects of the HH and HME on displayed expiratory V_T varied according to the brand of ventilator, using a model lung, we tested different ventilators: the Puritan-Bennett 7200ae (Nellcor Puritan Bennett, Pleasanton, CA, USA); the Evita 4 (Dräger Medical, Lubeck, Germany); and the Servo ventilator 300. The type of flow sensor and condition of volume measurement in each ventilator are shown in Table 1. Ventilator settings were: IMV mode, 10 breaths·min^{-1}; VCV; PEEP, $0\,cmH_2O$; and $F_{I_{O_2}}$, 0.4. At an inspiratory-to-expiratory ratio of 1:2.5, V_T was set at 300, 500, and 700ml.

Table 1. Type of flow sensor and condition of volume measurement in each ventilator

	Flow sensor	Volume measurement
Evita 4	Hot-wire flow sensor	BTPS
Puritan-Bennett 7200ae	Hot-wire flow sensor	BTPS
Servo 300	Heated pneumotachometer	ATPS

BTPS, body temperature and pressure, saturated with water vapor; ATPS, ambient temperature and pressure, saturated with water vapor
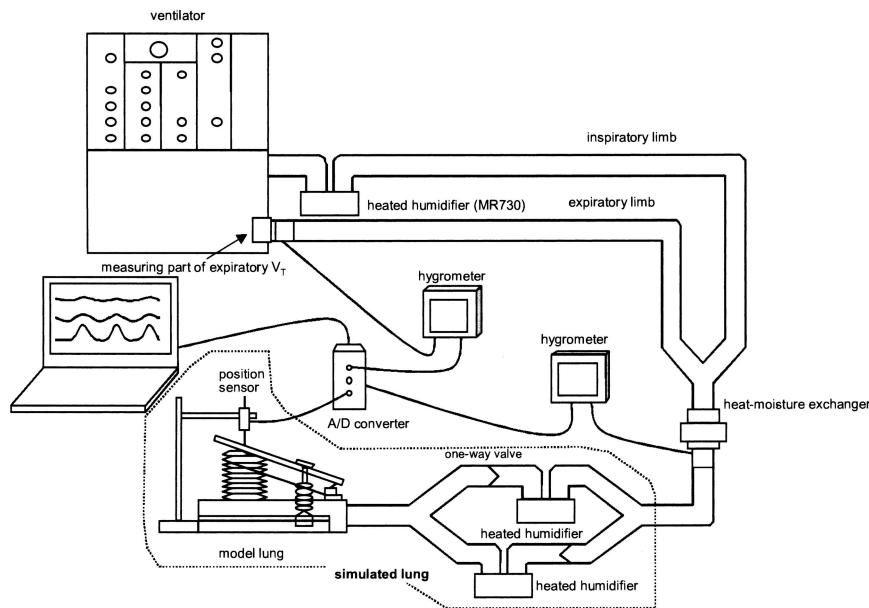
Fig. 1. Schematic diagram of experimental setup during the use of a heat-moisture exchanger (HME). At the airway opening side, the simulated lung consists of a short circuit with two one-way valves, two heated humidifiers (HHs; Hummax) and a model lung. One HH humidifies the gas entering the model lung and the other humidifies the gas going out of the lung. As a result, gas at 35°C, heated and humidified by the Hummax, flows into the model lung, and gas at 35°C, heated and humidified by the Hummax, flows into the HME. After the completion of the measurements with the HME, water was poured into the chamber (HH; MR290) in the ventilator circuit, the HME was removed, and the HH (HH; MR730) and double heating wire in the ventilator circuit were switched on. The displayed tidal volume (V_T) of each ventilator was measured at the end of the expiratory limb

We configured the model lung to simulate typical humidification conditions during patient ventilation. The configuration comprised a short circuit with two one-way valves, two HHs (Hummax; METRAN, Saitama, Japan), and the model lung (TTL; Michigan Instruments, Grand Rapids, MI, USA) (Fig. 1), to which the ventilators were connected via a ventilator circuit (Adult Breathing Circuit dual heated; Fisher & Paykel Healthcare) that had dual heated wires, a humidification chamber (MR290; Fisher & Paykel), and another HH (MR 730; Fisher & Paykel). The compliance of the ventilator circuit was $3.7\,\text{ml·cmH}_2\text{O}^{-1}$. We included an HME (DAR Hygrobac S) at the Y piece of the ventilator circuit and recorded the displayed expiratory V_T for sequences of ten breaths for each ventilator. After we completed the measurements with the HME, water was poured into the chamber, the HME was removed, and the MR730 was switched on. At each ventilator setting, the V_T of ten consecutive breaths was recorded. Because the Evita 4 had two separate settings, one for the HME and the other for the HH, we chose both settings for both humidification systems in this study. Moiscope sensors were set, one at the airway opening and one at the end of the expiratory limb.

The displacement of the TTL model lung bellows was measured by a position sensor (T 50; Novotechnik, Stuttgart, Germany). This position sensor measured the motion of a plate on the bellows in 0.01-mm increments.

Statistical analysis

The data values are presented as means ± SD. The values for expired V_T and the thoracic volume displacement of the RIP were analyzed with the unpaired *t*-test. Parametric data were analyzed with one-way or two-way analysis of variance, followed by post-hoc analysis with the Tukey honest significant difference test. We evaluated the agreement of thoracic volume displacement between the HME and the HH using Bland-Altman analysis. A statistics software package (STATISTICA 5.5; StatSoft, Tulsa, OK, USA) was used, and statistical significance was accepted when $P < 0.05$.

Results

Patient study

Table 2 shows the clinical profiles of the patients. Room temperature was 25.8 ± 1.1°C. Table 3 shows the results of displayed expiratory V_T on the ventilator, RIP thoracic volume displacement data, and humidity and temperature at the airway opening and at the end of the expiratory limb. Bland-Atman analysis revealed that the values for RIP thoracic volume displacement with the HME agreed well with those with the HH (bias, 0.06 volts; precision, 0.021 volts). At a setting of $12\,\text{ml·kg}^{-1}$ V_T, whereas the RIP thoracic volume displacement corresponded very closely regardless of whether the HME or the HH was used, the displayed expiratory V_T of the ventilator was 12% less with the HME than with the HH. Similarly, at the setting of $6\,\text{ml·kg}^{-1}$ V_T, 14% underestimation of the expiratory V_T ensued when the HME was used. Furthermore, this underestimation of the expiratory V_T due to the HME was observed in all

Table 2. Patient characteristics

No.	Sex	Age (years)	Height (cm)	Weight (kg)	Disease	Operation	Body temperature (°C)	Compliance (ml·cmH$_2$O^{-1})	PIP (cmH$_2$O)
1	M	43	165	59	AMI, ICM	CABG, LVAS implantation	39.1	55.4	28
2	M	65	166	62	AR, AAA	AVR, aortic replacement	36.8	45.9	31
3	M	80	166	70	TAA, Mediastinitis	Pericardial drainage	34.0[a]	49.0	25
4	F	78	155	40	AR, MR, IHD	AVR, MVP, CABG	37.7[a]	43.1	25
5	F	83	140	52	AS, AP	AVR, CABG	37.9	34.4	35
6	M	34	173	86	AR	AVR	37.7	55.6	34
7	M	78	170	45	ASR, MS, TR	DVR, TAP	36.0	77.1	20
8	M	81	166	59	TAA	Aortic replacement	36.9	64.5	31
9	F	43	160	68	ASR	AVR, Aortic replacement	37.9	61.5	33
10	M	67	164	67	ASR, MR	AVR, MVP	36.8	57.1	35
Mean		65	163	61			37.4	54.4	30
SD		18	9	13			1.0	12.0	5

Body temperature was calculated by rectal temperature as core temperature
PIP, peak inspiratory pressure; AMI, acute myocardial infarction; ICM, ischemic cardiomyopathy; CABG, coronary artery bypass graft; LVAS, left ventricular assist system; AR, aortic regurgitation; AAA, abdominal aortic aneurysm; AVR, aortic valve replacement; TAA, thoracic aortic aneurysm; IHD, ischemic heart disease; MVP, mitral valve plasty; AS, aortic stenosis; AP, angina pectoris; ASR, aortic stenosis and regurgitation; MS, mitral stenosis; TR, tricuspid regurgitation; DVR, aortic and mitral valve replacement; TAP, tricuspid annuloplasty
[a] Temperature was measured at the extremities

patients (Fig. 2). The AH and temperature at the airway opening were significantly higher when the HH was used than with the HME, whereas the AH exceeded $33\,mg\cdot l^{-1}$ with an RH of 100% in all settings. The AH, RH, and temperature at the end of the expiratory limb were significantly higher when the HH was used than with the HME (Table 3).

Model lung study

For all of the ventilators we tested, while the displacement of the lung bellows, as measured by the position sensor, was the same regardless of whether the HME or the HH was used, the displayed expiratory V_T was underestimated by 8%–14% with the use of the HME (Table 4). The AH, RH, and temperature at the end of the expiratory limb were also significantly higher when using the HH than with the HME, with all of the ventilators (data not shown).

Discussion

The major results of the present study were that displayed expiratory V_T was underestimated when an HME was used as a humidifying device, while thoracic volume replacement was identical with an HH and an HME. All three investigated ventilators exhibited smaller expiratory V_T with an HME than with an HH. When an HME was used, the displayed expiratory V_T was approximately 10% smaller than that with an HH. Although the precise reason for this underestimation was not investigated, there are a number of plausible explanations. First, it could be due to vapor loss. If the expired gas at 37°C is fully saturated with vapor, the expiratory V_T as measured by the flow-sensor should be equal to the V_T expired from the patient. However, when an HME traps the expired vapor, it takes away the volume occupied by the vapor, and this could account for the underestimation of the expiratory V_T, which would, consequently, be dependent on the amount of vapor lost. A rough calculation lends support to this speculation: saturated vapor pressure at 37°C is 47 mmHg, and the ventilator-monitored expired V_T can be anticipated to be $(760 − 47)/760 = 0.938$ times the actually expired V_T.

Another factor could be the cooling of the expired gas. If the HME perfectly traps the heat of the expired gas, the temperature at the expiratory flow-sensor may be close to room temperature. In fact, we observed that the temperature of the expired gas at the end of the expiratory limb was around 25°C (Table 3). Applying this, the monitored V_T may be $(273 + 25)/(273 + 37) = 0.961$ times the actually expired V_T. However, corrections for flow measurement depend on the ventilators

Table 3. Displayed tidal volume, humidity, and temperature in the clinical study

	V_T at 12 ml·kg^{-1}		V_T at 6 ml·kg^{-1}	
	HME	HH	HME	HH
Displayed expiratory V_T (ml)	682 ± 136*	772 ± 137	331 ± 66*	384 ± 72
Displayed expiratory V_T (ml·kg^{-1})	11.2 ± 2.2	12.7 ± 2.3	5.4 ± 1.1	6.3 ± 1.2
Thoracic volume displacement of RIP (volts)	0.96 ± 0.58	0.96 ± 0.58	0.49 ± 0.29	0.49 ± 0.30
Airway opening				
Absolute humidity (mg·l^{-1})	34.6 ± 1.0*	41.5 ± 1.3	35.6 ± 1.2*	42.6 ± 1.5
Relative humidity (%)	100.0 ± 0.0	100.0 ± 0.0	100.0 ± 0.0	100.0 ± 0.0
Temperature (°C)	32.4 ± 0.5*	35.9 ± 0.6	33.0 ± 0.7*	36.4 ± 0.7
End of the expiratory limb				
Absolute humidity (mg·l^{-1})	6.2 ± 1.3*	36.4 ± 5.4	4.0 ± 0.8*	34.6 ± 5.6
Relative humidity (%)	26.8 ± 6.7*	56.9 ± 12.5	17.6 ± 4.6*	54.7 ± 14.0
Temperature (°C)	25.1 ± 1.4*	44.9 ± 1.2	25.0 ± 1.5*	44.8 ± 1.9

*$P < 0.05$ vs HH for the specific tidal volume, two-way analysis of variance (ANOVA) and Tukey's post-hoc test
Displayed expiratory V_T was demonstrated as ATPS. The data for airway opening were measured at inspiratory phase, and those of end of the expiratory limb were measured at expiratory phase
V_T, tidal volume; HME, heat-moisture exchanger; HH, heated humidifier; RIP, respiratory inductive plethysmography

Table 4. Displayed tidal volume and model lung volume displacement of position sensor in the model lung study

	V_T (ml)	Displayed V_T (ml)		Measured displacement (volts)	
		HME	HH	HME	HH
Evita 4 HME	300	310 ± 2	342 ± 3*	0.54 ± 0.00	0.53 ± 0.00
	500	516 ± 3	564 ± 5*	0.92 ± 0.00	0.89 ± 0.00**
	700	726 ± 4	785 ± 2*	1.32 ± 0.01	1.27 ± 0.00**
Evita 4 HH	300	299 ± 2	334 ± 2*	0.51 ± 0.00	0.52 ± 0.00**
	500	500 ± 1	545 ± 2*	0.88 ± 0.00	0.89 ± 0.00**
	700	703 ± 1	760 ± 2*	1.26 ± 0.00	1.27 ± 0.00**
7200ae	300	300 ± 0	340 ± 0*	0.57 ± 0.00	0.58 ± 0.00**
	500	490 ± 0	558 ± 4*	0.94 ± 0.00	0.94 ± 0.00
	700	710 ± 0	800 ± 0*	1.36 ± 0.00	1.35 ± 0.00**
Servo 300	300	295 ± 3	318 ± 3*	0.54 ± 0.01	0.54 ± 0.01
	500	492 ± 6	540 ± 4*	0.93 ± 0.01	0.93 ± 0.01
	700	700 ± 8	764 ± 1*	1.32 ± 0.01	1.33 ± 0.01

*$P < 0.05$ vs displayed V_T with HME; **$P < 0.05$ vs measured displacement with HME, one-way ANOVA and Tukey's post-hoc test
Measured displacement (volts) was obtained by a position sensor. For Evita 4 HME, Evita 4 HH, and 7200ae, the values for displayed V_T were demonstrated as BTPS, and for Servo 300 as ATPS. Evita allows the clinician to input the type of humidifier being used
V_T, tidal volume; displayed V_T, displayed expiratory V_T; HME, heat-moisture exchanger; HH, heated humidifier; Evita 4 HH, Evita 4 in HH mode; Evita 4 HME, Evita 4 in HME mode
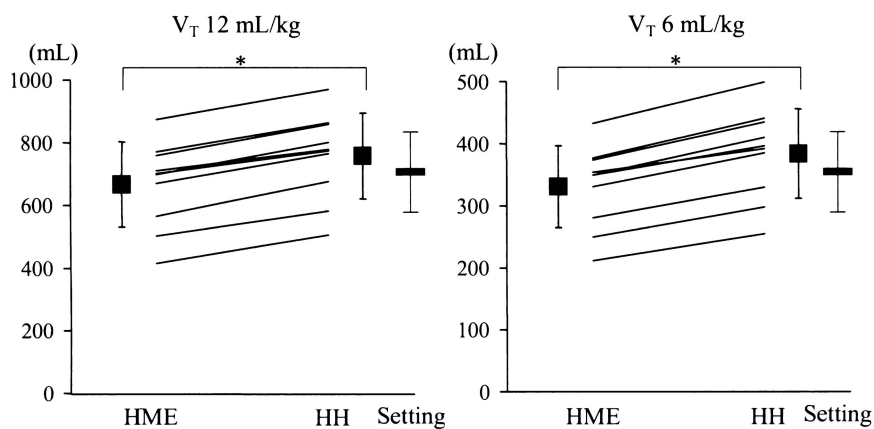
Fig. 2. Clinical study. This figure shows, at the tidal volumes of 6 and 12 ml·kg^{-1}, a comparison of ventilator-monitored expiratory tidal volume (V_T) during the use of an HME and an HH. During the use of an HH, V_T was higher than that during the use of an HME (*$P < 0.05$). *Setting*, volume setting of each patient (ml)

used. Some ventilators use ambient temperature and pressure (ATPS) corrections and others use body temperature and pressure (BTPS) corrections. The Puritan-Bennett 7200ae and Evita 4 ventilators display volume at 1 atmosphere, at 37°C, and 100% RH, while the Servo ventilator 300 displays volume at ambient pressure and at 21°C, without specifying humidity. In addition, the Puritan-Bennett 7200ae warms gas upstream of the flow-sensor to protect the sensor from condensation. Therefore, it was unlikely that the cooling of the expired gas influenced the measured V_T.

It is possible that the large ventilatory circuit and water chamber of the HH system might affect the displayed V_T by increasing the compliance of the circuit. To minimize differences in compliance, we used identical circuits with the HH and the HME. The only difference was the presence of 100 ml water in the chamber when using the HH. We estimated that the effect of the chamber water on the V_T reading would be smaller than 5 ml, because, in a circuit with a total volume of approximately 1000 ml, the compliance of the circuit was small (1.99 ml·cmH$_2$O^{-1}) and in most patients the airway plateau pressure was below 20 cmH$_2$O. While the HME itself increased the total volume of the circuit further (65 ml), the compliance was very similar in the circuit with the HH (1.89 ml·cmH$_2$O^{-1}) and that with the HME (2.10 ml·cmH$_2$O^{-1}) [9]. Although the effect of compressive volume is more significant in patients with ALI/ARDS than in those with normal respiratory mechanics, the effect of vapor on the measurement of V_T should be the same regardless of the respiratory mechanics in the patient.

The characteristics of the flow sensors in each ventilator are also important when evaluating an error of expiratory V_T measurement. For example, a pneumotachograph is affected by gas composition, humidity, temperature, and the existence of turbulence.

Importantly, we confirmed that changes in thoracic volume were similar during use of both the HME and the HH. In the patient study, we used an RIP system to evaluate thoracic volume displacement, because a device directly measuring the gas flow, such as a pneumotachometer, placed in the ventilatory circuit would have been influenced by humidity and temperature. Rather than needlessly going through elaborate calibration procedures to separately evaluate RC, AB, and SUM using the RIP system, we did not translate the output of RIP into milliliters, but compared the raw values. The absolute volume displacement measured by RIP shows some error; however, it reflects accurately differences in thoracic volume displacement unless the RespiBands move. The lack of significant differences in thoracic volume displacement when an HH and an HME were used strongly suggests that V_T was similar with both the HH and HME. Although the value of AH

at the airway opening was higher when the HH was used, the AH with either humidification system exceeded 33 mg·l^{-1} and it was likely that inspired gas was fully saturated in the patient's alveoli when either an HME or an HH was used [10,11]. Consequently, we assume that thoracic volume displacement was similar when either system was used.

Different brands of HME have different performances [12]. Because the humidity of the expired gas when it reaches the expiratory flow-sensor has a major influence on V_T monitoring, the performance of the HME is likely to affect the accuracy of V_T monitoring. If the HME worked perfectly, it would completely trap the vapor in the expired gas and reuse 100% of the vapor during the next inspiration. In reality, however, some of the vapor escaped from the HME into the expired gas, and the AH at the end of the expiratory limb was not zero (Table 3), even though the type of HME that we used is one of the better performers [13,14]. Although further study is needed to confirm effect of HME performance on the accuracy of V_T monitoring, we speculate that the better the performance of the HME, the less vapor passes through the HME; therefore, the larger will be the degree of underestimation of displayed V_T.

To find out whether V_T underestimation when using an HME is a general issue, we did a bench study with a model lung. To monitor both inspired V_T and expired V_T, modern ventilators incorporate various kinds of flow-sensor: pneumotachometer, hot-wire flow-sensor, and ultrasound flow-sensor [15,16]. The Servo 300 ventilator uses a flow-sensor composed of metal mesh that functions similarly to a pneumotachometer (Table 1). By contrast, both the Puritan-Bennett 7200ae and the Evita 4 incorporate a hot-wire flow-sensor. In the model lung study, for each of the ventilators we tested, the displayed expiratory V_T was about 10% less with an HME than with an HH. The level of underestimation was close to the results obtained in the patient study. These findings suggest that the effect of a humidifying system on displayed expiratory V_T is independent of the type of flow-sensor.

When it comes to the ventilatory management of patients with injured lungs, the only efficacious strategy that we currently know is the application of low V_T. Consequently, accurate V_T monitoring is essential. In an ARDS Network study, patients were ventilated with VCV and V_T of 6 ml·kg^{-1} predicted body weight [1]. When a ventilator delivers a set volume of dry gas, the actual volume that is delivered to the patient's lungs is greater, because of the addition of vapor and expansion due to warming. Besides this, each ventilator has its own algorithm to control delivery once V_T is set. For example, the Puritan-Bennett 7200ae ventilator compensates for circuit compliance, but the Servo 300 ven-

tilator does not. Thus, the V_T that is actually delivered to the patient's lungs depends on the brand of ventilator and, even during VCV, physicians cannot neglect careful monitoring of expired V_T. In the present study, the respiratory mechanics of the patients were within the normal range, and we are not sure whether our results can translate into the situation of patients with low-compliant lungs. In this study, the patients underwent mechanical ventilation with large V_T ($12\,\mathrm{ml \cdot kg^{-1}}$) for a given period. However, because they showed normal compliance of the respiratory system ($54.4 \pm 12.0\,\mathrm{ml \cdot cmH_2O^{-1}}$) and were sufficiently sedated, the plateau pressure was low ($<24\,\mathrm{cmH_2O}$) in all patients.

This study has several limitations. First, we did not measure airway flow directly along the ventilatory circuits, although it seems sufficient to simply assess the gas volume change through the humidifiers. However, a flow-sensor such as a pneumotachometer is influenced by humidity and temperature. Instead, we applied an RIP system in a clinical study and a position sensor in a model lung study to confirm, indirectly, that delivered tidal volume was equivalent for an HME and an HH. Second, it is not known whether a 10% difference in tidal volume is really important. However, because the mortality of ARDS patients increases in parallel with increases of plateau pressure [17], strict adjustment and monitoring of the tidal volume may be important.

In conclusion, displayed expiratory V_T was underestimated by about 10% when an HME system was used, compared to when an HH system was used, while thoracic volume displacement was identical. Loss of vapor by the HME seemed to be the major reason for the underestimation, although we were not able to explain the 10% difference completely. We should be aware of the possibly of underestimation of the monitored V_T with an HME.

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