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Comparison of the temperature and humidity in the anesthetic breathing circuit among different anesthetic workstations

Updated guidelines for reporting parallel group randomized trials

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Abstract

Background: For patients undergoing general anesthesia, adequate warming and humidification of the inspired gases is very important. The aim of this study was to evaluate the differences in the heat and moisture content of the inspired gases with low-flow anesthesia using 4 different anesthesia machines.

Methods: The patients were divided into 11 groups according to the anesthesia machine used (Ohmeda, Excel; Avance; Dräger, Cato; and Primus) and the fresh gas flow (FGF) rate (0.5, 1, and 4 L/min). The temperature and absolute humidity of the inspired gas in the inspiratory limbs were measured at 5, 10, 15, 30, 45, 60, 75, 90, 105, and 120 minutes in 9 patients scheduled for total thyroidectomy or cervical spine operation in each group.

Results: The anesthesia machines of Excel, Avance, Cato, and Primus did not show statistically significant changes in the inspired gas temperatures over time within each group with various FGFs. They, however, showed statistically significant changes in the absolute humidity of the inspired gas over time within each group with low FGF anesthesia ($P < .05$). The anesthesia machines of Cato and Primus showed statistically significant changes in the absolute humidity of the inspired gas over time within each group with an FGF of 4 L/min ($P < .05$). However, even with low-flow anesthesia, the temperatures and absolute humidities of the inspired gas for all anesthesia machines were lower than the recommended values.

Conclusion: There were statistical differences in the provision of humidity among different anesthesia workstations. The Cato and Primus workstations were superior to Excel and Avance. However, even these were unsatisfactory in humans. Therefore, additional devices that provide inspired gases with adequate heat and humidity are needed for those undergoing general anesthetic procedures.

Abbreviations: FGF = fresh gas flow, IGT = Inspired gas temperature, AH = Absolute humidity.

Keywords: absolute humidity, anesthesia machine, humidification, temperature

1. Introduction

No clear-cut values exist for the recommended temperatures and absolute humidities of the inspired gases during mechanical ventilation; however, in humans, the optimal temperature and absolute humidity at the mouth are considered to be approximately 32°C and 27.3 mg H_2O/L, respectively.[1] The American Association for Respiratory Care has recommended that a heated humidifier should be used to provide an inspired gas temperature of 33.2°C ± 2°C and a minimum of 30 mg H_2O/L of water vapor routinely for an intubated patient.[2] Thus, passive humidification (heat and moisture exchanger), active humidification (heated humidifier), or low-flow anesthesia are being nowadays used to provide physiological warm and wet gas for patients undergoing general anesthesia.[3–6]

Under low-flow anesthesia with a fresh gas flow (FGF) of 0.5 to 1 L/min, patients breathe from a circle-absorber breathing circuit, and heat and water vapor are added by rebreathing the exhaled gas; the heat and water vapor released from the CO_2 absorbent are also contributory. In a laboratory set up, the use of a circle system with an FGF of 0.5 L/min was more useful in terms of the humidity and inspired gas temperature than a nonrebreathing system with a disposable humidifier.[7] In an exothermic reaction between the expiratory anesthetic gas and the CO_2 absorber, 14 kcal of heat

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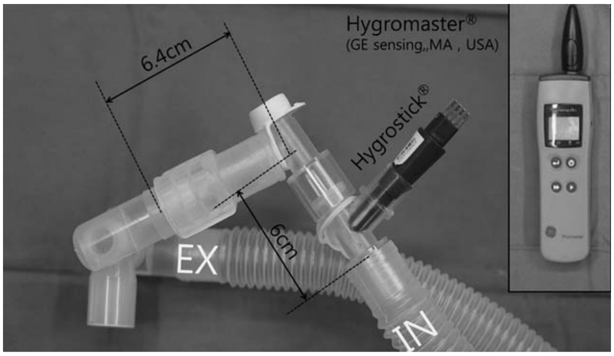


Figure 1. CONSORT flow diagram of this study.

and 2 mol of water are liberated for each mole of CO_2 absorbed.[8] These affect the temperature and humidity conditions during anesthesia.

However, the use of low-flow anesthesia during general anesthesia appears to have a different effect on the heat and moisture conditions, depending on the anesthesia machine. The Cato (Dräger) machine was more effective in warming and humidifying the respiratory gas than the Aestiva machine.[9] The Primus anesthesia workstation also had a significant effect on the temperature, relative humidity, and absolute humidity of the respiratory gas with low FGF.[10]

Therefore, evaluation of the heat and moisture conservation with different FGFs and different anesthesia machines or workstations is needed. We compared the heat and moisture conservation during variable FGF anesthesia (0.5, 1, and 4 L/min) among 4 different anesthesia machines or workstations (Ohmeda, Excel; Avance; Dräger, Cato; and Primus)

2. Methods

This study was approved by the institutional review board (IRB: ED09142) and registered in the clinical trial registry (https://clinicaltrials.gov: NCT01193465). Written informed consent was obtained from all subjects, a legal surrogate, the parents or legal guardians for minor subjects, or the requirement for a written informed consent was waived by the IRB. We studied 109 American Society of Anesthesiologists physical status I–II patients, aged 25 to 60 years, who were admitted for elective total thyroidectomy or cervical herniated nucleus pulposus operation. Patients with a history of smoking, respiratory disease, fever, or obesity (body mass index $>35\,kg/m^2$) were excluded.

The groups were divided according to the anesthesia workstations used (Ohmeda, Excel [Ohmeda Corporation, Chester, NJ]; Avance [GE Healthcare, Helsinki, Finland]; Dräger, Cato [Dräger, Lübeck, Germany]; and Primus [Dräger]). The groups were subdivided according to the FGF (0.5, 1, and 4 L/min) used. An FGF of 0.5 L/min was not considered for the Excel machine as FiO_2 monitoring is not possible at such a low flow rate. The groups with FGFs of 0.5 and 1 L/min were evaluated to assess the effect of low FGF anesthesia; some of the reported important advantages include maintaining the body temperature and decreased water loss.[11] Thus, 9 patients each were assigned randomly to 1 of the 11 groups, according to a computer-generated random number sequence (www.randomization.com; first generator; treatment labels: Excel1, Excel4, Avance0.5, Avance1, Avance4, Cato0.5, Cato1, Cato4, Primus0.5, Primus1, and Primus4; number of subjects per block/number of blocks, 11/11; initial subject ID number, 1; seed, 4444).

Patients were premedicated with intramuscular injections of midazolam 2 mg and glycopyrrolate 0.2 mg. General anesthesia was induced and maintained by 1 of 4 anesthesia workstations. Standard monitoring of various parameters, including the body

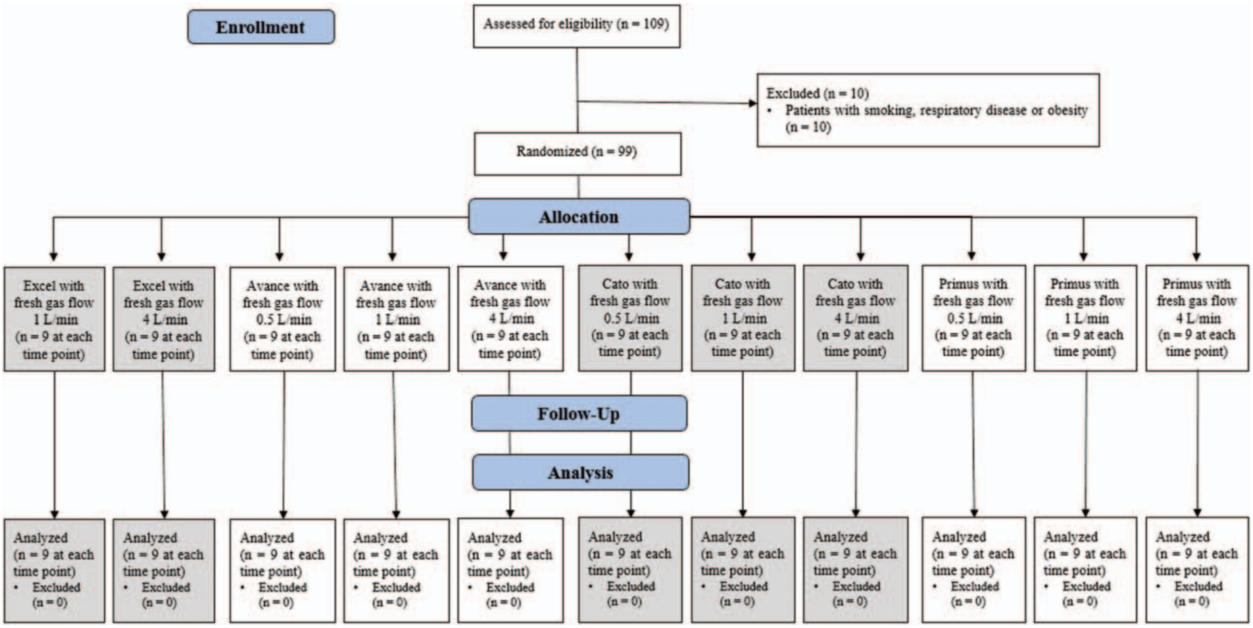


Figure 2. Hygrostick sensor integrated between the Y-piece and the inspiratory limb using a T-connector. IN = inspiratory limb of breathing circuit, EX = expiratory limb of breathing circuit.

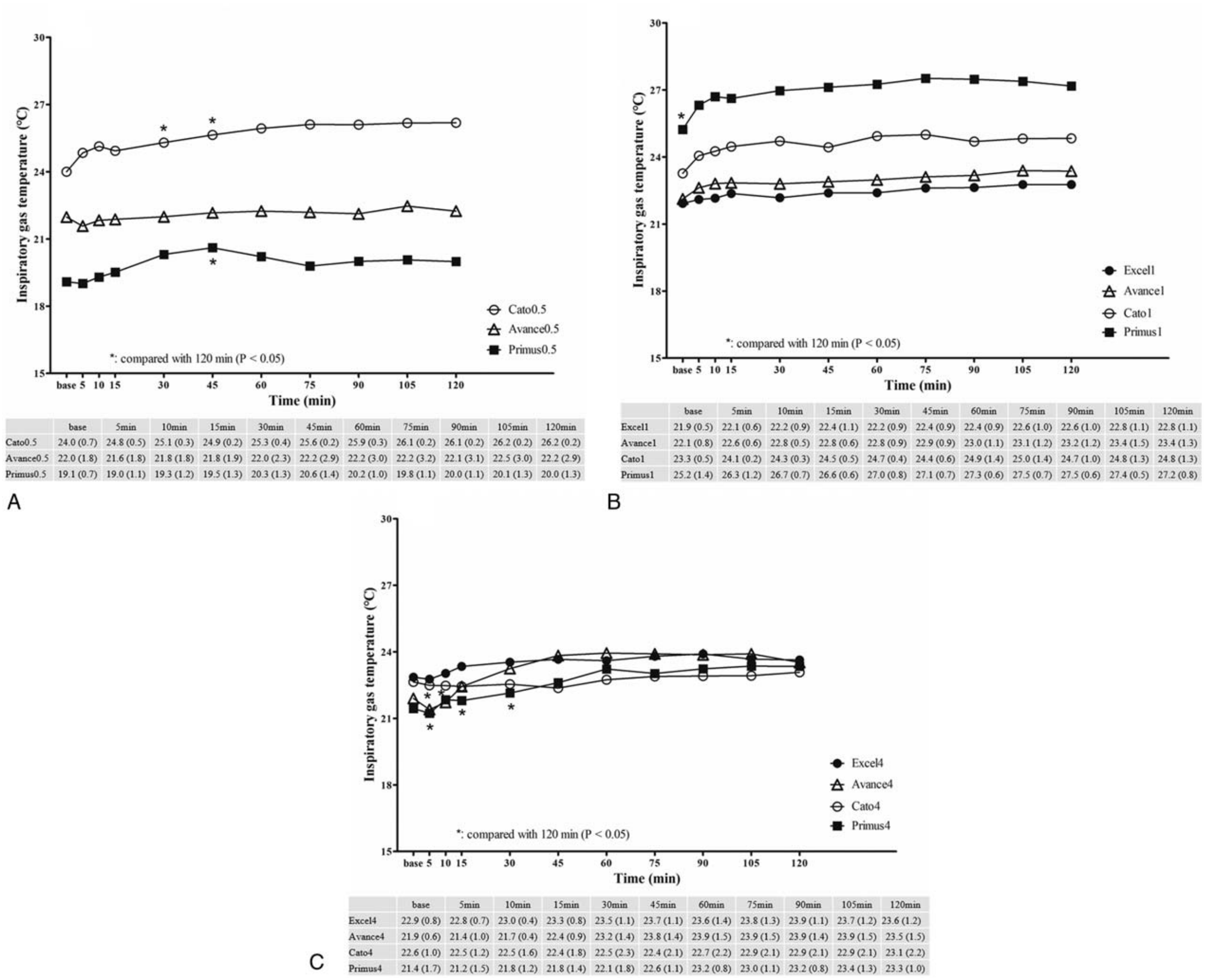
Table 1

Demographic data.

Workstation	Fresh gas flow (L/min)	Age (yr)	BMI (kg/m^2)	Room temperature (°C)
Excel (n=18)	1 (n=9)	43.2±7.1	23.0±2.0	22.6±1.5
	4 (n=9)	47.3±8.1	25.4±3.0	22.7±0.4
Avance (n=27)	0.5 (n=9)	47.7±9.6	24.5±2.6	22.8±1.0
	1 (n=9)	44.1±8.1	23.8±2.9	22.9±1.6
	4 (n=9)	44.7±10.5	25.4±2.7	22.5±1.6
Cato (n=27)	0.5 (n=9)	45.3±8.0	22.1±2.2	22.9±1.7
	1 (n=9)	44.3±7.3	23.1±3.7	22.9±0.8
	9 (n=9)	46.2±9.3	24.2±3.9	23.1±0.8
Primus (n=27)	0.5 (n=9)	45.6±6.3	21.9±3.5	23.1±0.5
	1 (n=9)	48.7±6.9	24.2±7.7	22.6±1.0
	4 (n=9)	42.9±10.3	22.0±1.8	22.6±0.5

The data are expressed as means±standard deviations. Excel (Ohmeda Corporation, Chester, NJ); Avance (GE Healthcare, Helsinki, Finland); Cato (Dräger, Lübeck, Germany); Primus (Dräger, Lübeck, Germany). There were no differences in the age, BMI, and room temperature among the groups.
BMI=body mass index.

temperature measured at the nasopharynx, bispectral index, electrocardiogram, noninvasive arterial blood pressure, pulse oximetry, expiratory gas concentration, and end-tidal CO_2, was carried out. In all cases, the CO_2 absorbent was changed to fresh soda lime and the room temperature was maintained at 20°C to 22°C by the air conditioning system. Anesthesia was induced with propofol 2 mg/kg and cisatracurium 0.15 mg/kg. After tracheal intubation, mechanical ventilation was initiated at a respiratory



	base	5min	10min	15min	30min	45min	60min	75min	90min	105min	120min
Cato0.5	24.0 (0.7)	24.8 (0.5)	25.1 (0.3)	24.9 (0.2)	25.3 (0.4)	25.6 (0.2)	25.9 (0.3)	26.1 (0.2)	26.1 (0.2)	26.2 (0.2)	26.2 (0.2)
Avance0.5	22.0 (1.8)	21.6 (1.8)	21.8 (1.8)	21.8 (1.9)	22.0 (2.3)	22.2 (2.9)	22.2 (3.0)	22.2 (3.2)	22.1 (3.1)	22.5 (3.0)	22.2 (2.9)
Primus0.5	19.1 (0.7)	19.0 (1.1)	19.3 (1.2)	19.5 (1.3)	20.3 (1.3)	20.6 (1.4)	20.2 (1.0)	19.8 (1.1)	20.0 (1.1)	20.1 (1.3)	20.0 (1.3)

	base	5min	10min	15min	30min	45min	60min	75min	90min	105min	120min
Excel1	21.9 (0.5)	22.1 (0.6)	22.2 (0.9)	22.4 (1.1)	22.2 (0.9)	22.4 (0.9)	22.4 (0.9)	22.6 (1.0)	22.6 (1.0)	22.8 (1.1)	22.8 (1.1)
Avance1	22.1 (0.8)	22.6 (0.6)	22.8 (0.5)	22.8 (0.6)	22.8 (0.9)	22.9 (0.9)	23.0 (1.1)	23.1 (1.2)	23.2 (1.2)	23.4 (1.5)	23.4 (1.3)
Cato1	23.3 (0.5)	24.1 (0.2)	24.3 (0.3)	24.5 (0.5)	24.7 (0.4)	24.4 (0.6)	24.9 (1.4)	25.0 (1.4)	24.7 (1.0)	24.8 (1.3)	24.8 (1.3)
Primus1	25.2 (1.4)	26.3 (1.2)	26.7 (0.7)	26.6 (0.6)	27.0 (0.8)	27.1 (0.7)	27.3 (0.6)	27.5 (0.7)	27.5 (0.6)	27.4 (0.5)	27.2 (0.8)

	base	5min	10min	15min	30min	45min	60min	75min	90min	105min	120min
Excel4	22.9 (0.8)	22.8 (0.7)	23.0 (0.4)	23.3 (0.8)	23.5 (1.1)	23.7 (1.1)	23.6 (1.4)	23.8 (1.3)	23.9 (1.1)	23.7 (1.2)	23.6 (1.2)
Avance4	21.9 (0.6)	21.4 (1.0)	21.7 (0.4)	22.4 (0.9)	23.2 (1.4)	23.8 (1.4)	23.9 (1.5)	23.9 (1.5)	23.9 (1.4)	23.9 (1.5)	23.5 (1.5)
Cato4	22.6 (1.0)	22.5 (1.2)	22.5 (1.6)	22.4 (1.8)	22.5 (2.3)	22.4 (2.1)	22.7 (2.2)	22.9 (2.1)	22.9 (2.1)	22.9 (2.1)	23.1 (2.2)
Primus4	21.4 (1.7)	21.2 (1.5)	21.8 (1.2)	21.8 (1.4)	22.1 (1.8)	22.6 (1.1)	23.2 (0.8)	23.0 (1.1)	23.2 (0.8)	23.4 (1.3)	23.3 (1.0)

Figure 3. Inspired gas temperature (IGT) in celsius degree at 0, 5, 10, 15, 30, 45, 60, 75, 90, 105, and 120 minutes. (A) IGT at a fresh gas flow of 0.5 L/min, (B) IGT at a fresh gas flow of 1 L/min, and (C) IGT at a fresh gas flow of 4 L/min. The groups were divided in accordance to anesthesia workstations used (Ohmeda, Excel [Ohmeda Corporation, Chester, NJ]; Avance [GE Healthcare, Helsinki, Finland]; Dräger, Cato [Dräger, Lübeck, Germany]; and Primus [Dräger, Lübeck, Germany]) and subdivided according to the fresh gas flow (0.5, 1, and 4 L/min). The data are expressed as means.

Table 2

Comparison of the inspired gas temperature with time and ventilator with 3 different fresh gas flow rates (0.5, 1, and 4 L/min).

Source	Sum of squares	df	Mean square	*F*	*P*	Noncent. parameter	Observed power*
Fresh gas flow, 0.5 L/min							
Between subjects							
Ventilator	1619.49	2	809.75	35.77	<.001	71.54	1.00
Error	543.27	24	22.64				
Within subjects							
Time	53.15	1.33	40.12	7.09	.01	9.40	0.81
Time × Ventilator	21.91	2.65	8.27	1.46	.25	3.87	0.33
Error (time)	179.86	31.80	5.66				
Fresh gas flow, 1 L/min							
Between subjects							
Ventilator	1225.85	3	408.62	64.92	<.001	194.76	1.00
Error	201.41	32	6.29				
Within subjects							
Time	70.10	2.02	34.73	21.35	<.001	43.10	1.00
Time × ventilator	13.46	6.06	2.22	1.37	.24	8.27	0.50
Error (time)	105.07	64.59	1.63				
Fresh gas flow, 4 L/min							
Between subjects							
Ventilator	53.33	3	17.78	1.07	.38	3.22	0.26
Error	530.88	32	16.59				
Within subjects							
Time	119.51	1.74	68.67	21.13	<.001	36.77	1.00
Time × Ventilator	48.10	5.22	9.21	2.83	.02	14.80	0.81
Error (time)	181.02	55.70	3.25				

* Computed using alpha = 0.05.

rate of 12/min, FGF of 8 L/min, and FiO_2 of 0.6. The tidal volume was controlled to maintain 30 to 35 mm Hg of end-tidal CO_2. Anesthesia was maintained with an end-tidal concentration of 2 to 3 vol% of sevoflurane with 8 L/min of FGF until the draping was performed. After 20 minutes of mechanical ventilation, the baseline temperature and absolute humidity were measured. Subsequently, the FGF was changed to 0.5, 1, or 4 L/min, according to the group; the data were recorded at 0, 5, 10, 15, 30, 45, 60, 75, 90, 105, and 120 minutes. The mean of the 3 lowest values during respiration was recorded. During the operation, tachycardia, hypertension, or hypotension more than 20% of the baseline was managed with fentanyl or ephedrine.

The sensor systems of the Protimeter Hygromaster and Hygrostick (GE Sensing, Billerica, MA) were used for monitoring the inspiratory temperature and absolute humidity. The sensor accuracy was ±3% (at 30%–40% relative humidity) or ±2% (at 40%–98% relative humidity) for humidity, and ±0.3°C for temperature. The sensors were located in the inspiratory limbs of the airway circuit (Fig. 1). Hence, the inspiratory limbs of the anesthesia breathing circuits (King System Co., Noblesville, IN) were disconnected from the Y-piece adaptor, and 2 T-connectors and 1 ring adaptor (which were detached from limb of another breathing circuit) were assembled between the Y-piece adaptor and the inspiratory limb. The sensor was positioned inside the side hole of the T-connector. The Hygromaster in the black box was connected by a BLD 5802 extension lead (GEsensing) to the Hygrostick. The sensor was funnel shaped and just fit into the side hole of the T-connector without any gas leak. It was integrated by a serial connection of 2 T-connectors and a ring adaptor after disconnecting the inspiratory limb from the Y-piece adaptor.

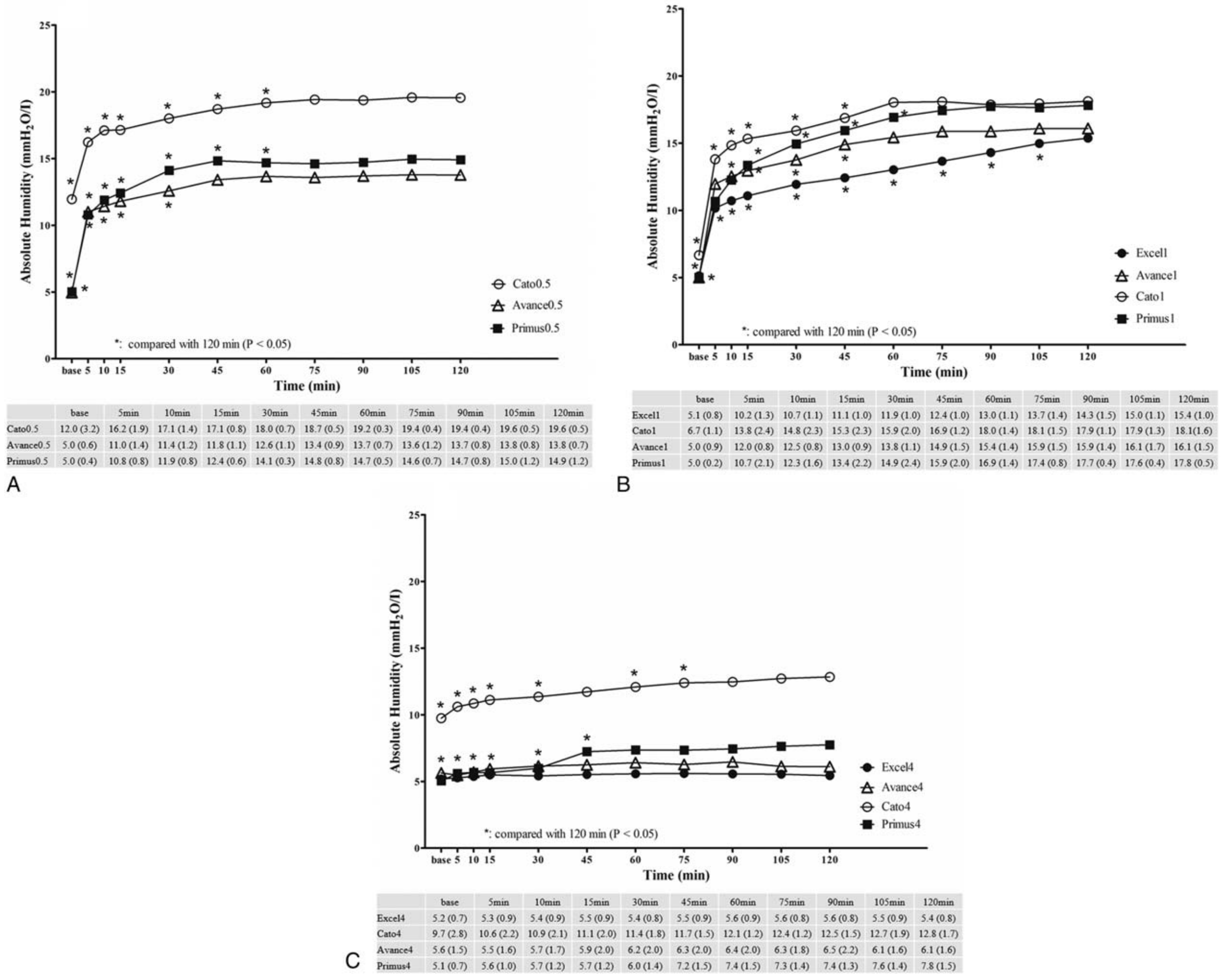
To estimate the sample size, a power analysis was performed; a sample size of 9 patients in each of the 11 groups was required to detect a 1°C intergroup difference in the body temperature; the power was set at 0.8, α at 0.05, and the standard deviation at 0.5 (obtained from preliminary results). To allow for a 10% drop-out rate, the present study needed a total of 109 participants. All data were represented as means ± standard deviations. The age, BMI, and room temperature were analyzed using the 1-way analysis of variance (ANOVA) test for normally distributed data. Differences within the groups were analyzed using the repeated-measures ANOVA test, and post-hoc comparisons were performed using the Bonferroni test. All statistical analyses were performed using SPSS (Windows ver. 22.0, IBM Corp, Armonk, NY). A $P < .05$ was considered significant.

3. Results

The CONSORT flow diagram is shown in Figure 2. Patients with a history of smoking, respiratory disease, or obesity (body mass index $>35\,kg/m^2$) were excluded (n = 10). A total of 99 patients fulfilled the study requirements. There were no significant differences in the age, body mass index, and room temperature, as shown in Table 1. The blood loss was <300 mL in all cases; blood transfusion or rapid hydration was not needed. There were no statistically significant differences among the group regarding demographic data (Table 1).

The decrease in body temperature during the study period was <1°C in each group; there were no differences among Excel, Avance, Cato, and Primus at the same FGF. Three (or 2) FGF groups using same anesthesia workstation showed no significant differences either.

The inspired gas temperatures with different FGFs or anesthesia workstations are shown in Figure 3 and Table 2. With an FGF of 0.5 and 1 L/min, there were no statistically significant changes in the inspired gas temperatures over time



	base	5min	10min	15min	30min	45min	60min	75min	90min	105min	120min
Cato0.5	12.0 (3.2)	16.2 (1.9)	17.1 (1.4)	17.1 (0.8)	18.0 (0.7)	18.7 (0.5)	19.2 (0.3)	19.4 (0.4)	19.4 (0.4)	19.6 (0.5)	19.6 (0.5)
Avance0.5	5.0 (0.6)	11.0 (1.4)	11.4 (1.2)	11.8 (1.1)	12.6 (1.1)	13.4 (0.9)	13.7 (0.7)	13.6 (1.2)	13.7 (0.8)	13.8 (0.8)	13.8 (0.7)
Primus0.5	5.0 (0.4)	10.8 (0.8)	11.9 (0.8)	12.4 (0.6)	14.1 (0.3)	14.8 (0.8)	14.7 (0.5)	14.6 (0.7)	14.7 (0.8)	15.0 (1.2)	14.9 (1.2)

A

	base	5min	10min	15min	30min	45min	60min	75min	90min	105min	120min
Excel1	5.1 (0.8)	10.2 (1.3)	10.7 (1.1)	11.1 (1.0)	11.9 (1.0)	12.4 (1.0)	13.0 (1.1)	13.7 (1.4)	14.3 (1.5)	15.0 (1.1)	15.4 (1.0)
Cato1	6.7 (1.1)	13.8 (2.4)	14.8 (2.3)	15.3 (2.3)	15.9 (2.0)	16.9 (1.2)	18.0 (1.4)	18.1 (1.5)	17.9 (1.1)	17.9 (1.3)	18.1(1.6)
Avance1	5.0 (0.9)	12.0 (0.8)	12.5 (0.8)	13.0 (0.9)	13.8 (1.1)	14.9 (1.5)	15.4 (1.4)	15.9 (1.5)	15.9 (1.4)	16.1 (1.7)	16.1 (1.5)
Primus1	5.0 (0.2)	10.7 (2.1)	12.3 (1.6)	13.4 (2.2)	14.9 (2.4)	15.9 (2.0)	16.9 (1.4)	17.4 (0.8)	17.7 (0.4)	17.6 (0.4)	17.8 (0.5)

B

	base	5min	10min	15min	30min	45min	60min	75min	90min	105min	120min
Excel4	5.2 (0.7)	5.3 (0.9)	5.4 (0.9)	5.5 (0.9)	5.4 (0.8)	5.5 (0.9)	5.6 (0.9)	5.6 (0.8)	5.6 (0.8)	5.5 (0.9)	5.4 (0.8)
Cato4	9.7 (2.8)	10.6 (2.2)	10.9 (2.1)	11.1 (2.0)	11.4 (1.8)	11.7 (1.5)	12.1 (1.2)	12.4 (1.2)	12.5 (1.5)	12.7 (1.9)	12.8 (1.7)
Avance4	5.6 (1.5)	5.5 (1.6)	5.7 (1.7)	5.9 (2.0)	6.2 (2.0)	6.3 (2.0)	6.4 (2.0)	6.3 (1.8)	6.5 (2.2)	6.1 (1.6)	6.1 (1.6)
Primus4	5.1 (0.7)	5.6 (1.0)	5.7 (1.2)	5.7 (1.2)	6.0 (1.4)	7.2 (1.5)	7.4 (1.5)	7.3 (1.4)	7.4 (1.3)	7.6 (1.4)	7.8 (1.5)

C

Figure 4. Absolute humidities (AHs) of the inspired gas at 0, 5, 10, 15, 30, 45, 60, 75, 90, 105, and 120 minutes. (A) AH at a fresh gas flow of 0.5 L/min, (B) AH at a fresh gas flow of 1 L/min, and (C) AH at a fresh gas flow of 4 L/min. The groups were divided according to the anesthesia workstations used (Ohmeda, Excel [Ohmeda Corporation, Chester, NJ]; Avance [GE Healthcare, Helsinki, Finland]; Dräger, Cato [Dräger, Lübeck, Germany]; and Primus [Dräger, Lübeck, Germany]) and subdivided according to the fresh gas flow (0.5, 1, and 4 L/min). The data are expressed as means.

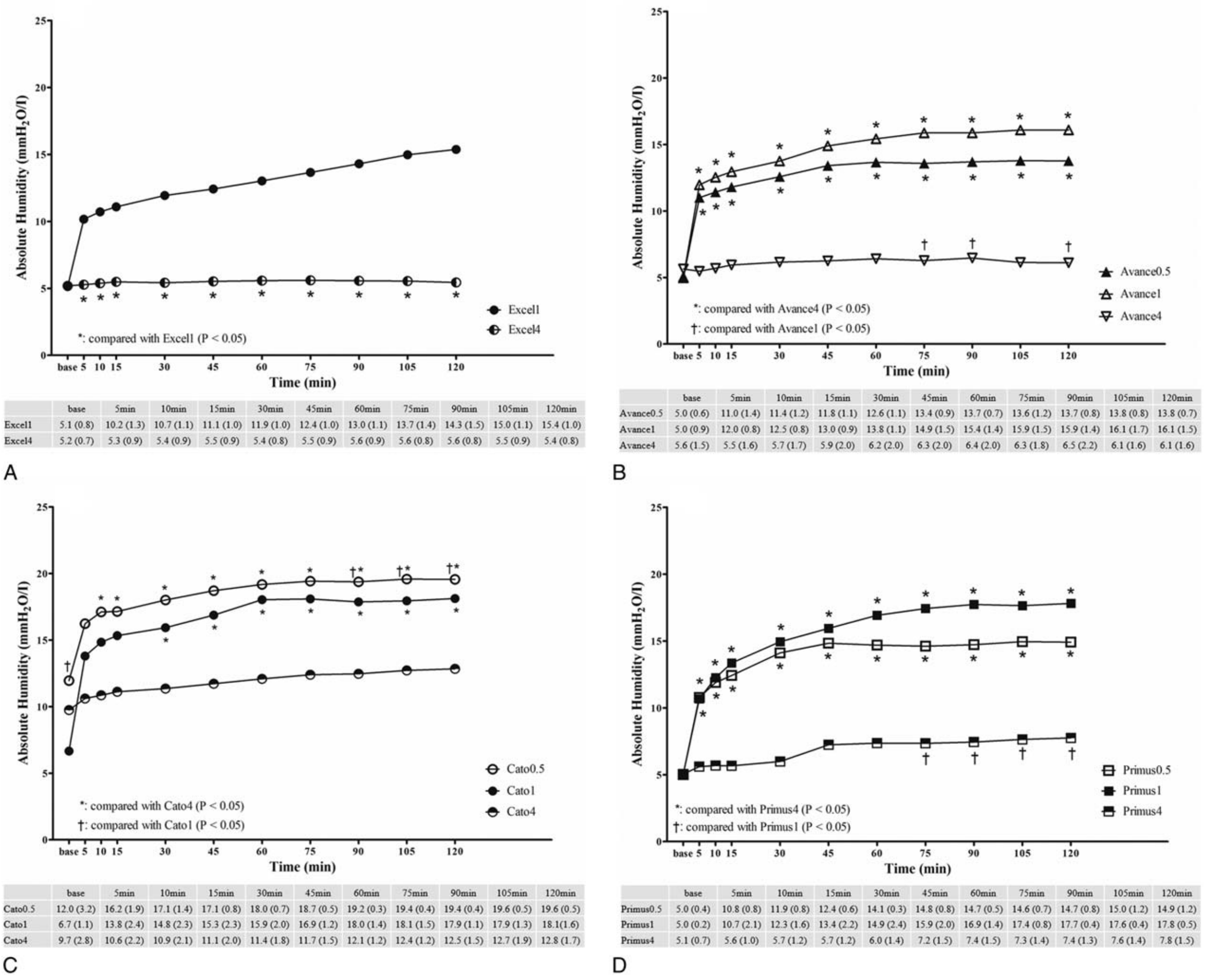
within the groups. With an FGF of 4 L/min, there were no statistically significant differences in inspired gas temperatures over time within the groups, except at some points with Primus4 and Avance4. The inspired gas temperatures of Excel4, Avance4, Cato4, and Primus4 did not differ statistically in our study. The inspired gas temperatures with all anesthesia machines for low-flow anesthesia were lower than the recommend temperature (i.e., 32°C).[1]

The absolute humidities of the inspired gas with different FGFs or anesthesia workstations are shown in Figures 4 and 5, and Table 3, respectively. The absolute humidities of the inspired gas with different FGFs or anesthesia workstations are shown in Figures 4 and 5. In low-flow anesthesia, the absolute humidities of the inspired gas with Excel, Avance, Cato, and Primus increased progressively for approximately 60 minutes before reaching a plateau ($P < .05$). The absolute humidities of the inspired gas with Cato and Primus increased progressively for approximately 30 minutes before reaching a plateau when an FGF of 4 L/min ($P < .05$) was administered. However, the absolute humidities of the inspired gas for all anesthesia machines under low-flow anesthesia were lower than recommended value (i.e., 27.3 mg H_2O/L).[1]

4. Discussion

According to our results, all the studied anesthesia machines or workstations provided heat and humidity to fresh gas under low-flow anesthesia. The Cato and Primus workstations provided heat and humidity to fresh gas even at an FGF of 4 L/min. However, even under low-flow anesthesia, the inspired gas temperatures and absolute humidities of all anesthesia machines were lower than the recommended values.

The consensus on the adequate temperature and absolute humidity of the inspired gas during mechanical ventilation using an endotracheal tube is not definite. Dery et al[12] suggested the concept of an isothermic saturation boundary. In the subglottic space, inhaled gas normally has a temperature of 31.2°C to 33.6°C, 95% to 100% relative humidity, and 33 mg H_2O/L of absolute humidity during spontaneous breathing.[13–15] Under normal physiological conditions, the humidity and temperature of the inhaled air increase when it passes through the nose and upper airways. Finally, the air reaching the alveoli attain a temperature of 37°C, the body temperature, with 100% relative humidity and 44 mg H_2O/L of absolute humidity at the isothermic saturation boundary during physiologic respiration.[14] Similarly, during expiration, the upper airways and



	base	5min	10min	15min	30min	45min	60min	75min	90min	105min	120min
Excel1	5.1 (0.8)	10.2 (1.3)	10.7 (1.1)	11.1 (1.0)	11.9 (1.0)	12.4 (1.0)	13.0 (1.1)	13.7 (1.4)	14.3 (1.5)	15.0 (1.1)	15.4 (1.0)
Excel4	5.2 (0.7)	5.3 (0.9)	5.4 (0.9)	5.5 (0.9)	5.4 (0.8)	5.5 (0.9)	5.6 (0.9)	5.6 (0.8)	5.6 (0.8)	5.5 (0.9)	5.4 (0.8)

	base	5min	10min	15min	30min	45min	60min	75min	90min	105min	120min
Avance0.5	5.0 (0.6)	11.0 (1.4)	11.4 (1.2)	11.8 (1.1)	12.6 (1.1)	13.4 (0.9)	13.7 (0.7)	13.6 (1.2)	13.7 (0.8)	13.8 (0.8)	13.8 (0.7)
Avance1	5.0 (0.9)	12.0 (0.8)	12.5 (0.8)	13.0 (0.9)	13.8 (1.1)	14.9 (1.5)	15.4 (1.4)	15.9 (1.5)	15.9 (1.4)	16.1 (1.7)	16.1 (1.5)
Avance4	5.6 (1.5)	5.5 (1.6)	5.7 (1.7)	5.9 (2.0)	6.2 (2.0)	6.3 (2.0)	6.4 (2.0)	6.3 (1.8)	6.5 (2.2)	6.1 (1.6)	6.1 (1.6)

	base	5min	10min	15min	30min	45min	60min	75min	90min	105min	120min
Cato0.5	12.0 (3.2)	16.2 (1.9)	17.1 (1.4)	17.1 (0.8)	18.0 (0.7)	18.7 (0.5)	19.2 (0.3)	19.4 (0.4)	19.4 (0.4)	19.6 (0.5)	19.6 (0.5)
Cato1	6.7 (1.1)	13.8 (2.4)	14.8 (2.3)	15.3 (2.3)	15.9 (2.0)	16.9 (1.2)	18.0 (1.4)	18.1 (1.5)	17.9 (1.1)	17.9 (1.3)	18.1(1.6)
Cato4	9.7 (2.8)	10.6 (2.2)	10.9 (2.1)	11.1 (2.0)	11.4 (1.8)	11.7 (1.5)	12.1 (1.2)	12.4 (1.2)	12.5 (1.5)	12.7 (1.9)	12.8 (1.7)

	base	5min	10min	15min	30min	45min	60min	75min	90min	105min	120min
Primus0.5	5.0 (0.4)	10.8 (0.8)	11.9 (0.8)	12.4 (0.6)	14.1 (0.3)	14.8 (0.8)	14.7 (0.5)	14.6 (0.7)	14.7 (0.8)	15.0 (1.2)	14.9 (1.2)
Primus1	5.0 (0.2)	10.7 (2.1)	12.3 (1.6)	13.4 (2.2)	14.9 (2.4)	15.9 (2.0)	16.9 (1.4)	17.4 (0.8)	17.7 (0.4)	17.6 (0.4)	17.8 (0.5)
Primus4	5.1 (0.7)	5.6 (1.0)	5.7 (1.2)	5.7 (1.2)	6.0 (1.4)	7.2 (1.5)	7.4 (1.5)	7.3 (1.4)	7.4 (1.3)	7.6 (1.4)	7.8 (1.5)

Figure 5. Absolute humidities (AHs) of the inspired gas at 0, 5, 10, 15, 30, 45, 60, 75, 90, 105, and 120 minutes. (A) AH of Excel, (B) AH of Avance, (C) AH of Cato, and (D) AH of Primus. The groups were divided according to the anesthesia workstations used (Ohmeda, Excel [Ohmeda Corporation, Chester, NJ]; Avance [GE Healthcare, Helsinki, Finland]; Dräger, Cato [Dräger, Lübeck, Germany]; and Primus [Dräger, Lübeck, Germany]) and subdivided according to the fresh gas flow (0.5, 1, and 4 L/min). The data are expressed as means.

nose maintain the heat and moisture of the air from the lower airways. However, in patients with tracheal intubation, tracheostomy, or those undergoing mechanical ventilation, this protective maintenance of the heat and moisture does not occur. In this situation, ventilation with dry and cold compressed gases leads to a shift in the isothermic saturation boundary from the carina to the lower respiratory tract, which is vulnerable to dehydration, unless appropriate means of humidification and heating are used.[16,17] The cold and dry medical gas, by downward shifting of the isothermic saturation boundary, can cause problems or complications in the respiratory tract, such as epithelial damage,[18] alteration and dysfunction of the mucociliary system,[17] leading to decreased gas exchange, postoperative atelectasis,[19] and increased airway response to histamine.[16]

During general anesthesia, maintaining the optimal temperature and humidification are very important issues to the anesthesiologist. With dry and cold inspired gases, epithelial damage[18] is likely to occur and the mucociliary system[17] may be altered; dysfunction of the mucociliary system leads to decreased gas exchange.[20] The airway response of the patients to histamine[16] and the extent of postoperative atelectasis[19] are also increased. Therefore, previous studies tried to control the temperature and humidification of the inspired gas during general anesthesia in many ways. Using closed-circuit anesthesia system with a CO_2 absorbent such as soda lime is 1 way to provide warm and humid gas to patients than a high-flow system.[21]

Thus, low-flow anesthesia may be the one of the methods providing physiologic warm and wet gas during general anesthesia.[22] According to a previous study,[23] low-flow anesthesia resulted in a greater preservation of the body heat than high-flow anesthesia (28.4°C ± 1.5°C vs 26.1°C ± 0.6°C after 120 min of anesthesia with an FGF of 1.0 or 6.0 L/min); moreover, low-flow anesthesia provided 2 times more humidification (26.6 ± 2.3 vs 13.0 ± 2.6 mg H_2O/L after 120 min of anesthesia with an FGF of 1.0 or 6.0 L/min FGFs) than high-flow anesthesia. Our results revealed that the moisture-providing effect of low-FGF anesthesia was effective in all the anesthesia machines, but insufficient.

In our study, the provision of heat and moisture was better in the anesthetic workstations of Primus and Cato. These differences might be due to the hot plate within the Dräger Primus anesthesia workstations, which were designed to avoid water condensation–induced trouble or malfunction. The built-in

Table 3

Comparison of the absolute humidities of the inspired gas with time and ventilator with 3 different fresh gas flow rates (0.5, 1, and 4 L/min).

Source	Sum of squares	df	Mean square	*F*	*P*	Noncent. parameter	Observed power*
Fresh gas flow, 0.5 L/min							
Between subjects							
Ventilator	1867.49	2	933.75	196.31	<.001	392.62	1.00
Error	114.16	24	4.76				
Within subjects							
Time	1850.82	1.57	1175.63	259.82	<.001	409.03	1.00
Time × ventilator	37.25	3.15	11.83	2.62	.06	8.23	0.61
Error (time)	170.97	37.78	4.53				
Fresh gas flow, 1 L/min							
Between subjects							
Ventilator	716.44	3	238.81	18.36	<.001	55.07	1.00
Error	416.28	32	13.01				
Within subjects							
Time	4032.31	2.53	1596.09	440.37	<.001	1112.52	1.00
Time × ventilator	120.57	7.58	15.91	4.39	<.001	33.27	0.99
Error (time)	293.02	80.84	3.62				
Fresh gas flow, 4 L/min							
Between subjects							
Ventilator	2385.78	3	795.26	37.31	<.001	111.92	1.00
Error	682.14	32	21.32				
Within subjects							
Time	124.76	1.51	82.92	30.56	<.001	45.98	1.00
Time × ventilator	64.80	4.51	14.36	5.29	<.001	23.88	0.97
Error (time)	130.64	48.15	2.71				

* Computed using alpha = 0.05.

hotplate performed the role of heating exhaled gases in the breathing circuit.[24,25] The exhaled gases were provided with heat and humidity while they moved through the hotplate and crossed the soda lime canister, even though they mixed with the cold and dry FGF. The Dräger Cato anesthesia machine has a unique mechanism of a built-in hotplate and repeated pathway of the CO_2 absorbent that adds more heat and moisture during each breath. Therefore, our result showed that the inspired gas temperature and absolute humidity of Cato0.5 were higher than those of Primus0.5 ($P < .05$).

However, our results were lower than the results of previous similar studies. According to Wada et al,[9] the temperature of the inspired gas in the Dräger Cato machine with an FGF of 0.5 L/min was 32.8°C ± 2.6°C and the absolute humidity was 34.8 ± 3.2 mg H_2O/L after 120 minutes, respectively. Other reports have also suggested that the temperature and absolute humidity values of the inhaled gas in the Primus anesthesia workstation were 25°C ± 1°C and 20.5 ± 3.6 mg H_2O/L, respectively. In our study, the inspiratory temperatures of the Cato and Primus workstations with an FGF of 0.5 L/min were 26.2°C ± 0.2°C and 20.0°C ± 1.3°C, respectively. Moreover, the absolute humidities were 19.6 ± 0.5 and 14.9 ± 1.2 mg H_2O/L, respectively, after 120 minutes. These results seem to be caused by the lower baseline values due to the long preparation time (10 vs 20 min). Moreover, we checked the temperature and absolute humidity of the inspiratory limb. Generally, previous reports checked the temperature and absolute humidity between the endotracheal tube and the Y-piece adaptor.[9,24,26,27] Subsequently, those results had a possibility of overestimating the heat- and moisture-providing effect.

This study had limitations regarding the calculation of the sample size. We calculated the sample size considering the temperature alone; however, if we had analyzed the sample size considering the time, the ventilator type, and the FGF, we could have obtained a more appropriate sample size.

In conclusion, the provision of heat and humidity under low-flow anesthesia was different for different anesthesia machines. However, even in the most efficient machine, these came short of the existing recommendations. It appears that an additional device that has better heat- and moisture-providing effects is needed for patients undergoing procedures under general anesthesia.

References

[1] Shelly MP, Lloyd GM, Park GR. A review of the mechanisms and methods of humidification of inspired gases. Intensive Care Med 1988;14:1–9.

[2] AARC clinical practice guideline. Humidification during mechanical ventilation. American Association for Respiratory Care. Respir Care 1992;37:887–90.

[3] Bickler PE, Sessler DI. Efficiency of airway heat and moisture exchangers in anesthetized humans. Anesth Analg 1990;71:415–8.

[4] Bissonnette B, Sessler DI. Passive or active inspired gas humidification increases thermal steady-state temperatures in anesthetized infants. Anesth Analg 1989;69:783–7.

[5] Siempos II, Vardakas KZ, Kopterides P, et al. Impact of passive humidification on clinical outcomes of mechanically ventilated patients: a meta-analysis of randomized controlled trials. Crit Care Med 2007;35:2843–51.

[6] Rathgeber J. Devices used to humidify respired gases. Respir Care Clin N Am 2006;12:165–82.

[7] Bengtson JP, Sonander H, Stenqvist O. Preservation of humidity and heat of respiratory gases during anaesthesia—a laboratory investigation. Acta Anaesthesiol Scand 1987;31:127–31.

[8] Foregger R. The regeneration of soda lime following absorption of carbon dioxide. Anesthesiology 1948;9:15–20.

[9] Wada H, Higuchi H, Arimura S. Temperature and humidity of the Dräger Cato anesthesia machine circuit. J Anesth 2003;17:166–70.

[10] De Castro J, Bolfi F, De Carvalho LR, et al. The temperature and humidity in a low-flow anesthesia workstation with and without a heat and moisture exchanger. Anesth Analg 2011;113:534–8.

[11] Aldrete JA, Cubillos P, Sherrill D. Humidity and temperature changes during low flow and closed system anaesthesia. Acta Anaesthesiol Scand 1981;25:312–4.

[12] Dery R, Pelletier J, Jacques A, et al. Humidity in anaesthesiology. 3. Heat and moisture patterns in the respiratory tract during anaesthesia with the semi-closed system. Can Anaesth Soc J 1967;14:287–98.
[13] Ingelstedt S. Studies on the conditioning of air in the respiratory tract. Acta Otolaryngol Suppl 1956;131:1–80.
[14] Dery R. The evolution of heat and moisture in the respiratory tract during anaesthesia with a non-rebreathing system. Can Anaesth Soc J 1973;20:296–309.
[15] Williams R, Rankin N, Smith T, et al. Relationship between the humidity and temperature of inspired gas and the function of the airway mucosa. Crit Care Med 1996;24:1920–9.
[16] Van Oostdam JC, Walker DC, Knudson K, et al. Effect of breathing dry air on structure and function of airways. J Appl Physiol 1986;61:312–7.
[17] Barra Bisinotto FM, Braz JR, Martins RH, et al. Tracheobronchial consequences of the use of heat and moisture exchangers in dogs. Can J Anaesth 1999;46:897–903.
[18] Barbet JP, Chauveau M, Labbe S, et al. Breathing dry air causes acute epithelial damage and inflammation of the guinea pig trachea. J Appl Physiol 1988;64:1851–7.
[19] Chalon J, Patel C, Ali M, et al. Humidity and the anesthetized patient. Anesthesiology 1979;50:195–8.
[20] Fonkalsrud EW, Sanchez M, Higashijima I, et al. A comparative study of the effects of dry vs. humidified ventilation on canine lungs. Surgery 1975;78:373–80.
[21] Kleemann PP. Humidity of anaesthetic gases with respect to low flow anaesthesia. Anaesth Intensive Care 1994;22:396–408.
[22] Baxter AD. Low and minimal flow inhalational anaesthesia. Can J Anaesth 1997;44:643–52. quiz 652–643.
[23] Johansson A, Lundberg D, Luttropp HH. The effect of heat and moisture exchanger on humidity and body temperature in a low-flow anaesthesia system. Acta Anaesthesiol Scand 2003;47:564–8.
[24] Gorayb SB, Braz JR, Martins RH, et al. Inhaled gases humidification and heating during artificial ventilation with low flow and minimal fresh gases flow. Rev Bras Anesthesiol 2004;54:20–36.
[25] Primus® Anaesthetic Workstation: Instructions for Use. 4th ed. Dräger Medical, Lübeck, Germany:2002.
[26] Inui D, Oto J, Nishimura M. Effect of heat and moisture exchanger (HME) positioning on inspired gas humidification. BMC Pulm Med 2006;6:19.
[27] Lu CC, Ho ST, Liaw WJ, et al. The effect of heat-moisture exchanger and closed-circuit technique on airway climate during desflurane anesthesia. J Anesth 2008;22:7–12.