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The effect of heat-moisture exchanger and closed-circuit technique on airway climate during desflurane anesthesia

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Abstract
Purpose. We assessed whether closed-circuit anesthesia (CCA) could provide a more favorable airway climate than semiclosed anesthesia (SCA), and we also determined the beneficial effect of heat moisture exchangers (HMEs) on the preservation of airway climate during desflurane anesthesia.
Methods. Forty patients scheduled for colorectal surgery (n = 10 for each group) were randomized to receive a fresh gas flow of 250 or 3000 ml·min^{-1} with or without HMEs. Anesthesia was maintained by adjusting the inspired concentration of 6% desflurane. Absolute moisture and temperature of inspired gases were measured as the baseline value first at 5 min after tracheal intubation, and then at 10, 20, 45, 60, 90, and 120 min after the induction of anesthesia.
Results. At 120 min, the inspiratory humidity and temperature were higher in CCA than in SCA. The HME led to major improvements of the humidity (from 22.1 to 35.7 mg H_2O·l^{-1}) and temperature (from 23.6°C to 31.5°C) of anesthetic gases in the CCA group.
Conclusion. CCA was much more advantageous than SCA for maintaing the patient's airway climate during the 2-h study. The beneficial effect of HME on the airway climate should be emphasized, especially in patients undergoing general anesthesia.

Key words Closed-circuit anesthesia · Semi-closed anesthesia · Airway humidity and temperature · Heat moisture exchangers (HMEs)

Introduction

Inadequate humidification of inspired gases occurs most obviously when a patient is ventilated with dry, compressed gases without additional humidification via an endotracheal tube [1]. A previous study indicated that lower fresh-gas flow (1000 ml·min^{-1}) provided better preservation of airway humidity than higher fresh-gas flow (6000 ml min^{-1}) in intubated patients [2]. To the best of our knowledge, the higher gas flow leads to considerable loss of water and heat from the respiratory tract as a result of vaporization of water [3–5]. Conversely, the lower gas flow leads to less loss of water and heat. According to Bengtson et al. [6], the use of a circle system with a fresh-gas flow of 500 ml·min^{-1} resulted in higher inspiratory gas temperature and humidity than a nonrebreathing system.

In the history of clinical anesthesia, closed-circuit anesthesia (CCA) has been practiced in the clinical arena for decades [7–10]. Compared to conventional higher fresh-gas flow anesthesia, the use of a closed-circuit or minimal low flow (flow rate, ≦500 ml·min^{-1}) technique has become increasingly popular in anesthesia practice because of several advantages, such as lower consumption of inhalational anesthetics, better hemodynamic stability, favorable skin blood flow improving postoperative recovery, and less environmental contamination with inhalational anesthetics [7–9, 11–13]. In considering the integrity of mucociliary function, recent studies have begun to elucidate the potential benefit of minimal low-flow anesthesia on a patient's airway climate. However little work has been done to evaluate the efficacy of CCA in preventing loss of airway temperature and moisture during general anesthesia [14,15]. The popular use of heat and moisture exchangers (HMEs) has been proven to improve airway climate. However, it is still controversial whether an HME in combination with CCA can possibly demonstrate added or synergistic effects on the preservation of airway heat and moisture during desflurane anesthesia.

The above consideration prompted us to investigate the different levels of airway humidity and temperature in patients who received either CCA or semiclosed anesthesia (SCA) for a 2-h period of study. We also evaluated the effectiveness of heat and moisture exchangers (HMEs) in improving airway temperature

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and humidity of respiratory gas in the presence of CCA or SCA during the first 2 h of CCA or SCA.

Patients, materials, and methods

The study was approved by the institutional review board, and written informed consent was also obtained from each patient. The study population consisted of 40 adult patients, American Society of Anesthesiologists (ASA) physical status 1 and 2, selectively scheduled for elective colorectal surgery with an anticipated anesthesia time of 2 h or longer. Patients with signs and symptoms of pulmonary or cardiovascular disease were excluded from the study. In the practice of SCA, a range of 2000 to 3000 ml·min^{-1} fresh-gas flow has been applied popularly in clinical anesthesia. Thus, we chose a 3000-ml fresh-gas flow for the SCA group. After induction, 6% desflurane in high O_2 flow (3000 ml·min^{-1}) was given for 10 min to all patients (both groups) initially to wash desflurane in the functional residual capacity of both lungs and the breathing circuit. For the CCA group, O_2 flow was reduced to 250 ml·min^{-1} after 10 min of high-flow wash-in period, while the vaporizer setting of desflurane was set at 10% for the maintenance of anesthesia [10]. Patients were randomly assigned to receive fresh-gas flows of either 250 ml·min^{-1} (CCA) or 3000 ml·min^{-1} (SCA). Twenty patients were allocated to SCA either with HME (n = 10) or without HME (n = 10), and the other 20 were allocated to CCA (fresh-gas flow about 250 ml·min^{-1}) either with HME (n = 10) or without HME (n = 10).

All patients were premedicated with midazolam 2 mg intravenously 10 min prior to their arrival at the operating room. Anesthesia was induced by the administration of 100% oxygen for 3 min, followed by 2 μg·kg^{-1} of fentanyl and 3–4 mg·kg^{-1} of thiopental. Then intubation was facilitated by 1.0–1.25 mg·kg^{-1} of succinylcholine with pancuronium priming (0.015 mg·kg^{-1}), and a maintenance dose, 0.045 mg·kg^{-1} pancuronium, was given in the course of 2-h desflurane anesthesia. Ventilation of the lungs was manually assisted with 100% oxygen via a breathing circuit until tracheal intubation was performed. A Datex-Ohmeda anesthetic machine (AS/4; Datex, Helsinki, Finland), used with soda lime as a CO_2 absorber in the anesthesia system, was connected. Sampled gases (approximately 210 ml·min^{-1}) were redirected into the breathing circuit.

After tracheal intubation, the lung was mechanically ventilated and the fresh-gas flow (100% oxygen) was supplied to the breathing system at 3000 ml·min^{-1} under 6% desflurane during the first 10 min of desflurane anesthesia for each group. Anesthetic gas was delivered using a desflurane vaporizer (Datex-Ohmeda, Helsinki, Finland), which was set up either at approximately 10% of desflurane in CCA or 6% of desflurane in SCA for the maintenance of anesthesia after 10 min of tracheal intubation. A humidity and temperature sensor system (Gibeck Respiration, Upplands Vaesby, Sweden) was normally placed between the tracheal tube and the Y-piece of the breathing system. Whenever HME (Gibeck Humid-Vent 2S; Gibeck; Upplands Vaesby, Sweden) is applied, the tracheal tube and the system need to be connected. The hemodynamic variables and inspiratory airway humidity and temperature were monitored and recorded at scheduled points of 5, 10, 20, 30, 45, 60, 90, and 120 min after tracheal intubation. The humidity sensor system had a sampling rate of 21 times per second and a sampling time of 17 s. Data were measured every 5–20 min during the anesthesia. The stated system accuracy was ± 2% relative humidity and ±1%°C. The response times were 1.4 s for a 90% relative humidity response and less than 150 ms for a 90% temperature response.

During anesthesia, routine monitoring included electrocardiogram, heart rate, and noninvasive mean arterial blood pressure (MABP), and pulse oximetry with a Datex AS/3 anesthesia monitor. The inspired oxygen concentration, end-tidal (ET) CO_2, and inspiratory and expiratory concentrations of desflurane were monitored at 1-min intervals during the first 10 min and thereafter at 5-min intervals throughout the study. Gases were sampled at the Y-piece and analyzed gas was returned to a port fitted into the CO_2 absorber. Prior to anesthetic administration, fresh soda lime (Absorber; Anmedic, Vallentuna, Sweden; 15% water) was used. The lungs were mechanically ventilated to maintain $ETCO_2$ between 35 and 42 mm Hg. The ventilatory rate was 10 min^{-1}, and ratio of time in each respiratory cycle (inspiratory to expiratory) was 1:2. Additional intravenous fentanyl and ephedrine were indicated if the blood pressure and heart rate fluctuated by more than 20% of baseline values at 5 min after tracheal intubation. A nasopharyngeal thermistor was used to measure body temperature, which was actively maintained at 35.5°C–37.5°C by a warmer during the study.

Data values were expressed as means (SEM). To determine intergroup differences, one way analysis of variance (ANOVA) was used. The Tukey test was used for post-hoc comparisons. Nonparametric values were compared using the χ^2 test. P values of less than 0.05 were considered statistically significant.

Results

The demographic profiles of the patients in the four groups were similar (Table 1). The baselines values for temperature and the relative humidity were also comparable between the groups. The profiles of inspiratory humidity and temperature for the four groups (CCA,

Table 1. Demographic data

Groups	CCA (n = 10)	SCA (n = 10)	CCA+HME (n = 10)	SCA+HME (n = 10)
Age (years)	47 ± 6	31 ± 6	40 ± 7	34 ± 7
Sex (F/M)	1/9	1/9	2/8	3/7
Weight (kg)	65 ± 3	62 ± 6	65 ± 4	63 ± 3
Height (cm)	167 ± 4	171 ± 5	168 ± 5	166 ± 3

Values are means ± SEM
CCA, Closed-circuit anesthesia; SCA, semi-closed anesthesia; CCA+HME, closed-circuit anesthesia + humidity moisture exchanger; SCA+HME, semi-closed anesthesia + humidity moisture exchanger

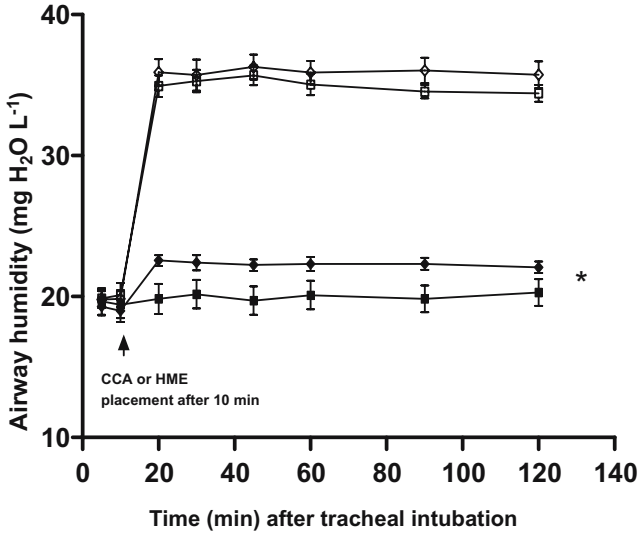

Fig. 1. Depiction of the profiles of absolute inspiratory humidity (mg $H_2O{\cdot}l^{-1}$) of the airway in CCA (*closed diamonds*), SCA (*closed squares*), CCA+HME (*open diamonds*), and SCA+HME (*open squares*) patients during the first 120 min of the study. The absolute inspiratory humidity in CCA was significantly higher than that in SCA ($P < 0.05$). There were no differences between the CCA+HME and SCA+HME groups. *CCA*, Closed-circuit anesthesia; *SCA*, semi-closed anesthesia; *CCA+HME*, closed-circuit anesthesia + humidity moisture exchanger; *SCA+HME*, semi-closed anesthesia + humidity moisture exchanger

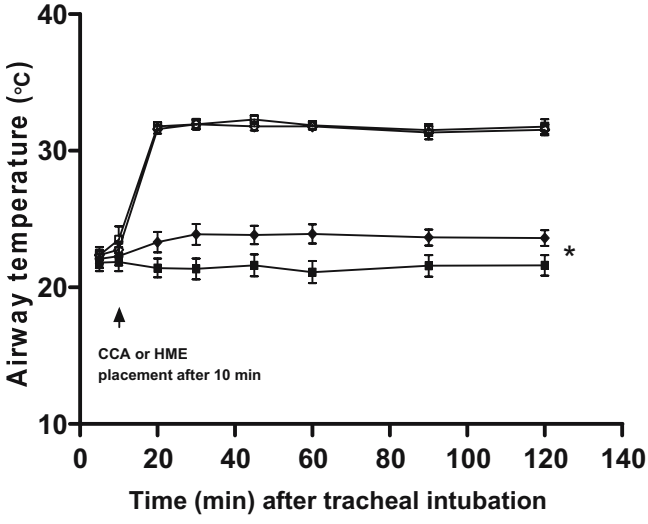

Fig. 2. Depiction of the profiles of temperature (°C) of the airway in CCA (*closed diamonds*), SCA (*closed squares*), CCA+HME (*open diamonds*), and SCA+HME (*open squares*) patients during the first 120 min of the study. The absolute inspiratory temperature in CCA was significantly higher than that in SCA ($P < 0.05$). There were no differences between the CCA+HME and SAC+HME groups. *CCA*, Closed-circuit anesthesia; *SCA*, semi-closed anesthesia; *CCA+HME*, closed-circuit anesthesia + humidity moisture exchanger; *SCA+HME*, semi-closed anesthesia + humidity moisture exchanger

SCA, CCA+HME, and SCA+HME) during the 120-min study are depicted in Figs. 1 and 2. During the study period of 20 to 120 min, the absolute inspiratory humidity in the CCA was significantly higher than that in SCA ($P < 0.05$) and the absolute inspiratory temperature in CCA was significantly higher than that in CCA ($P < 0.05$). The fluctuations of blood pressure and heart rate were maintained at less than 20% of baseline values (5 min after tracheal intubation) for each group, and there were no significant differences in $ETCO_2$ among the four groups (Table 2).

The inspiratory humidity was significantly higher in the CCA group than that in the SCA group at 20 min (22.6 ± 0.8 vs 19.2 ± 0.7 mg $H_2O{\cdot}l^{-1}$) and at 120 min (22.1 ± 0.6 vs 19.3 ± 0.8 mg $H_2O{\cdot}l^{-1}$). The inspiratory humidity in the CCA+HME group was much higher than that in the CCA group at 20 min (35.7 ± 0.6 vs 22.6 ± 0.8 mg $H_2O{\cdot}l^{-1}$) and at 120 min (35.7 ± 0.6 vs 22.1 ± 0.6 mg $H_2O{\cdot}l^{-1}$). The inspiratory humidity in the SCA+HME group was also much higher than that in the SCA group (34.9 ± 0.8 vs 19.2 ± 1.1 mg $H_2O{\cdot}l^{-1}$) at 20 min and (34.2 ± 0.5 vs 19.3 ± 0.8 mg $H_2O{\cdot}l^{-1}$) at 120 min of the study, but there were no significant differences noted between the CCA+HME and SCA+HME groups at 20 and 120 min.

Likewise, the inspiratory temperature in the CCA group was higher than that in the SCA group (23.3 ± 0.8°C vs 21.4 ± 0.7°C) at 20 min, and (23.6 ± 0.6°C vs 21.6 ± 0.8°C) at 120 min. The inspiratory temperature in the CCA+HME group was much higher than that in the CCA group (31.5 ± 0.3°C vs 23.3 ± 0.2°C) at 20 min and

Table 2. Cardiovascular and ventilatory variables in four study groups of patients during 2-h study

Time (min)	CCA ($n = 10$)	SCA ($n = 10$)	CCA+HME ($n = 10$)	SCA+HME ($n = 10$)
MABP				
5	86.7 (4.0)	92.4 (3.9)	76.9 (2.5)	90.5 (4.9)
10	83.3 (4.1)	85.9 (3.6)	77.2 (2.5)	83.4 (4.6)
20	80.7 (3.8)	85.7 (3.2)	80.3 (3.1)	89.0 (4.3)
30	87.4 (2.7)	88.1 (3.5)	81.6 (5.1)	91.0 (5.2)
60	81.7 (4.9)	89.4 (5.2)	81.2 (4.9)	84.3 (7.0)
120	86.5 (2.2)	83.8 (2.7)	74.5 (5.6)	83.1 (5.0)
HR				
5	73.3 (4.5)	83.0 (3.5)	79.3 (5.1)	95.2 (5.1)
10	73.1 (4.1)	82.4 (4.0)	75.8 (5.2)	90.0 (6.9)
20	73.3 (4.5)	80.3 (4.5)	76.3 (4.2)	85.7 (4.5)
30	75.7 (4.5)	80.3 (4.9)	76.0 (4.6)	87.6 (3.7)
60	75.3 (4.7)	82.6 (4.9)	81.5 (5.0)	84.7 (3.1)
120	77.5 (4.3)	81.2 (6.7)	83.4 (4.6)	87.1 (3.9)
$ETCO_2$				
5	37.1 (1.1)	38.1 (0.8)	37.3 (1.5)	35.7 (1.7)
10	37.0 (1.1)	36.8 (0.9)	38.0 (1.1)	35.1 (1.6)
20	39.1 (1.2)	35.9 (0.9)	40.3 (1.1)	36.7 (1.4)
30	38.6 (0.6)	38.6 (1.3)	41.8 (1.3)	37.6 (1.6)
60	38.6 (0.4)	38.3 (0.8)	41.1 (0.7)	37.1 (1.3)
120	39.9 (0.5)	37.8 (0.9)	40.8 (0.4)	38.4 (1.3)

Values are means (SEM)
CCA, Closed-circuit anesthesia; SCA, semi-closed anesthesia; CCA+HME, closed-circuit anesthesia + humidity moisture exchanger; SCA+HME, semi-closed anesthesia + humidity moisture exchanger; MABP, mean arterial blood pressure; HR, heart rate; $ETCO_2$, end-tidal CO_2

(31.5 ± 0.4°C vs 23.6 ± 0.6°C) at 120 min. The inspiratory temperature in the SCA+HME group was much higher than that in the SCA group (31.8 ± 0.3°C vs 21.4 ± 0.7°C) at 20 min and (31.8 ± 0.6°C vs 21.6 ± 0.8°C) at 120 min. However, there were no significant differences in inspiratory temperature between the CCA with HME and the SCA with HME groups.

Discussion

There were two main findings in this study: (1) Closed-circuit anesthesia (CCA) significantly preserved airway humidity and temperature to a smaller extent than semi-closed anesthesia (SCA) at the first 2 h of anesthesia. (2) Heat-moisture exchangers (HMEs) effectively increased airway temperature and moisture to a greater extent for patients undergoing either SCA or CCA, but no added or synergistic effect was noted in the CCA with HME group.

When a patient is intubated during general anesthesia, the airway is particularly exposed. Because of this, the normal humidity and heat-conserving mechanisms in the nose and upper airway are bypassed. Previous studies demonstrated that prolonged exposure of the tracheobronchial tree to cold and dry respiratory gases compromised mucociliary function [5, 16, 17]. In other words, the drier and colder respiratory gas would lead to more serious respiratory consequences, including increased viscosity of secretions atelectasis, and reduced endotracheal-tube patency [18]. Therefore, it is crucial to condition the inhaled gas and to saturate it with water vapor under general anesthesia via an endotracheal tube, especially for an anesthetized patient with compromised pulmonary function.

In considering the integrity of mucociliary function, it is understood, theoretically, that the lowest fresh-gas flow might cause the least loss of moisture and temperature of respiratory gas during anesthesia, thus protecting the mucosa from drying (consequently preserving ciliary activity and lung mechanics). Indeed, our study revealed that CCA significantly improved airway climate, which is advantageous for normal respiratory epithelia ciliary function during anesthesia. According to Kleemann [14], in their an experimental study in swine with minimal fresh-gas flow rates, there was significantly improved climatization of anesthetic gases. They found the minimal low-flow technique (500 ml·min^{-1}) facilitated the conditioning of respiratory gas and led to major improvement of heat (28°C to 32°C) and moisture (20 to 27 mg $H_2O \cdot l^{-1}$) in anesthetic gas in anesthesia systems after 10 h of anesthesia [14]. Thus, we speculated that airway humidity and temperature would have been kept at persistently higher levels in the CCA group than in the SCA group if the study had not finished at 2 h of anesthesia.

Various authors have suggested that the acceptable acclimatization of anesthetic gases during general anes-

thesia should provide adequate heat and moisture to inspired gases. Kleemann [14,19] suggested that a low fresh-gas flow, as low as 600 ml·min^{-1}, was able to keep the airway moisture and the temperature of respiratory gas above the acceptable levels, preserving the normal morphology of respiratory epithelial cilia and mucus after 10-h prolonged general anesthesia. Our results demonstrated that CCA which was designed to reduce the fresh gas flow to 250 ml·min^{-1} (in accordance with the popular practice of the CCA technique), to optimize the efficacy of the lowest fresh gas flow to improve the airway climate, provided improvement of inspiratory moisture and temperature compared with that in the SCA group during the first 2 h of desflurane anesthesia. We found that patients undergoing CCA were able to attain absolute inspiratory humidity of approximately 23 mg H_2O·l^{-1} after 20 min of the study, but this level was not attained for those patients undergoing SCA. These findings lead to the conclusion that the CCA technique is capable of providing better moisture-conserving properties for respiratory gas than SCA during general anesthesia.

In order to optimize the airway climate for those patients with compromised respiratory function undergoing prolonged surgery, the application of an HME is an effective way to improve the airway climate in a patient who is intubated during general anesthesia. When an HME is not available, the practice of CCA should benefit the patient's airway climate, despite the small extent of the improvement in airway climate compared with that of SCA. CCA could become a favorable anesthetic practice for patients receiving prolonged anesthesia. Notably, from environmental pollution and economic points of view, the application of CCA should be advocated rather than that of SCA.

The efficacy of the Humid-Vent 2S filter HME (Gibeck; Upplands Vaesby, Sweden) was investigated in an experiment done by Bengtson et al. [6]. They showed that this HME provided satisfactory humidity and temperature at different flow rates, in line with other results [20]. We also found that the addition of an HME greatly enhanced the airway humidity and temperature in patients who received either SCA or CCA. On average, our results demonstrated that an HME greatly improved the respiratory gas humidity Δ 14–16 mg H_2O·l^{-1}), and the inspiratory airway temperature (Δ 8°C–10°C) in all the patients, whether they received CCA or SCA. Consistent with the reports of Martin and colleagues [21,22], our results showed that the connection of an HME to a breathing circuit could guarantee the provision of excellent airway temperature (32°C) and humidity (34 mg H_2O·l^{-1}) when a patient received high-flow gas. The placement of an HME improved the airway climate to a great degree whether the patient received either CCA or SCA.

In conclusion, the CCA preserved a better airway climate and possibly provided better respiratory epithelial and mucosal function than the SCA in anesthetized patients. We recommend that the CCA technique should be encouraged when there are no HMEs available. Our findings also confirmed that the HME showed great capacity in preserving airway temperature and moisture, which masked the clinically significantly small improvement of airway climate provided by the CCA technique.

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