Novel Radiator for Carbon Dioxide Absorbents in Low-Flow Anesthesia

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Abstract. During long-term low-flow sevoflurane anesthesia, dew formation and the generation of compound A are increased in the anesthesia circuit because of elevated soda lime temperature. The object of this study was to develop a novel radiator for carbon dioxide absorbents used for long durations of low-flow sevoflurane anesthesia. Eleven female swine were divided into two groups comprising a “radiator” group (n = 5) that used a novel radiator for carbon dioxide absorbents and a “control” group (n = 6) that used a conventional canister. Anesthesia was maintained with N₂O, O₂, and sevoflurane, and low-flow anesthesia was performed with fresh gas flow at 0.6 L/min for 12 hr. In the “control” group, the soda lime temperature reached more than 40°C and soda lime dried up with severe dew formation in the inspiratory valve. In the “radiator” group, the temperature of soda lime stayed at 30°C, and the water content of soda lime was retained with no dew formation in the inspiratory valve. In addition, compound A concentration was reduced. In conclusion, radiation of soda lime reduced the amounts of condensation formed and the concentration of compound A in the anesthetic circuit, and allowed long term low-flow anesthesia without equipment malfunction. (received 28 March 2003; accepted 15 May 2003)

Keywords: carbon dioxide absorbents, low flow anesthesia, water evaporation.

Introduction

Low-flow anesthesia can reduce the costs of anesthetic gases, workplace contamination by anesthetic gases, and atmospheric pollution, since anesthetic gases are efficiently recycled [1-4]. In addition, low-flow anesthesia can maintain the stability of inspired concentration, and conserve respiratory moisture and heat [5-7].

However, the temperature inside canisters can reach up to 40-50°C during low-flow sevoflurane anesthesia, since the amounts of carbon dioxide reacting with carbon dioxide absorbents are increased in the circuit [8]. Consequently, the generation of compound A, a degradation product of sevoflurane, is increased [8-10], and severe dew formation is caused by the great difference of temperatures within the anesthesia circuit.

To reduce compound A production during low-flow sevoflurane anesthesia, Osawa et al [11] reported a method of cooling carbon dioxide absorbents with an intercooler device interposed before the canister in the circuit. Ruzicka et al [12] designed another method for maintaining carbon dioxide absorbents at 20-26°C by directly chilling the canister in an ice bath at 2°C. Both methods reduced compound A production during low-flow sevoflurane anesthesia, but neither study examined the influences of cooling carbon dioxide absorbents on dew formation in the circuit and on water content of the absorbents.

The goal of the present study was to develop a novel radiator for carbon dioxide absorbents used in long-term low-flow sevoflurane anesthesia, in order to reduce dew formation and compound A concentration in the anesthetic circuit.

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Materials and Method

Equipment. To limit the formation of condensation in artificial respirators, it is desirable to minimize variations in temperature in the artificial respirator circuit (including the canister temperature).

In this study, we designed a novel radiator for carbon dioxide absorbents that efficiently radiates heat to minimize increases in temperature of the carbon dioxide absorbents (Fig. 1). The canister container was made of aluminum with high thermal conductivity. To diffuse excessive heat production in the container, 6 aluminum radiator panels were set in the canister. Each panel was placed with equal spacing. Furthermore, a thermosensor for detecting soda lime temperature was placed in the middle layer inside the container. A thermostat for maintaining the temperature of the carbon dioxide absorbent at an arbitrary value, a heat sink, a thermo-module (Peruche), and a fan for temperature control were all components of the radiator for carbon dioxide absorbents. The radiator for carbon dioxide absorbents was installed in a closed anesthesia circuit (Fabius, Dräger, Lübeck, Germany).

Design of study. This study was initiated after approval by the Ethical Committee of Tokyo Medical University. Female swine weighing 24 to 34 kg were used. The animals were divided into 2 groups, comprising a radiator group (n = 5; body wt 28.7 ± 4.1 kg) that used the radiator for carbon dioxide absorbents and a non-radiator group (control group: n = 6; body wt 27.4 ± 1.7 kg) that used a conventional canister. In the radiator group, soda lime temperature was controlled at 30°C throughout the study. Fresh soda lime (1.5 L, Drägersorb™ 800 plus, Dräger, Lübeck, Germany) was used in both groups. Anesthesia was induced with 20 mg/kg of ketamine and 0.01 mg/kg of atropine im, and 5 mg/kg of thiamylal injected.

Fig. 1. Diagram of the carbon dioxide absorbent radiator: 1) canister container made of aluminum; 2) 6 radiating panels made of aluminum; 3) thermo-sensor; 4) thermo-module (Peruche); 5) heat sink; 6) fan, and 7) thermostat.
through a catheter placed in an ear vein. After oral intubation, 0.2 mg/kg of vecuronium was administered iv, and anesthesia was then maintained with nitrous oxide, oxygen, and sevoflurane.

For the first 5 min, high-flow anesthesia was performed with 6 L/min of fresh gas flow (FGF), and thereafter switched to low-flow anesthesia with 0.6 L/min of FGF. A Datex capnomac monitor (Datex Ltd., Helsinki, Finland) was connected to the inspiratory limb of the circle system to detect the concentrations of sevoflurane, carbon dioxide, oxygen, and nitrous oxide in the circuit. The concentration of inspiratory oxygen was adjusted to 50% by regulation of nitrous oxide and oxygen using the gas monitor, while inspiratory sevoflurane was adjusted to 3%. Ventilation tidal volume was 15 ml/kg. Regarding respiratory frequency, expiratory carbon dioxide concentration was maintained at 30 to 35 mmHg with an expiratory gas monitor. A thermometer (Mon-a-Therm 6510, Mallinckrodt, St Louis, MO) was placed in the esophagus to measure body temperature. Low-flow anesthesia was continued for 12 hr. Measurements were performed at 0, 2, 4, 8, and 12 hr after starting the low-flow anesthesia.

**Water content of soda lime.** Approximately 20 mg of fresh soda lime was reserved before the experiment. Immediately after completion of the experiment, approximately 20 mg samples of the soda lime used were collected from the top, middle, and bottom layers of the canisters. The collected soda lime was weighed, heated for 8 hr at 105°C in an oven, and weighed again. The water content of soda lime was determined by the difference between the wet wt and dry wt.

**Dew formation.** The severity of dew formation in the expiratory and inspiratory valves was visually observed at each measurement time, and classified into four grades (0 = none, 1 = mild, 2 = moderate, 3 = severe).
The amount of compound A was measured as previously reported [10]. Briefly, a 100 ml gas sample was collected from the inspiratory limb of the circle system at each measurement time. Compound A concentration in the sample was measured by gas chromatography (GC-7AG: Shimadzu, Kyoto, Japan). The gas chromatograph was calibrated with a standard calibration gas prepared from stock solutions of compound A (Maruishi Pharmaceutical Co., Osaka, Japan).

Statistical analysis. All data are reported as mean ± SD. Statistical differences were evaluated with Mann-Whitney U-test. Statistical significance was established at the level of p <0.05.

Results

In the control group, an interrupted case occurred in which it was difficult to close the exhaust valve due to severe dew formation; these data were omitted.

Between the “control” and “radiator” groups, there were no significant differences in body temperature, concentration of inspiratory sevoflurane, concentration of expiratory carbon dioxide (33-36 mmHg), or minute volume (7.2-8.6 L/min) at any measurement time.

The amount of carbon dioxide produced by swine in this study corresponded to that of an average human anesthetic model.

Changes in the temperature of soda lime are shown in Fig. 2. In the control group, the maximum temperature of soda lime reached 40.6 ± 1.6°C within 4 hr after the start of the experiments. In contrast, in the radiator group, the temperature of soda lime reached 29.5 ± 0.5°C within 1 hr after the start of experiments and then remained at about 30°C during the experiments.

Changes in water content of the soda lime are shown in Fig. 3. The water contents in the control and radiator groups before the experiment (baseline) were 15.5 ± 0.1% and 15.4 ± 0.1%, respectively. After completion of the experiments, water contents
of soda lime at the bottom layer of the canister in the control and radiator groups were 2.5 ± 0.4% and 11.9 ± 1.5%, respectively. Total amounts of water lost from soda lime in the control and radiator groups were 69.5 ± 22.0 g and 0.7 ± 7.8 g, respectively.

Changes in dew formation in the inspiratory and expiratory valves are shown in Fig. 4. In the control group, severe dew formation was observed in the inspiratory valve, but not in the expiratory valve. In contrast, in the radiator group, mild dew formation was observed in the expiratory valve, although dew formation in the inspiratory valve was not detected.

Changes in compound A concentration in the circuit are shown in Fig. 5. Compound A concentrations reached maximal values at 1 hr after initiation of the low-flow anesthesia. These values in the control and radiator groups were 26.6 ± 2.1 and 18.1 ± 2.2 ppm, respectively. The mean value in the control group was significantly higher than in the radiator group (p <0.001). Total exposure levels of compound A for 12 hr in the control and radiator groups were 274.8 ± 11.2 ppm•hr and 193.8 ± 17.4 ppm•hr, respectively, and were significantly different between the two groups (p <0.001).

Discussion

Relationship between soda lime temperature and water content. In the control group, soda lime temperature usually reached more than 40°C. Most of the soda lime that had already been consumed in the bottom layer was dried up, whereas the water content of soda lime increased in the top layer in the control group. This occurred presumably because the canister insufficiently radiated heat and the carbon dioxide absorbent insufficiently transmitted heat, so that the dried soda lime in the bottom layer was caused by gasification, and the increased water content in the top layer was caused by dew formation due to a relative decrease in temperature.

In the radiator group, the canister container was made of aluminum, which has high heat conductivity so as to release internal heat. Six panels made of aluminum were installed inside the canister to reduce the variations in temperature inside the canister. Therefore, the maximum temperature was generally kept at 30°C, and the amount of dried soda lime was reduced. Furthermore, variations in water content of soda lime inside the canister were minimized compared with the control group.

It is presumed that the water content of soda lime was maintained by heat radiation. However, temperature variations in the circuit may result in the formation of condensation. So it appears that a much lower soda lime temperature may excessively increase the water content of soda lime, leading to a decrease in carbon dioxide absorption (increasing the channeling effect) and an increase in gas flow resistance (diminished soda lime passage) caused by severe dew formation resulting from extremely low soda lime temperature in the circuit. In fact, we have demonstrated that a large amount of water was generated in the canister when the soda lime temperature was maintained at 25°C under low-flow anesthesia. In the present study, the temperature of soda lime was maintained at 30°C, and a decrease in carbon dioxide absorption and an increase in gas flow resistance were not observed. Additionally, the running cost of using soda lime was improved in the radiator group.

Dew formation in the circuit and equipment malfunction. Long-term low-flow anesthesia may cause dew formation in the circuit leading to equipment malfunction. In the present study, severe dew formation was observed in the inspiratory valve, and caused 2 instances with abnormal noise and a discontinued case in the control group due to difficulty shutting the exhaust valve. In the radiator group, however, mild dew formation was observed in the expiratory valve while no dew formation occurred in the inspiratory valves, and consequently, equipment malfunction did not occur. The suppression of dew formation in the circuit appeared to result from improving the temperature difference in the circuit by maintaining soda lime at 30°C and inhibiting the evaporation of water produced by soda lime gasification. These results indicate that dew formation in the circuit can be prevented by minimizing the increase of soda lime temperature, and that the radiator for carbon dioxide absorbents
allows for long duration of low-flow anesthesia without equipment malfunction.

**Production of compound A.** Previous studies showed positive correlation between compound A concentration and the temperature of soda lime \([8,11,12]\). To reduce compound A production during low-flow sevoflurane anesthesia, Ruzicka et al \([12]\) designed a method for maintaining the carbon dioxide absorbents at 20-26°C by directly chilling the canister in an ice bath at 2°C. By this method, the maximum compound A concentration was reduced to approximately 10 ppm \([12]\). In the present study, radiation of soda lime temperature at 30°C reduced the maximum compound A concentration to approximately 20 ppm, which was higher than that obtained with Ruzicka’s method. These results reflect differences in design of the studies, since the soda lime temperature in this study was higher than in Ruzicka’s study. However, in Ruzicka’s method the canister was directly chilled with a 2°C ice bath, producing temperature variations in the canister, may have also increased dew formation outside the canister, leading to decreased carbon dioxide absorption and increased gas flow resistance. Therefore, the present authors consider that Ruzicka’s method is impractical for clinical use. Novel radiators for carbon dioxide absorbents which minimize variations in soda lime temperature do not reduce the compound A concentration completely, but can reduce it significantly without increasing dew formation in the canister.

The safety of sevoflurane in low-flow anesthesia has been widely discussed because of renal toxicity observed in studies with rats \([13,14]\), although renal toxicity of compound A in humans has not been proven \([15]\). Recently, Amsorb® (Armstrong, Ltd., Coleraine, Northern Ireland), a new carbon dioxide absorbent has been developed that produces small amounts of compound A \([16,17]\). Therefore, compound A production in low-flow sevoflurane anesthesia may soon be resolved by the development of new carbon dioxide absorbents.

**Radiator for carbon dioxide absorbents.** To allow carbon dioxide absorbents to radiate heat efficiently, it is effective to use a Peltier radiator method such as in this study. Apparatuses that are not sufficiently safe (apparatuses that are prone to breakdown) are inappropriate medical instruments. Addition of the Peltier radiator method allows the temperature of carbon dioxide absorbents to be electrically controlled, but may also cause failures and increase the product costs. Hence, in view of the product price and in the interest of simplicity, the Peltier radiator method is not the only measure to take. In fact, it may be sufficient to use only the above-mentioned radiator canister without adding the Peltier radiator. Such a method also constitutes an inexpensive and simple carbon dioxide absorbent radiator. However, materials with high heat conductivity such as aluminum may be corroded by carbon dioxide absorbents, so it is desirable to coat these materials, for example, with chromium. The present study introduces an artificial respirator that can inexpensively and easily solve the common problems associated with low-flow anesthesia.

**In conclusion,** long duration low-flow sevoflurane anesthesia was performed using a novel radiator for carbon dioxide absorbents, which was devised by use of simple and inexpensive tools. Radiation of soda lime temperature reduced the amounts of condensation formed and the concentration of compound A concentration, which allowed long duration low-flow anesthesia without equipment malfunction.

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