Effects of carbon dioxide absorbent cooling and temperature gradient reduction on water condensation in the anaesthesia circuit

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Background. Large quantities of water condensation occur in the anaesthesia circuit during low-flow anaesthesia. We hypothesized that cooling of the CO2 absorbent would prevent water condensation.

Methods. To cool CO2 absorbent efficiently, we constructed a novel temperature gradient reduction (TGR) canister, which was cooled by a blower. Experiments were divided into three groups: the conventional canister group (control group, n=6), the TGR canister without cooling group (TGR group, n=6), and the TGR canister with cooling group (TGR cooling group, n=6). One kilogramme of CO2 absorbent was placed into the canister. The anaesthetic ventilator was connected to a 3 litre bag and 300 ml min⁻¹ of CO2 was introduced. About 500 ml min⁻¹ of oxygen was used as fresh gas. The anaesthetic ventilator was set at a ventilatory frequency of 12 bpm, and tidal volume was adjusted to 700 ml.

Results. The longevity of the CO2 absorbent was 437 (SD 7.8) min in the control group, 564 (13.8) min in the TGR group (P<0.001 vs control), and 501 (5.8) min in the TGR cooling group (P<0.001 vs control, TGR). Total water condensation in the anaesthesia circuit was 215 (9.4) mg min⁻¹ in the control group, 223 (9.7) mg min⁻¹ in the TGR group, and 47.7 (5.7) mg min⁻¹ in the TGR cooling group (P<0.001 vs control, TGR).

Conclusions. TGR of CO2 absorbent with cooling is a useful and simple method to reduce water condensation in the anaesthesia circuit in low-flow anaesthesia, with a little increase in the longevity of the CO2 absorbent.

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The considerably large quantity of water generated by chemical reaction of the CO2 absorbent in low-flow anaesthesia, compared with high-flow techniques, causes increased water condensation in the anaesthesia circuit. This water condensation may cause failure of the valves, failure of the gas monitor, and increased resistance of heat and moisture exchange filters. It is thought that cooling of the CO2 absorbent would reduce temperature gradients between the CO2 absorbent and the anaesthesia circuit, leading to reduced circuit water condensation. Cooling of the canister has been performed in several studies using various techniques. Those studies showed that cooling of CO2 absorbent decreased degradation products of anaesthetic volatiles such as compound A. However, the effects of CO2 absorbent cooling on CO2 absorption and water condensation in the anaesthesia circuit have not been clarified.

We constructed a novel temperature gradient reduction (TGR) canister, and reported that TGR (not cooling) of CO2 absorbent prevented excessive local increases in CO2 absorbent water content and improved its longevity. The CO2 absorbent in the TGR canister can efficiently be cooled by sending air from the outside. In the present study, using the TGR canister cooled by a blower, the
effects of CO₂ absorbent cooling on CO₂ absorption and water condensation in the anaesthesia circuit were investigated.

**Methods**

**TGR canister**

The TGR canister (Fig. 1A and B) was produced for the purpose of effective heat conduction between the CO₂ absorbents in the canister exterior and interior. Twelve aluminium plates were set into the canister vertically and radially, and the aluminium canister container was connected to these 12 aluminium plates. The aluminium container and aluminium plates were coated with electroless nickel plating to prevent corrosion by the CO₂ absorbent. Electroless nickel plating produces nickel deposits, which may contain phosphorus and boron, onto catalytic metallic or catalysed non-metallic substrates by chemical reduction. Electroless nickel plating produces very uniform, hard coatings, without an externally applied electric current, and are normally identified according to their phosphorus content. The TGR canister was designed to be mounted on an anaesthesia machine (Fabius™, Draeger, Lübeck, Germany), the same size as the conventional Fabius™ canister. Thermosensors (Sheath Thermocouple, Toho Electronics Inc., Kanagawa, Japan) were installed at seven sites (A, B1, C1, D1, B2, C2, and D2) in both the TGR canister and the conventional canister to measure the temperature at each site. A is a point at the canister outlet. B1, C1 and D1 are points 5 mm from the internal surface of the outer rim of the canister, with B1 being near the top of the CO₂ absorbent, C1 near the middle, and D1 near the bottom. B2, C2, and D2 are points 20 mm from the outer rim of the canister, corresponding in height to B1, C1, and D1, respectively. To cool the CO₂ absorbent, a blower (Abitelax™, Yoshii Electric Co., Ltd, Gunma, Japan) was set outside at a distance of 30 cm from the TGR canister. CO₂ absorbent, which has low thermal conductivity, is difficult to cool efficiently. Although not reviewed in the present study, if the conventional canister is cooled by a blower, only the area of CO₂ absorbent faced by the blower would be cooled, but that on the opposite side would not be cooled effectively. It would cause large temperature gradients of the CO₂ absorbent and low efficiency of cooling. The TGR canister reduces the temperature gradient of CO₂ absorbent and enables CO₂ absorbent to be cooled efficiently by a blower.

**Experimental protocol**

Experiments were divided into three groups according to the type of canister used: the normal conventional canister (control group, n=6), the TGR canister without cooling (TGR group, n=6), and the TGR canister with cooling (TGR cooling group, n=6). In the TGR cooling group, the canister was cooled by a blower set outside the canister. There was no cooling in either the control group or the TGR group.

One kilogramme of fresh CO₂ absorbent (Draegersorb free™, Draeger) was placed into the canister for each experiment. The anaesthetic ventilator was connected to a 3 litre bag. Oxygen was used as fresh gas at a flow rate of 500 ml min⁻¹. To simulate the oxygen consumption of a patient, sample gas was aspirated at a rate of approximately 200 ml min⁻¹ from the inspiratory limb of the circuit and delivered to a medical gas analyzer (Capnomac Ultima, Datex, Helsinki, Finland). Through a needle situated in the 3 litre bag, 300 ml min⁻¹ of CO₂ was introduced. During the experiment, the anaesthetic ventilator was set at an inspiratory:expiratory ratio of 1:2, a ventilatory frequency of 12 bpm, and tidal volume was adjusted to an expired tidal volume of 700 ml. Room temperature was maintained approximately at 20°C.

The longevity of CO₂ absorption was measured as the time taken for the inspired CO₂ tension (P_iCO₂) to increase from 0 to 5 mm Hg, and then the experiment was terminated. Water condensation at the manual (reservoir) bag, ventilator hose, breathing tube, 3 litre bag (simulated lung), and other sites in the anaesthesia circuit was measured (Fig. 2). The manual (reservoir) bag, breathing tube, and 3 litre bag (simulated lung) without water condensation before the experiments were weighed. Immediately after completion of the experiment, they were weighed again to measure the increase in water condensation. Water condensation at the ventilator hose was taken and measured whenever a bubbling sound was generated. Immediately after completion of the experiment, water condensation at other sites such as valves and any other
non-detachable components in the anaesthesia circuit was taken by absorption onto paper and weighed. Approximately 3 g of fresh CO₂ absorbent was saved before the experiment. Immediately after completion of the experiment, approximately 3 g each of CO₂ absorbent used was collected from six sites: B1, C1, D1, B2, C2, and D2. The collected CO₂ absorbent was weighed, heated for 8 h or longer at 105°C in an oven, and weighed again. The water content of CO₂ absorbent was determined by the difference between the wet and the dry weights.

Statistical analysis
All values are shown as means (SD). The data of three groups were compared by a one-way analysis of variance (ANOVA), followed by a Bonferroni multiple comparison test. A P-value of <0.05 was considered to indicate a statistically significant difference. Analyses were performed with Stat View 5.0 (SAS Institute, Cary, CA, USA).

Results

Equation (1) was maintained at approximately 30–31 mm Hg from the start of the experiments and increased to approximately 34–35 mm Hg at the end of the experiments in all groups.

The temperature of CO₂ absorbent at each site is shown in Figure 3A–C. In the control group, from the start to around 3–4 h, the area of maximum CO₂ absorbent temperature (reactive site) was D2, reaching approximately 50°C. Over time, the area of maximum temperature shifted from the bottom to the top of the canister. There were temperature gradients vertically between the local reactive site and the non-reactive site. In addition, the temperature of the CO₂ absorbent on the canister exterior was lower than that in the canister interior. In the TGR group, the temperature gradients of the CO₂ absorbent were reduced, and the maximum temperature of the CO₂ absorbent reached approximately 46°C. In the TGR cooling group, the maximum temperature reached only approximately 40°C.

The temperature of the canister outflow gas is shown in Figure 4. The temperature of the canister outflow gas in the TGR cooling group significantly decreased compared with that in the control (P<0.05) and TGR groups (P<0.05), throughout the experiments.

The longevity of the CO₂ absorbent was 437 (7.8) min in the control group, 564 (13.8) min in the TGR group (P<0.001 compared with control group), and 501 (5.8) min in the TGR cooling group (P<0.001 compared with control group, and P<0.001 compared with TGR group). The TGR group showed an approximately 30% increase in longevity of the CO₂ absorbent compared with the control. The TGR cooling group showed a decrease in CO₂ absorbent longevity compared with the TGR group, but an increase of approximately 15% compared with the control group.

Water condensation in the anaesthesia circuit is shown in Figure 5. The total water condensation in the anaesthesia circuit (divided by longevity of experiment; mg min⁻¹) was 92.8 (4.4) g [215 (9.4) mg min⁻¹] in the control group, 126 (5.2) g [223 (5.7) mg min⁻¹] in the TGR group, and 23.7 (2.7) g [47.7 (5.7) mg min⁻¹] in the TGR cooling group (P<0.001 compared with the control group, and P<0.001 compared with TGR group). The TGR cooling group showed a marked decrease in water condensation in the anaesthesia circuit compared with the control and TGR groups.

The water content of fresh CO₂ absorbent at each site is shown in Table 1. Before the experiment, the water content of fresh CO₂ absorbent was 16.1 (0.9)% in the control group, 15.7 (1.1)% in the TGR group, and 15.6 (0.5)% in the TGR cooling group. After the experiment,
The water content of CO2 absorbent at B1 increased excessively to 32.4 (0.7)% in the control group, but increased only to 20.6 (1.3)% in the TGR group (\( P, 0.001 \) compared with control group), and 17.4 (0.4)% in the TGR cooling group (\( P, 0.001 \) compared with control group). CO2 absorbent in the middle or bottom layer of the canister (C1–2, D1–2) had dried to 1.5 (0.3)–3.8 (1.1)% in the control and TGR groups, but dried only to 7.7 (0.7)–11.3 (0.7)% in the TGR cooling group (\( P, 0.001 \) compared with control group, and \( P, 0.001 \) compared with TGR group).

**Discussion**

TGR cooling markedly reduced water condensation in the anaesthesia circuit and the water content of the CO2 absorbent increased. These results indicate that reduced water condensation in the anaesthesia circuit is thought to depend on increased water condensation in the CO2 absorbent.

**Origins of supplied water**

In the present study, using a simulated anaesthesia circuit, the gas in the 3 litre bag (simulated lung) was not heated or humidified. All water supplied in the anaesthesia circuit depends on chemical reaction of the CO2 absorbent. Water supplied by chemical reaction of the CO2 absorbent causes water condensation mainly from the canister to the 3 litre bag. Gas from the 3 litre bag reaches the canister as 100% moisture at approximately room air temperature.

However, in clinical use, expiratory gas is heated and humidified by the lungs. Therefore, water supplied in the anaesthesia circuit depends not only on chemical reaction of the CO2 absorbent but also on heating and humidification by the lungs. Heated–humidified expiratory gas is cooled by room air by the time it reaches the canister. Water supplied by the lungs causes water condensation mostly at the expiratory breathing tube. The expiratory gas reached the canister under the same conditions in the present study. The conditions of chemical reaction of the
CO₂ absorbent and quantity of water condensation from the canister to the patient are thought to be the same in the present study. However, it must be noted that, in clinical use, water condensation at the expiratory breathing tube depending on heating—humidification by the lungs occurs in addition to the water condensation mainly from the canister to the 3 litre bag depending on chemical reaction of the CO₂ absorbent seen in the present study.

### Distribution of supplied water

As the CO₂ absorbent absorbs 1 mol of CO₂, 1 mol of water contained in soda lime is consumed, and 13.7 kcal and 2 mol of water are formed. Water generated by chemical reaction of the CO₂ absorbent is distributed to water condensation at the CO₂ absorbent or the anaesthesia circuit, or the remainder is exhausted. In the present study, under the same condition of low-flow anesthesia, the quantity of water generated by reaction of the CO₂ absorbent was the same and that of exhausted water was small in all groups. It is thought that if water condensation increases in the CO₂ absorbent, it adversely decreases water condensation in the anesthesia circuit.

In the control group, the CO₂ absorbent in the middle and bottom layers of the canister was dry as a result of chemical reaction. The water content of the CO₂ absorbent at B1 increased excessively because of large temperature gradients. Compared with the control group, excessive local water content increases in the CO₂ absorbent at B1 were prevented in the TGR group. Because these differences were only within a limited area, there was only a small difference in total quantity of water content at the CO₂ absorbent between the control group and the TGR group. In the TGR cooling group, compared with the control group, excessive local water content increases in the CO₂ absorbent at B1 were prevented. However, in the middle and bottom layers of the CO₂ absorbent (C1—2, D1—2) drying was impeded, whereas the CO₂ absorbent was nearly completely dry in the control and TGR groups. The total quantity of water content at the CO₂ absorbent is thought to be increased largely compared with the control and TGR groups. Decreased water condensation in the anesthesia circuit in the TGR cooling group is thought to depend on the quantity of water condensation in the CO₂ absorbent.

### Longevity of CO₂ absorbent

In the present study, the water content of the CO₂ absorbent increased excessively at B1 in the control group. In the TGR group, excessive local water content increases at B1 were prevented, and longevity of CO₂ absorbent was increased by approximately 30% compared with the control group. The longevity of CO₂ absorbent is decreased by adding water. CO₂ absorbent such as at B1 in the control group with high-water content is thought to have a slower rate of absorption, stickiness, and increased resistance. However, excessive local water content increases at B1 occurred only within a limited area. It is reasonable to say that the expired gas was by-passed without absorption of CO₂ through the low reactivity area, leading to decreased longevity of CO₂ absorbent in the control group. TGR of CO₂ absorbent might prevent local excessive water content and preserve the reactivity of the CO₂ absorbent, leading to improved longevity of the CO₂ absorbent. The TGR cooling group showed an increase of approximately 15% compared with the control group, but a decrease in longevity of CO₂ absorbent compared with the TGR group. These results indicate that cooling of the CO₂ absorbent decreases reactivity. The mechanism of decreased reactivity of CO₂ absorbent is not clear. It is believed that channelling of the expired gas along preferential paths of lesser resistance through the CO₂ absorbent decreases the efficiency and reliability of CO₂ absorption. Usually these preferential paths are along the container walls, where granules cannot fit snugly against the plane surfaces (wall effect). In the present study, changes in reactivity of CO₂ absorbent were not measured. Our study indicates that the factors of decreased longevity of CO₂ absorbent not only include the wall effect but also heterogeneity of reactivity degradation, due to heterogeneity of low temperature and excessive water content. The TGR canister without cooling is an effective method to use CO₂ absorbent economically.

### Problems due to water condensation

In the present study, there was around 100 g of water condensation in the anesthesia circuit, leading to some problems due to water condensation. The Fabius™ used in the present study is a piston pump arrangement driven by an electric motor. As long as the manual bag, serving as a gas reservoir, is sufficiently filled, ventilation continues properly. Because the ventilator hose and manual (reservoir) bag are placed after the canister, there is water condensation at the ventilator hose and manual (reservoir) bag (Fig. 2). Water condensation at the ventilator hose generated a bubbling sound, and needed to be disposed of frequently. In a few cases, the manual (reservoir) bag collapsed completely and an emergency air intake valve
opened with a marked sound during the expiratory retraction of the piston. This phenomenon occurred when the breathing tube was disconnected—connected from the breathing system (never when the ventilator hose was disconnected), and the anaesthesia circuit was suddenly cooled off. Water condensation at the reservoir bag might contribute to collapse of the manual (reservoir) bag, by gravity and surface tension.

In general, water condensation may cause failure of the valves, failure of the gas monitor, increased risk of cross-infection, and increased resistance of heat and moisture exchange filters. The TGR canister with cooling is a useful method to reduce these problems. In clinical settings, these problems are usually not too serious because most cases are performed with fresh gas flow over 2 litre min⁻¹, approximately 5–7 litre min⁻¹ minute volume. The present study was performed under the condition of 500 ml min⁻¹ of fresh gas flow, approximately 8 litre min⁻¹ minute volume. It should be noted that low-flow anaesthesia with less than 1 litre min⁻¹ of fresh gas flow may cause serious problems due to water condensation.

**Conclusions**

TGR of CO₂ absorbent with cooling is a useful and simple method to reduce water condensation in the anaesthesia circuit in low-flow anaesthesia, with a small increase in the longevity of CO₂ absorbent.

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