Effects of temperature gradient correction of carbon dioxide absorbent on carbon dioxide absorption†

G. Hirabayashi*, H. Uchino, T. Sagara, T. Kakinuma, Y. Ogihara and N. Ishii

Department of Anaesthesiology, Hachioji Medical Center Tokyo Medical University, 1163 Tatemachi, Hachioji, Tokyo 193-0998, Japan
*Corresponding author. E-mail: goh@tokyo-med.ac.jp

Background. The effects of temperature gradients in CO₂ absorbents on water content and CO₂ absorption are not clear. We constructed a novel temperature gradient correction (TGC) canister, and investigated the effects of temperature gradient correction on the water content and longevity (time to exhaustion) of CO₂ absorbent using a simulated anaesthesia circuit.

Methods. Experiments were divided into two groups according to the type of canister used: the TGC canister (n=6) or the conventional canister (n=6). One kilogram of fresh 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. Oxygen (500 ml min⁻¹) 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. Before the experiment, the water content of the fresh CO₂ absorbent in the conventional canister and TGC canister was 16.1 (0.9)% and 15.7 (1.1)%, respectively. After the experiment, the water content of CO₂ absorbent near the upper outer rim of the canister increased to 32.4 (0.7)% in the conventional canister, but increased to only 20.6 (1.3)% in the TGC canister (P<0.01). The longevity of CO₂ absorbent in the conventional canister and TGC canister was 434 (9) min and 563 (13) min (P<0.01).

Conclusions. Temperature gradient correction prevented a local excessive increase in water content and improved the longevity of CO₂ absorbent.

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Temperature gradients in CO₂ absorbents resulting from local heat production and contact with the canister container, cooled by room air, may locally increase the water content by dew condensation. Previous studies reported that CO₂ absorption is decreased by addition of water to the CO₂ absorbent.¹⁻³ However, the effects of temperature gradients on water content and CO₂ absorption are not clear.

We hypothesized that correction of the temperature gradients will prevent excessive water content preserving the reactivity of the CO₂ absorbent, thereby increasing its longevity. We constructed a novel temperature gradient correction (TGC) canister, and investigated the effects of TGC on water content and longevity (time to exhaustion) under low-flow anaesthesia using a simulated anaesthesia circuit.

Materials and methods

TGC canister
The TGC canister (Fig. 1A and B) was produced for the purpose of correcting temperature gradients between the reactive and non-reactive sites of the CO₂ absorbent, and between the canister exterior (cooled by room air) and canister interior. It is different from canisters for refrigeration.⁴⁻⁶ To conduct heat easily from the reactive site to the non-reactive site and the canister container, 12 aluminium plates were set into the canister vertically

†Declaration of interest. All experiments were performed in the Department of Anaesthesiology, Hachioji Medical Center Tokyo Medical University.
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. Unlike electrolytically plated nickel coatings, electroless nickel plating produces very uniform, hard coatings, without an externally applied electric current, and are normally identified according to their phosphorus content. By varying the percentage of phosphorus or boron in the coating, deposits can be produced to exhibit non-magnetic and highly corrosion resistant characteristics or hard deposits with excellent wear resistance. The TGC canister was designed to be mounted on an anaesthesia machine (Fabius/C212, Draeger, Luèbeck, Germany), the same size as the conventional Fabius™ canister. Thermosensors (Sheath thermocouple, Toho Electronics Inc., Kanagawa, Japan) were installed at eight sites (A, B, C1, D1, E1, C2, D2 and E2) in both the TGC canister and conventional canister to measure the temperature at each site. A and B are points at the canister inlet and outlet, respectively. C1, D1 and E1 are points 5 mm from the internal surface of the outer rim of the canister, with C1 being near the top of the CO₂ absorbent, D1 near the middle and E1 near the bottom. C2, D2 and E2 are points 20 mm from the outer rim of the canister, corresponding in height to C1, D1 and E1, respectively.

**Experimental protocol**

Experiments were divided into two groups according to the type of canister used: the TGC canister (n=6) or conventional canister (n=6). One kilogram of fresh CO₂ absorbent (Drägersorb free™, Dräger) 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 flow rates 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 (Datex, Helsinki, Finland). CO₂ (300 ml min⁻¹) was introduced through a needle situated in the 3 litre bag. 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 at approximately 20°C.

Longevity (time to exhaustion) was measured as the time taken for the inspired CO₂ tension (PᵢCO₂) to increase from 0 to 5 mm Hg, and then the experiment was halted. PᵢCO₂, end tidal CO₂ (P₇₅CO₂), temperature of CO₂ absorbent at each site of the canister and temperature of the canister inflow gas and outflow gas were continuously monitored during the experiment. 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: C1, D1, E1, C2, D2 and E2. The collected CO₂ absorbent was weighed, heated for 8 h or longer at 105°C in an oven and weighed again. The water content was determined by the difference between the wet and dry weights.

**Statistical analysis**

All values are shown as means (SD). Statistical differences were evaluated with the Mann–Whitney U-test. Statistical significance was established at the level of P<0.05.
Results

$E_{CO_2}$ 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 both canisters.

The temperatures of canister inflow and outflow gas are shown in Figure 2A and B. There were no significant differences in the temperature of the canister inflow gas between the TGC and conventional canisters, and no significant differences in the temperature of the canister outflow gas.

The temperature of the CO$_2$ absorbent at each site is shown in Figure 3A and B. In the conventional canister, from the start to around 3–4 h, the area of maximum absorbent temperature (reactive site) was E2, reaching approximately 30°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 absorbent temperature on the canister exterior was lower than that in the canister interior. On the other hand, in the TGC canister, the temperature gradients between the reactive site and non-reactive site and between the canister exterior and canister interior were reduced.

The temperature gradients between the reactive site (maximum temperature area) and C1 are shown in Figure 4. These were reduced in the TGC canister throughout the experiment, compared with the conventional canister ($P<0.01$).

The absorbent water content is shown in Table 1. Before the experiment, the water content was 16.1 (0.9)% in the conventional canister and 15.7 (1.1)% in the TGC canister. At the end of the experiment, the absorbent in the middle or bottom layer of the canister had dried in both canisters. The water content at C1 increased excessively to 32.4 (0.7)% in the conventional canister, but increased to only 20.6 (1.3)% in the TGC canister ($P<0.01$). The longevity of CO$_2$ absorbent in the conventional canister and TGC canister was 434 (9) min and 563 (13) min, respectively ($P<0.01$), i.e. approximately 30% increase.

Discussion

The water content of the CO$_2$ absorbent increased excessively at C1 in the conventional canister. Temperature gradient correction prevented the local excessive water content increases in the TGC canister. The TGC canister increased...
During this exothermic reaction 1 mol of water contained in soda lime is consumed, and 13.7 kcal and 2 mol of water are formed by the absorption of 1 mol of CO$_2$.

$$\text{CO}_2 + \text{H}_2\text{O} \leftrightarrow \text{H}_2\text{CO}_3$$

$$\text{H}_2\text{CO}_3 + 2\text{NaOH(KOH)} \leftrightarrow \text{Na}_2\text{CO}_3(\text{K}_2\text{CO}_3) + 2\text{H}_2\text{O} + 13.7 \text{ kcal}$$

$$\text{Na}_2\text{CO}_3(\text{K}_2\text{CO}_3) + \text{Ca(OH)}_2 \leftrightarrow \text{CaCO}_3 + 2\text{NaOH(KOH)}$$

The Fabius™ canister used in the present study has an inflow passage pipe in the centre of the canister. The reactive site shifts from the bottom of the canister to the top with time. The CO$_2$ absorbent, which reacts with CO$_2$ locally at the reactive site, generates heat and water, resulting in drying of the absorbent. The CO$_2$ absorbent in the middle and bottom layer of the canister is dry as a result of chemical reaction.

In the conventional canister, there were large temperature gradients vertically between the local reactive site and the non-reactive downstream site. In addition, the temperature of the CO$_2$ absorbent on the canister exterior cooled by room air was lower than that in the canister interior. These large temperature gradients between the reactive site and lower temperature sites (especially C1) might cause excessive water content at C1 by dew condensation.

In the TGC canister, the temperature gradients were reduced throughout the experiment, compared with the conventional canister. This temperature gradient correction prevented local excessive increases in water content.

It is reasonable to suggest that the expired gas was bypassed through the top of the exterior of the canister, so that a large mass of unused CO$_2$ absorbent inside the canister was wasted, leading to decreased longevity of CO$_2$ absorbent in the conventional canister, because the water content increased excessively and the reactivity decreased locally at C1. Therefore, correction of temperature gradients prevents development of local excessive water content and preserves the reactivity of the CO$_2$ absorbent, leading to improved longevity.

This hypothesis implies channelling because of heterogeneity of reactivity degradation, and warrants an investigation about degradation of reactivity, distribution of reactivity degradation, and the pattern and direction of flow.

### Degradation of reactivity

The reactivity of CO$_2$ absorbent changes depending on its water content. Water is present as a thin film on the granule surface. Water is essential because the reactions take place between ions that exist only in the presence of water. Absorbents with low water content exhaust rapidly. On the other hand, those with high water content have a slower rate of absorption, stickiness and increased resistance. Previous studies reported that CO$_2$ absorption is decreased by addition of moisture to the CO$_2$ absorbent. Moisture is necessary, but reactivity decreases when the CO$_2$ absorbent is excessively moist.

Changes in reactivity of CO$_2$ absorbent were not measured in the present study. However, in the conventional canister, the reactivity of CO$_2$ absorbent at C1 is thought to be decreased largely because its water content exceeds 30%. The expired gas should be bypassed without absorption of CO$_2$ through the low reactivity area, leading to channelling.

### Distribution of degraded reactivity

Distribution of degraded reactivity becomes massive if exposed to large temperature gradients for long times leading to enhanced channelling effects. Distribution of degraded reactivity along the direction of the gas flow enhances the channelling effect, while distribution of degraded reactivity perpendicular to the direction of the

### Table 1 Water content of CO$_2$ absorbent.

<table>
<thead>
<tr>
<th></th>
<th>Conventional canister (%)</th>
<th>TGC canister (%)</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before experiment</td>
<td>16.1 (0.9)</td>
<td>15.7 (1.1)</td>
<td>0.51</td>
</tr>
<tr>
<td>After experiment</td>
<td>32.4 (0.7)</td>
<td>20.6 (1.3)</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>C1</td>
<td>3.3 (0.6)</td>
<td>3.8 (1.1)</td>
<td>0.07</td>
</tr>
<tr>
<td>D1</td>
<td>2.1 (0.4)</td>
<td>1.8 (0.3)</td>
<td>0.34</td>
</tr>
<tr>
<td>E1</td>
<td>20.2 (1.2)</td>
<td>19.1 (1.5)</td>
<td>0.23</td>
</tr>
<tr>
<td>C2</td>
<td>1.8 (0.6)</td>
<td>2.8 (1.0)</td>
<td>0.07</td>
</tr>
<tr>
<td>D2</td>
<td>1.7 (0.3)</td>
<td>1.5 (0.3)</td>
<td>0.39</td>
</tr>
</tbody>
</table>

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gas flow does not. In the present study, the water content of the CO₂ absorbent was excessive only at C1 in the conventional canister, while not in the TGC canister. However, distribution details are not clear.

**Pattern and direction of flow**

It is believed that channelling of 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). This refers to channelling because of heterogeneity of gas flow.

However, the channelling effect should be considered on the basis of both the distribution of degraded reactivity and the pattern of flow. In the case of strongly decreased reactivity, a wide distribution of decreased reactivity and preferential gas flow in the decreased reactivity area, the channelling effect would be enhanced. Adversely, dew condensation might occupy the void space (between the granules) along the container walls, leading to increased resistance to gas flow. Decreased gas flow at the decreased reactivity site would not enhance the channelling effect.

In the present study, the pattern and direction of flow were not measured, and the effect of 12 aluminium plates set into the TGC canister on the pattern and direction of flow is not clear.

However, in the conventional canister, the channelling effect might be synergistically enhanced because of heterogeneity of gas flow and degraded reactivity. On the other hand, in the TGC canister the channelling effect might be improved mainly because of improved degradation of reactivity.

**Conclusions**

We constructed a novel TGC canister. Temperature gradient correction prevented a local excessive increase in water content and improved the longevity of CO₂ absorbent. The TGC canister is a useful and simple device to improve the CO₂ absorbent longevity in low-flow anaesthesia.

**Acknowledgements**


**References**