

# Physical Factors Affecting the Production of Carbon Monoxide from Anesthetic Breakdown

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**Background:** Parameters determining carbon monoxide (CO) concentrations produced by anesthetic breakdown have not been adequately studied in clinical situations. The authors hypothesized that these data will identify modifiable risk factors.

**Methods:** Carbon monoxide concentrations were measured when partially desiccated barium hydroxide lime was reacted with isoflurane (1.5%) and desflurane (7.5%) in a Draeger Narkomed 2 anesthesia machine with a latex breathing bag substituting for a patient. Additional experiments determined the effects of carbon dioxide (0 or 350 ml/min), fresh gas flow rates (1 or 4 l/min), minute ventilation (6 or 18 l/min), or absorbent quantity (1 or 2 canisters). End-tidal anesthetic concentrations were adjusted according to a monochromatic infrared monitor.

**Results:** Desflurane produced approximately 20 times more CO than isoflurane when completely dried absorbents were used. Peak CO concentrations approached 100,000 ppm with desflurane. Traces of water remaining after a 66-h drying time (one weekend) markedly reduced the generation of CO compared with 2 weeks of drying. Reducing the quantity of desiccated absorbent by 50% reduced the total CO production by 40% in the first hour. Increasing the fresh gas flow rate from 1 to 4 l/min increased CO production by 67% in the first hour but simultaneously decreased average inspiratory concentrations by 53%. Carbon dioxide decreased CO production by 12% in completely desiccated absorbents.

**Conclusion:** Anesthetic identity, fresh gas flow rates, absorbent quantity, and water content are the most important factors determining patient exposures. Minute ventilation and carbon dioxide production by the patient are relatively unimportant.

CARBON monoxide (CO) results from reaction of some anesthetics with desiccated carbon dioxide absorbents. These reactions have been studied in small reactors<sup>1</sup> and using 25-kg swine,<sup>2</sup> but these situations may not model human exposures<sup>3</sup> because of differences in scale. Bonome *et al.*<sup>4</sup> demonstrated that fresh gas flow rate, animal size, anesthetic concentration, and identity affect exposures. Measurements of CO production may also be

confounded by patient absorption<sup>5</sup> and exhalation from smokers.<sup>6</sup> Scale is important because these chemical reactions are temperature-dependent<sup>1</sup> and exothermic.<sup>2,7</sup> We hypothesized that quantitative CO production data in the absence of a patient will identify additional safety factors.

## Methods

### *Reaction of Anesthetics and Measurement of Carbon Monoxide*

An anesthesia machine (Narkomed 2; North American Draeger, Telford, PA) was equipped with two canisters of barium hydroxide lime. A polyethylene breathing circuit was completed with a latex breathing bag at the patient Y-connector. A cannula was inserted into the latex bag for addition of carbon dioxide to simulate respiration. The fresh gas flow rate was 1.0 l oxygen/minute unless otherwise specified. Measurements of halogenated anesthetics were performed with a monochromatic infrared monitor measuring C-H stretch at approximately 3.3  $\mu$  (RGM 5250; Ohmeda, Louisville, CO). Trifluoromethane and CO were measured every 5 minutes for 60 min with gas chromatography as previously described.<sup>7</sup> Temperature was monitored with a range exceeding 0.0–100.0°C.

### *Experimental Protocol*

At time = 0 the carbon dioxide and the anesthetic agent were administered. The end-tidal anesthetic concentrations were adjusted to 7.5% (desflurane) or 1.5% (isoflurane) using the monochromatic infrared monitor. Interference from trifluoromethane is expected to produce falsely high indications of the actual inhaled anesthetic because of the infrared absorption of trifluoromethane, but this is a clinically relevant model of adjusting anesthetic concentration because monochromatic monitors do not provide warning of CO production *via* the display of mixed agents or the wrong anesthetic agent.<sup>8</sup>

In the first set of experiments, absorbents of 0.02–15% water content were studied with 0 or 350  $\pm$  50 ml/min carbon dioxide. These water contents represent the smallest and largest amounts likely to be clinically encountered and were produced by the desiccation of barium hydroxide lime by the upward flow of 10 l/min of dry oxygen for 7 h to 4 weeks. This method produces a gradient of water content in partially dried absor-

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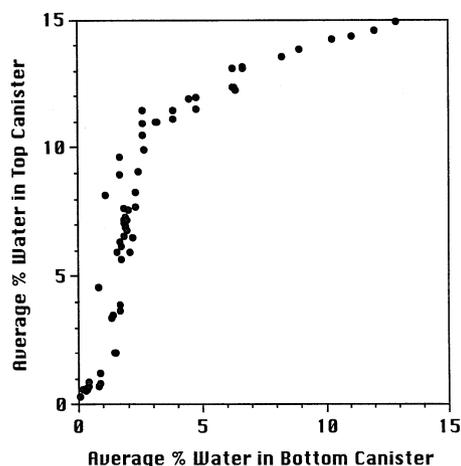


Fig. 1. Relation of the upper and lower canister average water contents when dried at ambient temperature by the upward flow of 10 l/min oxygen.

bents,<sup>2</sup> and the average water content of each canister is reported.

Because of the extreme sensitivity of CO production to absorbent water content and the small difference expected to result from the presence or absence of carbon dioxide, paired experiments of equally and homogeneously dried absorbents were performed using desflurane with 0 or 350 ml/min carbon dioxide. These paired experiments were performed to determine the effects of carbon dioxide input (0 or 350 ml/min), fresh gas flow rates (1 or 4 l/min), minute ventilation (6 or 18 l/min), or absorbent quantity (1 or 2 canisters).

#### Statistical Analysis

An unpaired *t* test was used to compare two canisters versus one canister. Paired *t* tests were used for other single variable comparisons using paired experiments. The values are reported as mean  $\pm$  SEM.

## Results

#### Production of Carbon Monoxide

The water contents of the upper and lower canisters were related, as shown in figure 1. The production of CO in the first hour was extremely sensitive to absorbent water content, as shown in figure 2. Peak temperatures also increased with lower water contents, as shown in figure 3.

#### Effect of Carbon Dioxide

No effect in CO production by carbon dioxide could be graphically demonstrated in figure 2. Very low absorbent water contents were further explored with paired experiments ( $n = 4$  pairs at equal water content, range = 0.6–1.1%), which demonstrated that CO production in the first hour in the presence of carbon dioxide at  $350 \pm 50$  ml/min was approximately 12% less than the CO

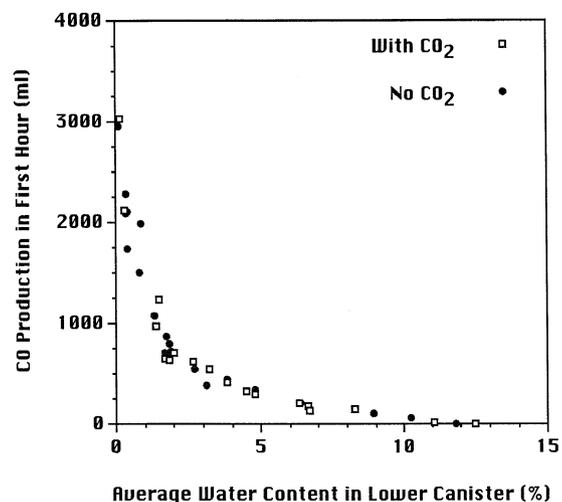


Fig. 2. Production of carbon monoxide (CO) in the first hour resulting from desflurane breakdown in barium hydroxide lime at the specified water content. CO<sub>2</sub> = carbon dioxide.

production without carbon dioxide ( $2,670 \pm 160$  ml vs.  $2,980 \pm 190$  ml;  $P = 0.002$ ). Although the production of CO was similar, figure 3 shows that peak absorbent temperatures were markedly different.

#### Effect of Absorbent Quantity

Paired experiments ( $n = 4$  pairs) demonstrated that two canisters (water content = 0.3%) produced more CO ( $2,510 \pm 200$  ml) than one canister ( $1,500 \pm 90$  ml) during the first hour ( $P = 0.004$ ) in the presence of  $350 \pm 50$  ml/min carbon dioxide.

#### Effect of Fresh Gas Flow

Paired experiments ( $n = 4$  pairs at equal water content; range = 0.8–1.7%) demonstrated that CO production was greater at a fresh gas flow rate of 4,000 ml/min ( $3,600 \pm 510$  ml) than at 1,000 ml/min ( $2,150 \pm 330$  ml;  $P = 0.0045$ ). However, the average inspiratory limb CO<sub>2</sub> concentrations were lower at 4,000 ml/min ( $19,200 \pm 2,800$  ppm) than at 1,000 ml/min ( $40,500 \pm 6,200$  ppm;  $P = 0.0084$ ).

#### Effect of Minute Ventilation

The quantity of CO produced at 6 versus 18 l of minute ventilation were similar ( $1,888 \pm 139$  ml vs.  $1,853 \pm 167$  ml,  $P = \text{NS}$ ). However, the inspiratory concentrations were greater at 6 l of minute ventilation (mean difference, 5,200 ppm;  $P < 0.0001$ ). The differences between inspired and expired concentrations were greater at 6 versus 18 l minute ventilation ( $6,062$  ppm vs.  $1,026$  ppm, respectively; difference between groups = 5,036 ppm;  $P < 0.001$ ). The upper canister was an average of 18.6°C cooler and the lower canister was 8.8°C warmer at 18 versus 6 l/min during minutes 10–60 ( $P < 0.0001$  in both cases).

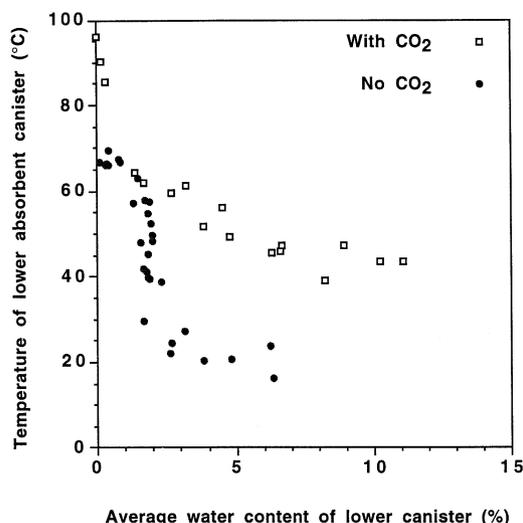


Fig. 3. Scattergram of the peak absorbent temperature measured in the center of the lower canister during the first hour resulting from desflurane breakdown in barium hydroxide lime at the specified water content with or without 350 ± 50 ml/min carbon dioxide (CO<sub>2</sub>).

*Effect of Anesthetic Identity*

Desflurane (7.5% end tidal) produced 20 times greater peak CO concentrations than isoflurane (1.5% end tidal), but these peak concentrations occurred during the first 10-15 min and rapidly decreased. In contrast, the CO concentrations produced by isoflurane were sustained for more than an hour with little decrement, as shown in figure 4.

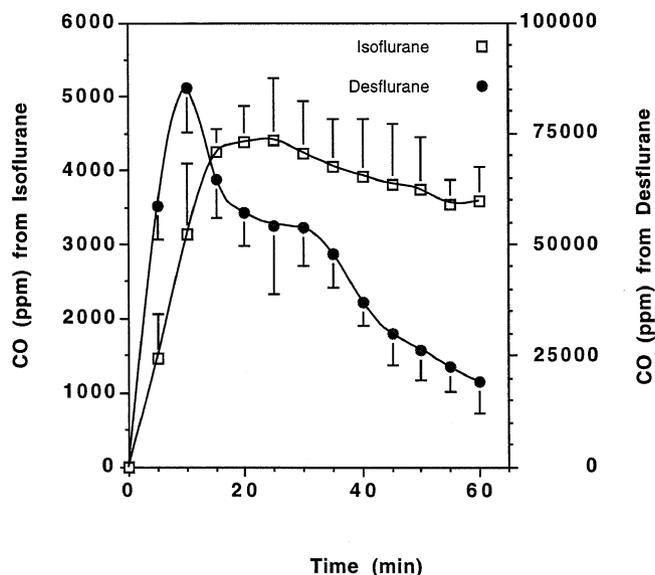


Fig. 4. Difference in time course in carbon monoxide (CO) production during 1.5% isoflurane and 7.5% desflurane breakdown at 1 l/min fresh gas flow. Error bars represent SDs. Isoflurane and desflurane are significantly different at all times greater than 0 (*P* < 0.01).

**Discussion**

*Absorbent Drying*

Although new formulations of carbon dioxide absorbents may eliminate the potential for CO formation when desiccated,<sup>9</sup> prevention of absorbent drying remains the major factor preventing CO exposures.<sup>10</sup> Overnight drying for 14 h at 10 l/min results in minimal CO production. Reducing the average absorbent water content to less than or equal to 5% water is associated with clinically significant CO formation and requires more than or equal to 24 h of drying. The time interval between 1400 Friday to 0800 Monday is 66 h, which desiccates both canisters enough to produce CO in each. These data explain the severity of CO exposures on Monday mornings and the lack of serious exposures with overnight drying. A factor not previously reported is that completely dry absorbents produce three times the amount of CO as 66 h of desiccation. Therefore, patient risk increases dramatically when absorbent desiccation time exceeds one weekend in length at 10 l/min.

*Effect of Carbon Dioxide*

Consistent with results of Knolle and Gilly,<sup>11</sup> carbon dioxide at 350 ml/min produced a 10-12% reduction in CO formation, but only with homogenous and completely desiccated absorbent, which is rarely encountered in clinical practice. We suggest that the effect of carbon dioxide on CO production is clinically insignificant in all cases, and is nonexistent in most situations because desiccation is greatest at the bottom of the absorbent canister, but expired gas enters at the top. If the absorbent is not completely desiccated, carbon dioxide exhausts and further hydrates the absorbent, which is initially too wet to produce CO. Most carbon dioxide is absorbed before reaching absorbent at the bottom, where desiccation is greatest and most CO is produced.

*Effect of Absorbent Quantity*

When comparing one canister (1,180 g initial weight) versus two canisters (2,360 g initial weight) of com

**Table 1. Range of Water Contents Found in This Study of the Lower Barium Hydroxide Lime Canister When Dried at Ambient Temperature by the Upward Flow of 10 l/min Oxygen**

Drying Time (h)	Lower Canister Water Content (%)
7	10-12
9	9-11
14	8-10
24	5-6
48	1.6-2.2
66	1.2-1.4
168	0.2-0.4

These data fit the following power function:  $y = 121 \cdot x^{-1.083}$ , where *y* = % water content and *x* = drying time in hours.

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pletely desiccated absorbent, the CO production was 67% greater in the first hour when two canisters were used. In some situations, the absorbent quantity limits the production of CO. This suggests that safety can be enhanced if only the minimum quantity of absorbent is used.

#### *Effect of Fresh Gas Flow Rates*

Higher fresh gas flow rates removed more of the reacted gas containing CO, producing lower CO concentrations. Nevertheless, more CO was produced at higher fresh gas flow rates because of the greater quantity of anesthetic reacting with desiccated absorbent. One should not extrapolate this finding to situations with minimally dried absorbents because the quantity of sufficiently desiccated absorbent capable of reaction may be the limiting factor, not the quantity of anesthetic. If experiments were conducted for more than 60 min, absorbent quantity may again become the limiting factor.

#### *Effect of Minute Ventilation*

Although the total production of CO was similar, greater minute ventilation was associated with different absorbent temperature profiles, which could be explained by greater heat transfer from the upper canister to the lower by the greater flow of gas through the absorbent. Minute ventilation was not an important factor in the production of CO, although in an actual anesthetic minute ventilation affects uptake through effects on respiratory physiology.

#### *Effect of Anesthetic Identity and Concentration*

Isoflurane produced lower concentrations of CO than desflurane, although the CO concentrations produced by desflurane decreased more rapidly than isoflurane on a percentage basis, as shown in figure 4. This effect may be caused by the lower clinical concentrations of isoflu-

rane (1.5%) used in these experiments, which depleted the absorbent more slowly, as well as a lower molar fraction of CO per molecule of anesthetic than desflurane.<sup>1</sup> This is clinically significant because nearly maximal absorbent drying with approximate 1 minimum alveolar concentration of desflurane results in rapidly lethal concentrations of CO within the first 10–15 min. Conversely, isoflurane may produce 20-fold lower peak CO concentrations, but these may be sustained with minimal decrement for more than an hour.

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