Anesthesiology
1997; 86:1061–5

Rehydration of Desiccated Baralyme Prevents Carbon Monoxide Formation from Desflurane in an Anesthesia Machine

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Background: **Desiccated carbon dioxide absorbents degrade desflurane, enflurane, and isoflurane to carbon monoxide (CO) *in vitro* and in anesthesia machines, which can result in significant clinical CO exposure. Carbon monoxide formation is highest from desflurane, and greater with Baralyme than with soda lime. Degradation is inversely related to absorbent water content, and thus the greatest CO concentrations occur with desflurane and fully desiccated Baralyme. This investigation tested the hypothesis that rehydrating desiccated absorbent can diminish CO formation.**

Methods: **Baralyme was dried to constant weight. Carbon monoxide formation from desflurane and desiccated Baralyme was determined in sealed 20.7-ml vials without adding water, after adding 10% of the normal water content (1.3% water), and after adding 100% of the normal water content (13% water) to the dry absorbent. Similar measurements were made using an anesthesia machine and circle system. Carbon monoxide was measured by gas chromatography–mass spectrometry.**

Results: **Carbon monoxide formation from desflurane *in vitro* was decreased from 10,700 ppm with desiccated Baralyme to 715 ppm and less than 100 ppm, respectively, when 1.3% and 13% water were added. Complete rehydration also decreased CO formation from enflurane and isoflurane to undetectable concentrations. Desflurane degradation in an anesthesia machine produced 2,500 ppm CO in the circuit, which was reduced to less than 180 ppm when the full complement of water (13%) was added to the dried absorbent.**

Conclusions: **Desflurane is degraded by desiccated Baralyme in an anesthesia machine, resulting in CO formation. Adding water to dried Baralyme is an effective means of reducing CO formation and the risk of intraoperative CO poisoning. Although demonstrated specifically for desflurane and Baralyme, rehydration is also applicable to enflurane and isoflurane, and to soda lime. (Key words: Anesthetics, volatile: desflurane; enflurane; isoflurane. Toxicity: carbon monoxide. Carbon dioxide: Baralyme, soda lime.)**

THE problem of intraoperative carbon monoxide (CO) formation and potential toxicity has become increasingly apparent.[1–3] Moon *et al.* described 31 cases of intraoperative CO poisoning during enflurane or isoflurane anesthesia, with some CO concentrations exceeding 1,000 ppm and carboxyhemoglobin levels reaching 30% or more.[‡§] Often CO poisoning occurred in patients on Monday mornings when an anesthesia machine was used that had been idle during the weekend, and the carbon dioxide absorbent was implicated in CO formation. An association between a long duration of carbon dioxide canister use and high CO concentrations also has been noted. The first case of CO poisoning during desflurane anesthesia was reported recently, and it was associated with peak carboxyhemoglobin levels of 32% and required unanticipated postoperative mechanical ventilation.[1] This was also the first case on a Monday morning, when unchanged soda lime and an anesthesia machine idled for more than 24 h had been used. A recent prospective analysis estimated the overall risk for CO exposure as 0.26%, with that risk increasing to 0.44% for the first case of the day.[3]

The toxic effects of CO are well described.[4] Acute CO toxicity results in neurologic and psychologic alterations ranging from headache to visual and motor disturbances and loss of consciousness. Perhaps more disturbing than acute central nervous system CO poisoning, which may be recognized after surgery and treated immediately, are delayed neuropsychologic sequelae such as cognitive deficits, personality changes, demen-

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Received from the Departments of Anesthesiology and Medicinal Chemistry, University of Washington, and the Puget Sound Veterans Affairs Health Care System, Seattle, Washington. Submitted for publication September 12, 1996. Accepted for publication January 30, 1997. Supported by grants from Abbott Laboratories and the Pharmaceutical Research and Manufacturers of America Foundation. Dr. Kharasch is a consultant to Abbott Laboratories and to Zeneca Pharmaceuticals.

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tia, incontinence, and gait disturbances.[5,6] These sequelae occur unpredictably in as many as 67% of patients and appear 3 to 21 days after CO exposure, even in patients who were otherwise asymptomatic or who recovered shortly after exposure.

Results of both clinical and laboratory investigations show that CO arises from the degradation of certain volatile anesthetics by soda lime or barium hydroxide lime (Baralyme).[1,3,7–11]‡§ The water content of the carbon dioxide absorbent is a critical determinant of CO formation: native absorbent, which contains approximately 13% water, forms no CO, whereas completely dry absorbent causes the greatest CO formation. Desflurane, enflurane, and isoflurane are degraded to CO, but sevoflurane and halothane are not, and degradation is greater with Baralyme than with soda lime.[7,8,10,11] Peak CO concentrations formed *in vitro* from desiccated Baralyme, and equivalent minimum alveolar concentrations of desflurane, enflurane, and isoflurane were 19,700, 5,380, and 1,250 ppm, respectively.[7] Using swine and a clinical anesthesia machine, Frink *et al.*[10,11] found peak CO concentrations of 11,700, 5,800, and 1,500 ppm with desflurane, enflurane, and isoflurane, respectively, which were associated with peak carboxyhemoglobin concentrations of 73%, 59%, and 21%. Thus desflurane and desiccated Baralyme cause the greatest amount of CO formation and pose the greatest risk for clinical CO poisoning.

Results of these studies have afforded recommendations for reducing the risk of CO poisoning, including frequent absorbent changes and high-flow oxygen to purge the system of any residual CO.[8,12] The former is expensive and the latter only accelerates desiccation of the absorbent, increasing the potential for CO formation. Suggestions for monitoring CO production in the anesthesia circuit also have been made.[3,9] Clearly the best solution to the problem is to eliminate CO production.

Because CO formation increases as carbon dioxide absorbent water content diminishes,[7,8] we tested the hypothesis that adding water back to carbon dioxide absorbent that had become dried could decrease or prevent CO formation. We used desiccated Baralyme and desflurane to test this hypothesis because this combination forms the greatest amount of CO.[7,10]

Materials and Methods

Anesthetics were used as obtained from their manufacturers. Baralyme was purchased from Chemtron Medical Division, Allied Healthcare, St. Louis, Missouri. The fresh absorbent contained 13% water by weight. To obtain completely desiccated absorbent, the material was dried to a constant weight by blowing oxygen through an absorbent-packed cylinder or in a muffle furnace at 110°C. A CO standard of 952 ppm in air (Matheson Gas Products, Montgomeryville, PA) was used to prepare standards for quantitative analysis.

Laboratory experiments were performed in triplicate at room temperature (23°C) in sealed 20.7-ml vials containing 4 g fresh or desiccated Baralyme. Water equivalent to either 1.3% (52 μl) or 13% (520 μl) of the Baralyme weight (or no water) was added by pouring it on top of the absorbent. A small strip of Whatman #1 filter paper was placed in the vial, which was then sealed. A blank gas sample (0.5 μl) was drawn from one vial of each pair and injected into a 12-ml sealed headspace vial. Desflurane (5 ml) was injected directly onto the filter paper, which provided a uniform surface for volatilization and prevented direct contact between liquid anesthetic and absorbent. The resultant desflurane concentration was 4.3%, measured by gas chromatography–mass spectrometry. Vials were placed on a rotary mixer at 60 rpm. A 0.5-ml headspace sample was withdrawn 0, 30, 60, 180, and 300 min after desflurane introduction and injected into a second, sealed vial. These samples were analyzed for CO by gas chromatography–mass spectrometry.

After determining that CO formation from desflurane and desiccated Baralyme could be reduced by adding water, a second set of experiments was performed using an anesthesia machine (Narkomed 2A; North American Drager, Telford, PA) equipped with a circle circuit, bellows ventilator, gas scavenging system, and an anesthesia gas monitor (POET II; Criticare Systems, Waukesha, WI) attached *via* a sampling line at the Y piece of the breathing circuit. The breathing circuit was equipped with a foam nose, and a 2-l rebreathing bag was used as a model lung. Desflurane was delivered with an Ohmeda Tec 6 vaporizer (West Yorkshire, UK).

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§ Moon RE, Ingram C, Brunner EA, Meyer AF: Spontaneous generation of carbon monoxide within anesthetic circuits. ANESTHESIOLOGY 1991; 75:A873

Experiments were conducted at room temperature (20°C), and exogenous carbon dioxide was not added to the circuit. Desiccated Baralyme (2,350 g) was divided equally and placed in two carbon dioxide absorbent canisters. In each case, water was added to Baralyme that was cooled to room temperature. Baralyme rehydration with 1.3% water was accomplished by pouring 15.2 ml (30.4 ml total) into each canister divided in three equal aliquots to the bottom, middle, and top of the absorbent. To rehydrate with 13% water, 153 ml (306 ml total) was added to each canister. Ventilator settings were 750 ml tidal volume and 8 breaths per minute, and 9% desflurane (1.5 minimum alveolar concentration) was delivered at 3 l/min. Gas samples (0.5 ml) were obtained from the inspiratory limb of the circuit using a gas-tight syringe equipped with a sealing valve, through an adapter placed just distal to the respiratory valve 0, 1, 3, 5, 10, 20, 30, 45, 60, 90, 120, and 180 min after desflurane was started and analyzed for CO by gas chromatography–mass spectrometry. Each experiment was performed in duplicate or triplicate, each time using fresh Baralyme dried to a constant weight.

Carbon monoxide concentrations were determined by gas chromatography–mass spectrometry with headspace sampling. Analyses were performed on a 5890 Series II+ gas chromatograph (Hewlett-Packard, Wilmington, DE) with an HP 7694 headspace sampler interfaced to an HP 5971 mass selective detector, using an Rt-Msieve 13X porous layer open tubular capillary column (30 m x 0.32 mm; Restek, Bellefonte, PA). The GC injector and detector temperatures were 150 and 250°C, respectively, and the column head pressure was 2.5 psi. For the headspace GC/MS analysis of CO, the headspace sampler parameters were as follows: agitation = high; sample equilibration time = 0.5 min; vial pressurization = 0.05 min; loop fill time = 0.5 min; loop equilibration time = 0.15 min; sample injection time = 0.5 min; oven, loop, and transfer line temperatures were 50, 60, and 70°C, respectively. The GC oven temperature was held at 40°C for 7 min, increased at 40°C/min to 200°C, and held at this temperature for 1 min. Carbon monoxide was eluted isothermally and monitored by selected ion monitoring of *m/z* 12. This ion was chosen over the other possibilities (*m/z* 16 and *m/z* 28) because it provided the greatest signal-to-noise ratio. Standard curves of peak area *versus* concentration were constructed by analyzing CO standards of known amount and were used to measure CO concentrations in experimental samples. The detection limit was approximately 4 ppm, and because all samples were diluted 24 times, the actual detection limit was approximately 100 ppm.

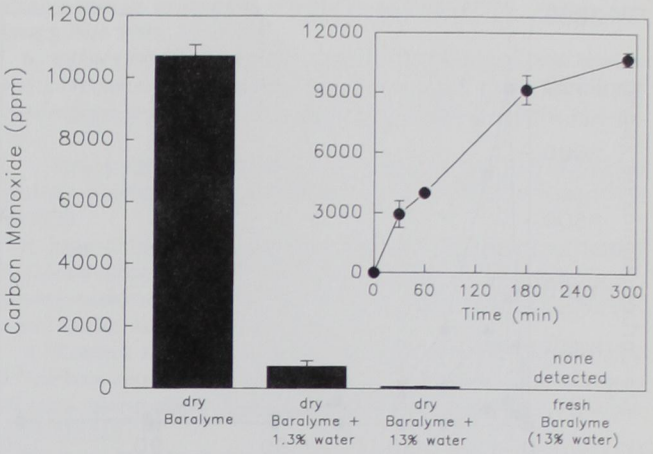

Fig. 1. Desflurane degradation by dry and rehydrated Baralyme in closed vials. The inset shows time-dependent CO accumulation with desflurane and desiccated Baralyme. The main figure shows the effect of rehydrating desiccated Baralyme on the extent of CO formation from desflurane after 300 min. Results are the means ± standard deviations of three determinations.

Results

Laboratory experiments in closed vials with desflurane and desiccated Baralyme showed an accumulation of CO with increasing incubation time (fig. 1, inset). No CO was detected when desflurane was omitted from the vials or when fresh Baralyme was used. Results were similar whether the Baralyme was dried to constant weight by a stream of oxygen or by heat (average CO formation from desflurane corresponded within 5%). The CO concentration from desflurane averaged 10,700 ppm after 5 h. Adding water to dried Baralyme markedly reduced CO formation (fig. 1). After adding only 10% of the normal water content (1.3% water), total CO accumulation was reduced more than 15 times and CO was not detectable until 60 min had elapsed. When the full water complement (13%) was replaced, CO was detected in only one of the three replicates, in which it was just above the limit of detection. Completely rehydrating dry Baralyme also reduced CO formation from enflurane and isoflurane, from 8,400 ± 150 and 1,240 ± 30 ppm, respectively, after 3 h, to undetectable concentrations.

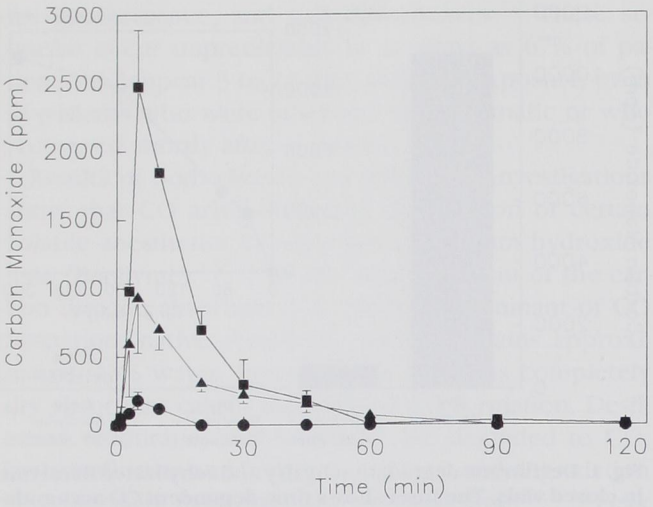

Fig. 2. Effect of rehydrating desiccated Baralyme on CO formation from desflurane in an anesthesia machine. Results are the means ± standard deviation of two or three determinations. Completely dry Baralyme was used without water replacement (squares), with 10% of the water replaced (triangles), and with 100% of the total water replaced (circles).

These *in vitro* results suggested that the addition of water to dried carbon dioxide absorbent might have clinical utility, so additional studies were performed with an anesthesia machine. When desiccated Baralyme was used, CO was detected within 3 min, and concentrations peaked at 2,500 ppm after 5 min (fig. 2). When 10% of the normal water content was added back to the dry Baralyme (1.3% water), CO concentrations were decreased to only one third of those seen with dry Baralyme, and the duration of CO formation was shortened from 120 to 90 min. When water was added back to the dry Baralyme to provide a theoretically full amount (13%) of water, the CO concentrations were diminished to 180 ppm. Further, CO formation after 60 min was either not detectable or only slightly above the detection limit (100 ppm).

‖ Carbon dioxide (5%) was passed through a tube packed with desiccated, rehydrated, or fresh Baralyme, and the effluent carbon dioxide concentration was measured by infrared analyzer. Desiccated absorbent was partially and then nearly completely exhausted after 5 and 10 min (effluent carbon dioxide, 3.2 ± 0.3% and 4.7 ± 0.0%; n = 3). In contrast, effluent carbon dioxide concentrations with rehydrated or fresh Baralyme were only 1.7 ± 0.4% and 2.3 ± 0.3% after 5 min, respectively, and 3.1 ± 0.4% and 3.4 ± 0.2% after 10 min.

Discussion

The results show that desflurane was degraded by desiccated Baralyme in an anesthesia machine, resulting in the formation of CO that reached a peak inspiratory concentration of 2,500 ppm and an average concentration of 520 ppm for the first hour. These CO concentrations occurred under conditions typical of those that might be used at the beginning of anesthetic maintenance (9% inspired desflurane, 3 l/min flow). Such CO concentrations exceed the Environmental Protection Agency's recommended limit of 35 ppm for a 1-h period.[13] The 2500 ppm CO concentration is also sufficient to produce carboxyhemoglobin concentrations that can cause clinically significant CO poisoning.[1] ‡§ Previous investigations have shown that carbon dioxide absorbents degrade desflurane to CO *in vitro*.[7,8] The present results show that desflurane degradation and CO formation occur in anesthesia machines with desiccated carbon dioxide absorbent and confirm the results of Frink *et al.*[10,11] Our experiments were performed at ambient operating room temperature and without carbon dioxide added to the circuit. Higher absorbent temperatures, resulting from scavenging of carbon dioxide produced during anesthesia, will result in greater anesthetic degradation and higher CO concentrations.[8,11]

Measurement of CO formation resulting from desflurane degradation by Baralyme in a closed vial system was an excellent model for cumulative CO production from desflurane degradation by Baralyme in an anesthesia machine. Further, both systems behaved similarly when water was added.

The results show that adding water to desiccated (or partially dry) Baralyme is an effective way to reduce desflurane degradation to CO. Importantly, adding water to desiccated Baralyme did not diminish the capacity to absorb carbon dioxide. Rather carbon dioxide absorption was diminished by desiccation, but restored by rehydration,‖ which further supports the clinical utility of rehydration. Adding greater amounts of water might completely prevent CO formation. The risk of intraoperative CO poisoning with desflurane and desiccated Baralyme, the "worst-case scenario," therefore can be effectively reduced or eliminated by adding water to the absorbent. This approach is equally applicable for preventing degradation of enflurane and isoflurane, which result in comparatively lower CO concentrations, and for rehydrating desiccated soda lime.

One typical scenario for CO poisoning is the first case on a Monday morning when desflurane, enflurane, or isoflurane are used in an anesthesia machine through which high gas flows were maintained over the weekend, resulting in drying of the carbon dioxide absorbent.[‡§,1,3] Should a practitioner suspect desiccation of the absorbent, the current Food and Drug Administration recommendation is to replace the carbon dioxide absorbent. Adding water to rehydrate the absorbent may be a practical and cost-effective alternative that obviates the need to prematurely discard unexhausted absorbent that has become desiccated.

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