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Reduction in the Incidence of Carbon Monoxide Exposures in Humans Undergoing General Anesthesia

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Background: **Carbon monoxide forms *via* reaction of isoflurane, enflurane, and desflurane with dried CO_2 absorbents. The authors hypothesize that interventions by nonphysician support personnel to decrease absorbent drying will decrease the exposure rate of patients to carbon monoxide from anesthetic breakdown.**

Methods: **In the control group, all anesthetizing personnel were made aware of the factors enabling CO generation from anesthetic breakdown, and prevention techniques were left to the anesthetizing personnel. After data collection was complete, the following interventions were initiated to reduce absorbent drying: Anesthesia technicians and housekeeping personnel were instructed to turn off all anesthesia machines after the last case of the day in each room, and the CO_2 absorbent was changed each morning if fresh gas was found flowing. Baralyme® was used in all phases of this study.**

Results: **Five cases of intraoperative carbon monoxide exposure occurred among 1,085 (0.46%) first cases in the control group. Postintervention, patient carbon monoxide exposures decreased ($P < 0.05$), with one exposure among 1,961 (0.051%) first cases in the main operating room. Two exposures among 68 (2.9%) first cases occurred in remote locations ($P < 0.001$) *versus* main operating room. Predisposing factors for absorbent drying include the prolonged use of anesthesia machines for monitored anesthesia care, inappropriate drying techniques for expiratory flowmeters, understaffing of support personnel, and anesthesia in remote locations.**

Conclusions: **These interventions reduced patient exposure to carbon monoxide. Monitoring for carbon monoxide exposures during general anesthesia may be necessary to recognize and end patient exposures that occur despite preventative measures. (Key words: Anesthetics, volatile: desflurane, enflurane, isoflurane. Toxicity: carbon monoxide, carbon dioxide, Baralyme®, soda lime.)**

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CARBON monoxide is produced when isoflurane, enflurane, or desflurane are passed through dry carbon dioxide absorbents.[1] Cases reported in the Anesthesia Patient Safety Foundation (APSF) Newsletter have identified carboxyhemoglobin (COHb) concentrations of more than 30% during inhalation anesthesia.§ Although fresh carbon dioxide absorbents contain 10-15% water by weight, the absorbents can dehydrate if dry gases are passed through them for prolonged periods. Oxygen and nitrous oxide used in the delivery of anesthesia are essentially dry because water vapor is removed in the liquefaction process. Because it takes approximately 24-48 h to dry canisters of carbon dioxide absorbents by the flow of dry oxygen at room temperature,[2-4] case reports of carbon monoxide exposure have been most common on Monday mornings, presumably because oxygen dehydrated the absorbents over a weekend. Figure 1 shows the possible pathways taken by fresh gas to exit the anesthesia machine. When the reservoir bag is in place, the possible pathways for fresh gas to exit the machine are (1) through the inspiratory limb of the patient breathing circuit or (2) through the absorbent and the pressure relief valve. When the reservoir bag is removed, there should be less resistance for gas to flow through the absorbent because the gas no longer must pass through the pressure relief valve but can

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§ Moon RE: Cause of CO poisoning, relation to halogenated agents still not clear. Anesthesia Patient Safety Foundation Newsletter 1994; 9(2):13-6.

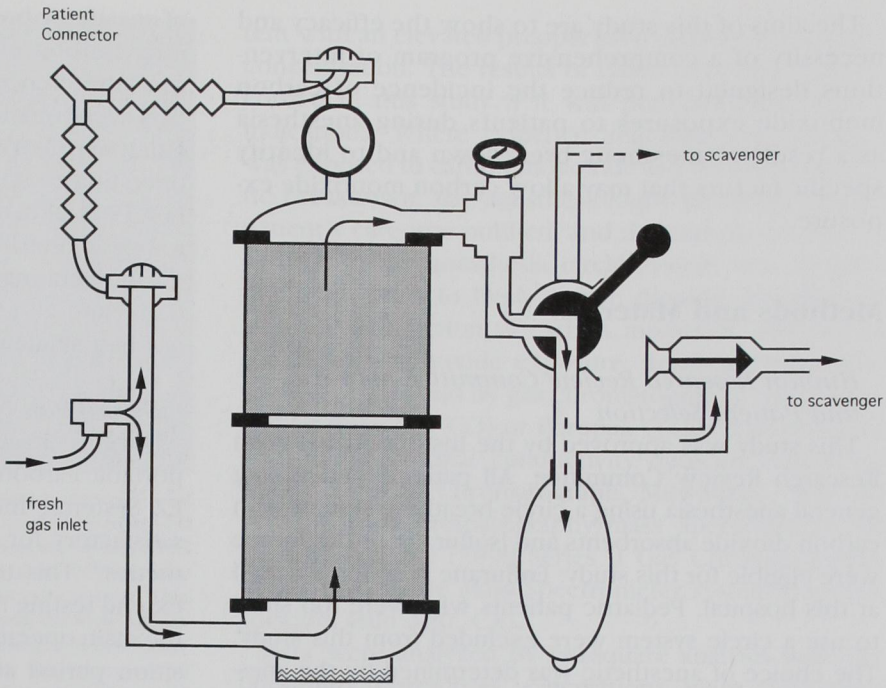

Fig. 1. A schematic diagram of a Narkomed anesthesia machine. Possible pathways taken by fresh gas to exit the anesthesia machine are shown. See text for further details. If the negative pressure relief valve of the scavenger malfunctions so that atmospheric pressure holds the inspiratory valve closed, the fresh gas flow may preferentially be directed through the carbon dioxide absorbent with the potential for absorbent dehydration even if the reservoir bag is in place.

exit directly through the reservoir bag connector. This speculation is consistent with the results of Frink *et al.*, who have shown that in Drager anesthesia machines not connected to a patient, the absorbent dries faster with the reservoir bag removed.[3]

Many recommendations have been published to reduce potential exposures,§‖#** but no studies have evaluated the efficacy of these recommendations. Exposure prevention guidelines from the APSF Newsletter** can be summarized as follows: (1) ensure the use of standard absorbents that are adequately hydrated by using low fresh gas inflow rates, (2) reduce high inflow rates as soon as possible, and replace absorbent that has been subjected to the flow of drying gas over the weekend, (3) use soda lime instead of Baralyme®. In the Winter 1994-1995 APSF newsletter, Epstein‖ speculated that the laboratory conditions that result in the production of carbon monoxide may represent only rare and brief clinical conditions. His editorial opinion suggested that if using a conventional circle system, simply turning off the fresh gas at the end of each case should be sufficient prevention and that anesthesia technicians should ensure that this was done. If this could not be done reliably, it was suggested that the carbon dioxide absorbent should be changed frequently, perhaps on Monday mornings. In addition, the suggestion was made that the potential to produce carbon monoxide should not be the sole basis for the choice of anesthetic or carbon dioxide absorbent.†† Recently, an decision by the Food and Drug Administration‡‡ has been issued to address carbon monoxide poisoning; replacement of carbon dioxide absorbent with fresh absorbent is recommended whenever desiccation is suspected. However, these recommendations depend on the recognition or suspicion of absorbent desiccation, and this may not always be possible.

‖ Epstein RA: Carbon monoxide: What should we do? Anesthesia Patient Safety Foundation Newsletter 1994; 9(4):37-41.

Lentz RE: CO poisoning during anesthesia poses puzzles. Anesthesia Patient Safety Foundation Newsletter 1994; 9(2):13-14.

** Fang ZX, Eger EI: Source of toxic CO explained: -CHF2 anesthetic + dry absorbent. Anesthesia Patient Safety Foundation Newsletter 1994; 9(3):25-36.

†† Eger EI: Letter to the editor: CO researcher notes, compares CO production from different absorbents; not to be basis for choice. Anesthesia Patient Safety Foundation Newsletter 1994; 9(4):41.

‡‡ Bedford RF: From the FDA: Carbon monoxide. ANESTHESIOLOGY 1995; 83(4):33A.

The aims of this study are to show the efficacy and necessity of a comprehensive program of interventions designed to reduce the incidence of carbon monoxide exposures to patients during anesthesia as a result of anesthetic breakdown and to identify specific factors that may allow carbon monoxide exposure.

Methods and Materials

Human Research Review Committee Approval and Patient Selection

This study was approved by the Institutional Human Research Review Committee. All patients undergoing general anesthesia using a circle breathing system with carbon dioxide absorbents and isoflurane or desflurane were eligible for this study. Enflurane is no longer used at this hospital. Pediatric patients who were too small to use a circle system were excluded from this study. The choice of anesthetic was determined by the anesthesiologist without regard for this study. Baralyme® was used as the carbon dioxide absorbent in all phases of this study and was changed when the color indicator changed, indicating exhaustion, and also according to the specific criteria listed below. Interventions to reduce carbon dioxide absorbent drying were imposed midway through the study. Data were obtained before (control group) and after intervention in the same operating rooms with the same anesthesia technicians and support personnel and also with the same attending anesthesiologists and certified registered nurse anesthetists (CRNAs).

Description of the Control Group

This study began after Fang *et al.*** reported the requirements for carbon monoxide generation by anesthetic decomposition in dry carbon dioxide absorbents. The investigators insured that all faculty anesthesiologists were aware of the mechanism of carbon monoxide generation from anesthetic breakdown before data collection for the control group began, and efforts were made to prevent absorbent drying by educating the anesthetizing personnel (residents, CRNAs, and attending anesthesiologists) about the consequences of prolonged flow of dry gas through the absorbent.** With the equipment used in this study (MGA1100 magnetic sector mass spectrometer, Marquette Electronics, Milwaukee, WI), carbon monoxide exposures as a result of anesthetic breakdown could be detected with a minimum carbon monoxide concentration of 30 ppm *via* the interference of trifluoromethane.[5] Respiratory gas data were obtained in 1,085 patients who were undergoing the first general anesthetic of the day in each operating room. Data were collected between November 1994 and June 1995 and included only operating rooms monitored with mass spectrometry. None of these operating rooms were in physically remote locations, and all anesthesia machines were dedicated for use in a single operating room.

Description of the Interventions

During the 4-month transition period, we tested a portable carbon monoxide monitor (CO Sleuth, Breathe EZ Systems, Inc. Shawnee Mission, KS) and found it satisfactory for use in the presence of inhalation anesthetics.[6] This tool was used as a screening device to extend testing for carbon monoxide generation beyond the main operating rooms to remote locations. The transition period also was used to educate and train the anesthesia support personnel in the procedures to be described. To prevent exposures to carbon monoxide, in addition to education of the anesthetizing personnel (residents, CRNAs, and attending anesthesiologists), the following specific interventions were made to prevent absorbent drying:

1. Anesthesia technicians and housekeeping personnel were instructed to turn off all anesthesia machines at the main switch after the last case of the day in each operating room. With all anesthesia machines used in our operating rooms, this procedure stops the flow of fresh gas.
2. Anesthesia technicians were instructed to change the carbon dioxide absorbent if fresh gas was found flowing during the morning machine check. This intervention was started after one exposure was identified, despite intervention #1.
3. Anesthesia technicians were instructed not to dry expiratory limb flowmeters with dry oxygen for longer than 10 min. See figure 2 and the discussion for details of the drying process.

In addition to the previously mentioned responsibilities, anesthesia technicians at our institution staff the operating room laboratory, assist with intraoperative blood salvage, fiberoptic intubations, neurophysiologic monitoring, and invasive hemodynamic monitoring. All cleaning and reprocessing of anesthesia equipment and

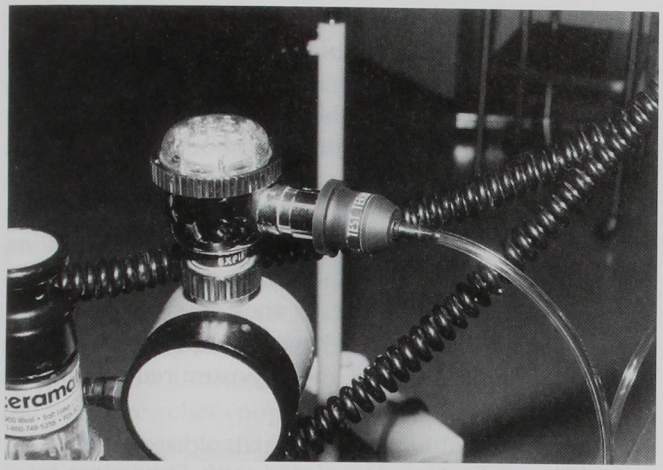

Fig. 2. The photograph shows oxygen flowing through the expiratory limb flowmeter in an attempt to dry condensed water from the apparatus. This procedure was recommended to the anesthesia technicians at our institution by representatives from a regional distributor of anesthesia equipment. This practice directs all gas flow through the carbon dioxide absorbent and out the inspiratory limb if the pressure relief (pop-off) valve is closed or is not forced open by the pressure of dry oxygen. This method of flowmeter drying should not be allowed to continue for more than a few minutes.

the ordering and restocking of anesthesia supplies became the responsibility of anesthesia technicians.

Description of the Postintervention Group

Respiratory gas data were obtained in 1,961 patients during the first general anesthetic of the day in each of the main operating rooms between October 1995 and December 1996. Exhaled carbon monoxide concentrations were determined with the portable electrochemical carbon monoxide monitor placed into the expiratory limb of the anesthesia circle. When more than 50 parts per million carbon monoxide were present, inspiratory carbon monoxide concentrations also were determined. Elevated carbon monoxide concentrations were assigned to represent intraoperative exposure from anesthetic destruction if (1) trifluoromethane was present, or if (2) the average water content of the Baralyme® in either absorbent canister was less than 6%.[1,5] Elevated breathing circuit carbon monoxide concentrations were assigned to represent expiration of carbon monoxide from previous exposure such as smoking (1) if expiratory carbon monoxide concentrations were more than inspiratory carbon monoxide concentrations, or (2) if the patient had a smoking history consistent with an elevated preoperative carboxyhemoglobin concentration. The results of blood oximetry were recorded in this study if it was performed for clinical indications. Where evidence indicated that a patient was exposed to carbon monoxide as a result of anesthetic breakdown, the anesthesiologist in charge of that patient's care was notified, and the carbon dioxide absorbent in the anesthesia circle system was changed intraoperatively to fresh carbon dioxide absorbent to stop the production of carbon monoxide and to end the carbon monoxide exposure. Respiratory gas samples were analyzed by gas chromatography using a molecular sieve (for CO) or Poropak Q (for trifluoromethane) and a thermal conductivity detector (QuinTron Model 225 Gas Chromatograph, Milwaukee, WI) and also by gas chromatography/mass spectrometry for trifluoromethane (5890 Series II Gas Chromatograph/5989A MS Engine Mass Spectrometer system (Hewlett Packard, Palo Alto, CA).

Data were analyzed by chi-square analysis with the continuity correction. Calculations were performed with Statview for the MacIntosh (Abacus Concepts, Berkley, CA).

Results

In the control group, five carbon monoxide exposures occurred as a result of anesthetic breakdown with carbon monoxide generation. All of these carbon monoxide exposures occurred during the first general anesthetic of the day in each operating room for 1,085 cases, resulting in an exposure rate of 0.46%. During the transition phase, an exposure to carbon monoxide occurred on a Friday after several days of monitored care cases in that operating room. In the postintervention group, elevated breathing circuit carbon monoxide concentrations were assigned to represent intraoperative exposure from anesthetic destruction or expiration of carbon monoxide from previous exposure such as smoking. This assignment was made without conflict in every case, with at least two of the previous criteria satisfied. Elevated carbon monoxide concentrations usually were a result of exhalation of carbon monoxide in patients known to be smokers, although patients with recent transfusions, hemolytic disease, or recent trauma often exhaled high carbon monoxide concentrations even in the absence of smoking. After intervention #1 had been enforced, one patient exposure to carbon monoxide

occurred during this study in operating rooms previously monitored. After this, additional checks were performed in the morning by the anesthesia technicians. The carbon dioxide absorbent was changed if gas was found flowing through the anesthesia machine overnight (intervention #2). Although no further carbon monoxide exposures occurred after this intervention, statistical analysis cannot determine whether an additional decrease in incidence had occurred with this sample size. The incidence of carbon monoxide exposures from intraoperative anesthetic breakdown in anesthetizing locations that were monitored in the control group and available for comparison from the main operating suite was 1 of 1,961 cases (0.051%) after the interventions in this study and is less ($P < 0.05$) than the exposure rate before the interventions in the same operating rooms.

Two additional exposures to carbon monoxide occurred during the postintervention phase in remote anesthetizing locations. Although these locations were not monitored in the control group, these two exposures occurred among only 68 first anesthetics in remote locations. The carbon monoxide exposure rate (2.9%) among first cases in remote locations was greater ($P < 0.001$) than the carbon monoxide exposure rate among first cases in the main operating rooms. Both remote carbon monoxide exposures occurred during the first general anesthetic of the week. After these exposures, anesthesia technicians were instructed to change the carbon dioxide absorbent every Monday morning in remote locations. Of the three exposures to carbon monoxide that occurred in the postintervention groups, two exposures occurred during vacation or illness of anesthesia support personnel, which created inadequate staffing.

Discussion

Comparative Data

The incidence of patient exposures to carbon monoxide was reduced during this study. In the main operating rooms, the single carbon monoxide exposure from anesthetic breakdown occurred after the intervention #1 was in effect, but contributing factors included inadequate knowledge and incomplete understanding of the protocol by an anesthetist and understaffing of anesthesia technicians during vacation and illness of the support personnel. Although greater education of the anesthetizing personnel may have prevented this or other patient carbon monoxide exposures, the occurrence of two of the three carbon monoxide exposures during understaffing of the anesthesia support staff strongly suggests that their involvement was contributory to the reduction of exposures. However, the particular practice situation at this medical center may reduce the generalizability of these findings to other institutions because the rotation of anesthesia residents through this institution and the use of anesthesia machines by several staff members may have an impact on the incidence rate and efficacy of any exposure reduction protocol.

Additional Factors Associated with Exposures to Carbon Monoxide

One carbon monoxide exposure occurred on a Friday in an operating room that is traditionally used for monitored anesthesia care on Mondays through Thursdays. A contributing factor may be the practice of running oxygen for administration *via* nasal cannula or face mask through the breathing circle.[7] There is a potential for fresh gas to pass through and dehydrate the absorbent in some anesthesia machines if nasal cannulae are connected to the patient Y-connector and if the pressure relief valve is partially open. The anesthesia machine in this operating room was replaced with a different anesthesia machine equipped with a separate flow meter for supplemental oxygen.

The carbon monoxide exposure rate in remote locations was more than 50 times greater than the exposure rate in the main operating rooms. This finding may result from missed equipment checks or unregulated access to anesthesia equipment in remote locations.

Another practice that may result in carbon monoxide exposures was discovered when a nondedicated anesthesia machine and circuit were being prepared for a malignant hyperthermia susceptible patient by draining the vaporizers and intentionally flushing the machine for several days with more than 10 l/min of oxygen. The vaporizers were empty for the patient with malignant hyperthermia, therefore eliminating the potential for carbon monoxide generation. However, the subsequent use of dried carbon dioxide absorbent after refilling the vaporizers with isoflurane, enflurane, or desflurane could potentially result in an exposure to carbon monoxide during the next anesthetic.

Drying of the carbon dioxide absorbents also can result from a procedure, which was suggested to our

anesthesia technicians by a representative of a regional distributor of anesthesia equipment. Representatives of this company indicated that it was necessary to dry the expiratory volume flowmeters with dry oxygen for approximately 15 min at the end of each workday. If this practice was carried out for longer periods of time, the potential for significant absorbent drying may be present, especially if this drying apparatus was forgotten and if the flow of dry gas was allowed overnight. An illustration of this technique is provided in figure 2. Separate testing confirmed that this practice directs all (dry) gas flow through the carbon dioxide absorbent if the pressure relief (pop-off) valve is closed.

It also is possible that a malfunctioning scavenger can enhance absorbent drying in some anesthesia machines. Figure 1 shows the schematic of a Drager Narkomed anesthesia machine (North American Drager, Telford, PA).[8] If the scavenger has an improperly functioning negative pressure relief valve and if fresh gas is flowing through the machine, the suction created by the scavenging system can preferentially direct this fresh gas through the absorbent and through an open pressure relief valve instead of exiting harmlessly through the patient Y-connector. This may increase the absorbent drying by fresh gas flow even if the breathing bag is left in place.

Criteria for Evaluating Carbon Monoxide Exposures

The control group used mass spectrometry and the interference of trifluoromethane to indicate anesthetic breakdown, and an electrochemical carbon monoxide monitor also was available in the later phases of this study.[6] Both techniques had a similar sensitivity to carbon monoxide.

Because carbon monoxide was present in measurable concentrations in all breathing circuits,[9,10] it was necessary to distinguish between the measurement of exhaled carbon monoxide from previous exposures like smoking, endogenous production, and carbon monoxide that resulted from anesthetic destruction. Our criteria for making this determination included documenting that conditions permitting reaction existed (dry absorbent) or that trifluoromethane, another product of reaction, was present. Comparison of inspiratory and expiratory carbon monoxide concentrations provided additional evidence of the source of carbon monoxide.

Table 1. CO Exposure during the Study Period

Group	Anesthetic	CO (ppm)	COHb (%)	Day of the Week
Control	Isoflurane	NA	6.9	Monday
Control	Isoflurane	NA	NA	Thursday
Control	Isoflurane	31	<1.5	Monday
Control	Isoflurane	408	<1.5	Tuesday
Control	Isoflurane	100	<1.5	Wednesday
Transition	Isoflurane	104	4.8	Friday
Remote	Desflurane	207	NA	Tuesday*
Remote	Isoflurane	78	NA	Monday
Postintervention	Isoflurane	52	2.6	Tuesday

CO = carbon monoxide; COHb = carboxyhemoglobin; NA = not available.

Anesthetic breakdown was confirmed in each exposure. Approximately 90% of the anesthetics used isoflurane and 10% used desflurane.

* No case was performed on the preceding Monday in this location.

Patient Safety and Monitoring

Because carbon monoxide and oxygen competitively bind to hemoglobin and cytochrome C oxidase, high inspired oxygen concentrations may protect patients from symptomatic poisoning during the delivery of anesthesia. This equilibrium can be represented by the following equation: $(pCO/pO_2) \times 230 = (COHb/O_2Hb)$.[11] Although several patient exposures to carbon monoxide were identified during this study, the carbon monoxide exposures were terminated only because the carbon monoxide exposures were recognized and because corrective action was taken. In some cases, patient carbon monoxide exposures were stopped before significant quantities of COHb were formed, as shown in table 1. Although it may be attractive to use anesthetics that do not have the potential for carbon monoxide generation, other currently available potent inhalation anesthetics (halothane and sevoflurane) have other potential toxicities. Therefore, it may be equally important to develop policies and procedures that prevent carbon monoxide exposures and also to monitor for any carbon monoxide exposures that occur despite preventative measures.

In conclusion, we have shown a statistically significant decrease in the incidence of carbon monoxide exposures and attribute this to a combination of education and assistance from anesthesia technicians. Nevertheless, these interventions did not completely eliminate intraoperative carbon monoxide exposures at our institution. The findings of this study support the opinion of Epstein|| and suggest that safety checks by anesthesia technicians may be necessary to prevent absor-

bent drying in operating locations used by multiple staff members. In addition, the especially high risk in remote anesthetizing locations requires greater vigilance than the main operating suites.

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