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Use of Medical Simulation to Explore Equipment Failures and Human-Machine Interactions in Anesthesia Machine Pipeline Supply Crossover

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BACKGROUND: High-fidelity medical simulation can be used to explore failure modes of technology and equipment and human-machine interactions. We present the use of an equipment malfunction simulation scenario, oxygen (O_2)/nitrous oxide (N_2O) pipeline crossover, to probe residents' knowledge and their use of anesthetic equipment in a rapidly escalating crisis.

METHODS: In this descriptive study, 20 third-year anesthesia residents were paired into 10 two-member teams. The scenario involved an Ohmeda Modulus SE 7500 anesthetic machine with a Datex AS/3 monitor that provided vital signs and gas monitoring. Before the scenario started, we switched pipeline connections so that N_2O entered through the O_2 pipeline and vice versa. Because of the switched pipeline, the auxiliary O_2 flowmeter delivered N_2O instead of O_2. Two expert, independent raters reviewed videotaped scenarios and recorded the alarms explicitly noted by participants and methods of ventilation.

RESULTS: Nine pairs became aware of the low fraction of inspired O_2 (F_{IO_2}) alarm. Only 3 pairs recognized the high fraction of inspired N_2O (F_{IN_2O}) alarm. One group failed to recognize both the low F_{IO_2} and the high F_{IN_2O} alarms. Nine groups took 3 or more steps before instigating a definitive route of oxygenation. Seven groups used the auxiliary O_2 flowmeter at some point during the management steps.

CONCLUSIONS: The fact that so many participants used the auxiliary O_2 flowmeter may expose machine factors and related human-machine interactions during an equipment crisis. Use of the auxiliary O_2 flowmeter as a presumed external source of O_2 contributed to delays in definitive treatment. Many participants also failed to notice the presence of high N_2O. This may have been, in part, attributable to 2 facts that we uncovered during our video review: (a) the transitory nature of the "high N_2O" alert, and (b) the dominance of the low F_{IO_2} alarm, which many chose to mute. We suggest that the use of high-fidelity simulations may be a promising avenue to further examine hypotheses related to failure modes of equipment and possible management response strategies of clinicians. (Anesth Analg 2010;110:1292–6)

Simulation has been used in various industries, most notably in aviation, to explore failures of equipment and technology and the role of human-machine interactions.[1,2] The aviation industry in its investigation of airline accidents has used simulation to conduct observations and tests of airplane design issues. In their investigation of the crash of American Airlines Flight 587 (on November 12, 2001, near John F. Kennedy International Airport), the National Transportation Safety Board used a vertical motion simulator to evaluate possible causes of the accident, such as rudder system design and malfunction and flight crew actions. One of the goals of their study was to reproduce the details of the event in a high-fidelity simulator and, in the process, uncover any hidden roles that pilot perception of cockpit displays during acceleration and deceleration may have played during the crash. The National Transportation Safety Board mentions in its report that the use of the simulator "provided insight and was a beneficial tool . . . as opposed to just looking at tabular or charted data."[3] In other words, the simulator helped to recreate conditions for investigators, an environment, real-life pressures, and decision making, which enhanced review of paper records.

A similar, promising role for high-fidelity simulation may lie within anesthesiology. We can create rare situations specific to our domain that effectively push and test equipment to its limits while examining consequent human-machine interactions.[4,5] Furthermore, medical simulations afford the advantage of creating ongoing reproducible scenarios that can be recorded and of obtaining responses of practitioners studied.[6]

Oxygen (O_2) pipeline crossover with nitrous oxide (N_2O) is a rare but potentially lethal event within the practice of anesthesiology.[7,8] It can occur at any point from source to patient delivery, e.g., inadvertent crossing of central O_2 and N_2O pipeline supplies, delivery of a different central gas tank, or switched installation of pipelines to the back of the anesthesia machine. Regardless of the cause,

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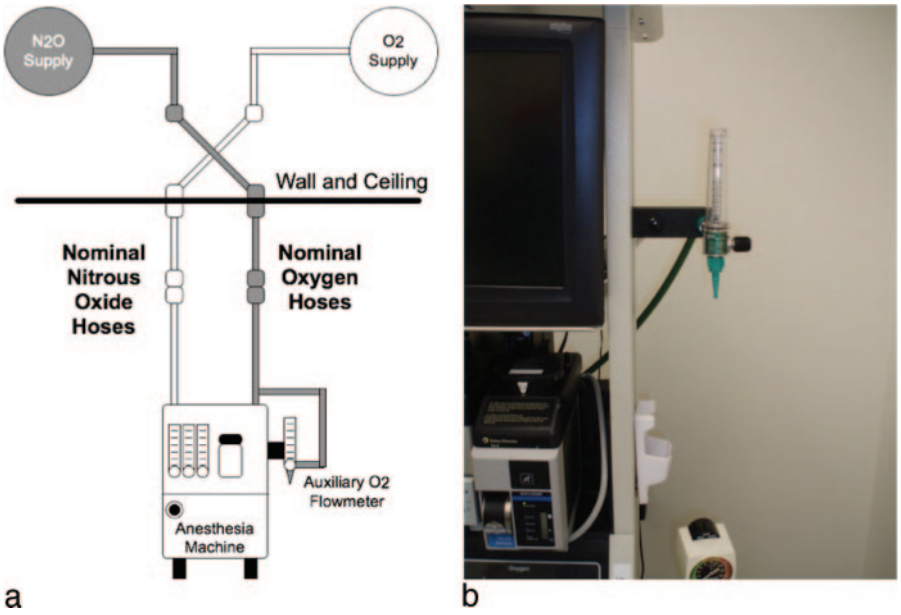

Figure 1. a, Schematic diagram of oxygen/nitrous oxide pipeline crossover. After the crossover, nitrous oxide flows to hoses that would nominally contain oxygen. The source of gas for the auxiliary oxygen flowmeter is the intermediate pressure system for oxygen in the anesthesia machine. The intermediate pressure system, in turn, is supplied from the oxygen pipeline and/or the reserve oxygen tank(s) on the machine. b, Photograph of an auxiliary O_2 flowmeter at the side of the Ohmeda Modulus SE 7500 anesthetic machine.

inhaling of 100% N_2O leads rapidly to hypoxia, cardiac arrest, and brain injury or death. An O_2 pipeline crossover crisis shares characteristics in common with 2 larger classes of events that the American Society of Anesthesiologists Closed Claims Analysis Database refers to as respiratory (e.g., low fraction of inspired O_2 [F_{IO_2}]) and equipment events.[9,10] Both respiratory and equipment events constitute a significant source of malpractice claims. Within the category of equipment events in general, it was noted that equipment misuse was 3 times more likely to be the cause than equipment failure.[9] The term "equipment failure" means the machine does not function as expected, despite regular maintenance, whereas the term "equipment misuse" means the problem lies in the preparation, maintenance, or use of a machine as might occur with pipeline O_2 supplies and an O_2 crossover crisis.

Currently, in the majority of anesthesia departments, equipment is maintained, inspected, and serviced by ancillary personnel, not by anesthesiologists, leaving a potential training gap for anesthesia residents.[11–13]*† High-fidelity medical simulation could both teach anesthesia residents about equipment function and examine their management strategies during an equipment-related crisis. In this article, we explore the clinical management of a simulation scenario involving the crossover of O_2 and N_2O supplies, and we report on issues uncovered during residents' responses to this event.

METHODS

The O_2/N_2O crossover scenarios were captured on video recordings during Anesthesia Crisis Resource Management (ACRM) training sessions as described previously.[6,14] The Human Subjects Review Committee approved the protocol, and subjects gave written informed consent for review of the recordings for research purposes. In this prospective descriptive study, third-year anesthesia residents (1–4 months before graduation) took part in 10 scenarios in groups of 2 (n = 20). One person held the "hot seat," initially managing the situation, and the other was the "first responder" called in to assist. All residents had at least 2 previous full days of ACRM simulation sessions and were familiar with the simulation environment.

Before the scenario started, the subjects were oriented to the following: the simulation facility, the patient simulator (MedSim Eagle, Binghamton, NY), the general supplies available, the anesthesia machine (Ohmeda Modulus SE 7500, Datex-Ohmeda, GE Healthcare, United Kingdom), and the monitor (Datex AS/3 physiologic monitor, Datex-Ohmeda). As is customary during ACRM courses, all subjects were requested to "think out loud" and mention their diagnosis and management options during the course of scenario management.

Scenario Description

The simulation center has pipeline O_2 and N_2O supplied from hose drops. An auxiliary O_2 flowmeter, located on the side of the machine, normally would have received O_2 from the same wall source, a standard arrangement (Fig. 1). Before the start, however, investigators switched pipeline connections "behind the wall," so that N_2O entered through the O_2 pipeline and vice versa.

The simulated patient was a healthy 43-year-old man undergoing an inguinal herniorrhaphy repair under general endotracheal anesthesia. Anesthesia was maintained with 50% O_2, 50% N_2O, and 1% isoflurane. The participants took over from a confederate (a simulation instructor role-playing an anesthesiologist) toward the end of surgery. During emergence, when the patient was given what was thought to be 100% O_2, he was actually receiving 100% N_2O. Shortly thereafter, first a low O_2 and then a high N_2O visual alarm appeared on the monitor screen. The low O_2

*American Society of Anesthesiologists' 2008 Recommendations for Preanesthesia Checkout Procedures. Available at: http://www.asahq.org/clinical/FINALCheckoutDesignguidelines02-08-2008.pdf. Accessed May 1, 2009.
†Canadian Anesthesiologists' Society Guidelines to the Practice of Anesthesia. Available at: http://www.cas.ca/members/sign_in/guidelines/practice_of_anesthesia/default.asp?load=appendix_iii. Accessed May 1, 2009.

Table 1. Alarms Noted and Ventilation Modes Used in the Scenarios[a]

Group	Primary alarms used for diagnosis	Ventilation step 1	2	3	4	5	6	No. of steps
1	Low F_{IO_2}[b]	BVM + Aux Flo	EOT on AM	BVM + Air	BVM + EOT	BVM + AuxFlo	AM + COS	6
2	Low F_{IO_2} and High F_{IN_2O}[c]	BVM + Aux Flo	AM + COS	BVM + Aux Flo	BVM + EOT	BVM + AuxFlo	BVM + Air	6
3	Low F_{IO_2}	BVM + Aux Flo	AM + COS	BVM + Air	AM + MAS	BVM + Air	BVM + EOT	6
4	Low F_{IO_2}	BVM + Aux Flo	EOT on AM	AM + COS	MO + ET	BVM + EOT		5
5	Low F_{IO_2}	BVM + Air	BVM + EOT	EOT on AM	BVM + EOT			4
6	Low F_{IO_2} and high F_{IN_2O}	BVM + Aux Flo	BVM + EOT	BVM + Air	BVM + EOT			4
7	Low F_{IO_2} and high F_{IN_2O}	AM + COS	EOT on AM	AM + MAS	BVM + EOT			4
8	Low Spo_2[d]	EOT on AM	BVM + Aux Flo	BVM + EOT				3
9	Low F_{IO_2}	EOT on AM	BVM + Air	BVM + EOT				3
10	Low F_{IO_2} and low Spo_2	BVM + Aux Flo	BVM + EOT					2

BVM + Aux Flo = bag valve mask and auxiliary flowmeter; BVM + Air = bag valve mask and air; BVM + EOT = bag valve mask and external oxygen tank; EOT on AM = use of external oxygen tanks on anesthesia machine without disconnecting O_2 wall pipeline hose (i.e., delivering 100% N_2O); AM + COS = use of anesthesia machine and circuit with crossed oxygen supply (i.e., delivering 100% N_2O); AM + MAS = use of anesthesia machine and circuit with machine air supply; MO + ET = mouth to endotracheal tube.

[a] Before start of scenario, O_2 and N_2O pipeline supplies were switched so that both anesthesia machine oxygen flowmeter and auxiliary O_2 flowmeter were instead delivering 100% N_2O.

[b] Low F_{IO_2} alarm = a visual alarm indicating low fraction inspired oxygen concentration (displayed as "F_{IO_2} <18%").

[c] High F_{IN_2O} alarm = a visual alarm indicating high fraction inspired nitrous oxide concentration (displayed as "F_{IN_2O} >82%").

[d] Low Spo_2 alarm = an audio alarm that would be triggered when oxygen saturation fell below 90%.

alarm indicated a low F_{IO_2} concentration and displayed "F_{IO_2} <18%." The high N_2O alarm indicated a high fraction of inspired N_2O (F_{IN_2O}) concentration and displayed "F_{IN_2O} >82%." Subsequently, the low O_2 audio alarm sounded. The simulated patient became markedly hypoxemic, which would normally lead rapidly to death unless corrective measures were taken. To allow more time to see participants' decision-making processes, we let the nadir of hypoxemia remain at 70% O_2 saturation (Spo_2) for up to 30 minutes; although dysrhythmias did occur, we did not allow the scenario to proceed to a cardiac arrest. Each team managed almost the entire period of the crisis in pairs. Once the anesthesiologist in the "hot seat" asked for help, the "first responder" was available within 10 to 20 seconds.

Data Collection

The actions and statements of subjects were recorded using multiple microphones and video cameras, positioned to capture subjects' comments and actions. For retrospective review of recorded performance, a picture in "picture view" simultaneously displayed 2 camera angles of the subjects, along with a view of the patient's vital signs.

Data Analysis

Two raters (SM and RF) independently evaluated and scored the videos. Because this scenario examined the management of anesthesia machine equipment failure in a patient with severe hypoxemia, the raters gave particular attention to the low O_2 and high N_2O alarms used for diagnosis, the use of the auxiliary O_2 flowmeter, the modes of ventilation, and the sequence of management actions. An alarm was scored as being used for diagnosis if a group member articulated a statement referencing it, e.g., "The low O_2 alarm is blinking." Observation and recording of the modes of ventilation and management began when the low O_2 visual alarm appeared, whether or not the team recognized the low O_2 alarm. The raters came together to discuss or clarify any questions that arose about statements subjects made regarding alarms or modes of ventilation (e.g., bag valve mask to air or to machine). Our participants went through a number of ventilation steps and modes, very often and quickly moving from a successful and safe strategy to an unsuccessful one. An acceptable end point for management occurred when subjects persisted in a ventilation mode that successfully delivered an F_{IO_2} including and higher than that found in room air concentration. During retrospective video analysis, each subject's responses were annotated using StudioCode (Version 2.9.165, Studiocode Business Group, Los Angeles, CA), a video control and analysis software package.

RESULTS

The sequences of the participants' diagnostic and treatment strategies are listed in Table 1. Results are aggregated at the group level (the anesthesiologist in the "hot seat" plus "first responder" colleague).

For diagnostic alarms, 9 groups became aware of the low F_{IO_2} alarm and alert. Three groups recognized the high F_{IN_2O} alert; this subset also recognized the low F_{IO_2} alarms. One group failed to recognize both the low F_{IO_2} and high F_{IN_2O} alarms/alerts. This group became aware of an oxygenation problem only because of a low Spo_2 alarm.

For ventilation management strategies, 9 groups performed 3 or more steps before applying a definitive route of oxygenation, and 7 groups used the auxiliary O_2 flowmeter at some point during the management steps. For ventilation step 1, 6 groups used the auxiliary O_2 flowmeter. In ventilation step 2, after the patient continued to desaturate, 5 groups went back to using the anesthesia machine. None of the participants disconnected the wall pipeline supplies when attempting to use the O_2 tanks mounted on the anesthesia machine. Two groups persisted with the crossed O_2 flowmeter, attempting to somehow increase the F_{IO_2} (but they did not increase the "N_2O" flow). In ventilation step 2, 5 groups ensured adequate oxygenation either with an external O_2 tank or with air from the anesthesia machine itself. However, at this point, despite adequate oxygenation, almost all groups then persisted in further trying

various combinations of gas delivery. These methods included machine and air, machine and auxiliary O_2 flowmeter, or mouth-to-tube ventilation before settling back to ventilation with an external O_2 tank. One group was never able to definitively provide O_2 to the simulated patient.

DISCUSSION

This study illustrates how a number of machine factors and related human-machine interactions were exposed during an equipment-related crisis. There were features of the anesthesia machine that affected how our subjects managed this scenario. First, participants used the auxiliary O_2 flowmeter as a presumed external source of O_2, which contributed to delays in definitive treatment (all groups) or failure to successfully treat the hypoxia (9 groups). In real life, use of the auxiliary flowmeter with 100% N_2O would be quickly lethal.

When an anesthesiologist is faced with a situation involving anesthesia gas delivery equipment malfunction, the first step should be to ensure that the patient receives O_2. Our subjects did recognize that there were problems with the O_2 source, and 60% chose the auxiliary nozzle as a first step in their management. When this failed and the patient continued to desaturate, the subjects persisted in attempts to diagnose the cause of machine malfunction and also continued to try to find ways to oxygenate using the machine, e.g., using anesthesia machine O_2 tanks without disconnecting wall pipeline supplies. None of our subjects attempted to turn on the N_2O flowmeter or disconnect the central O_2 pipeline supplies. The latter action would have made using the external O_2 tanks on the anesthesia machine (EOT + AM in Table 1) an acceptable solution. Because these tank pressures are reduced to 45 psig while the central pressure is 50 psig, the wall supply must be disconnected before the anesthesia machine O_2 tanks can be used. Why many participants persisted with attempting to get O_2 from malfunctioning equipment is unclear, but it was apparent that many of our subjects (8 groups) incorporated steps into their management that delayed definitive treatment.

Second, many participants failed to notice the presence of the high N_2O alarm. Although 9 groups noted the low O_2 alarm, only 3 groups recognized the high N_2O alarm. Possible causes uncovered were the transitory nature of the high N_2O alarm and the dominance of the O_2 alarm that can be muted. The high N_2O alarm appeared when 100% N_2O was administered but quickly disappeared from the screen despite the fact that a high concentration of N_2O persisted. This disappearance made it difficult to discern the reason for a low F_{IO_2}. Simultaneously, the low F_{IO_2} alarm was activated and produced a loud distracting sound, which subjects frequently muted as they focused on management. Whether muting the alarm allowed subjects to "forget" the problem is debatable. Another source of concern was that one group did not recognize either the low O_2 or the high N_2O alarm but was alerted to the presence of a problem only when made aware through a low Spo_2 alarm. In a real-life situation, this lapse would represent a significant failure in the ability to quickly diagnose or manage a rapidly deteriorating hypoxemic patient.

Anesthesia gas delivery system design has focused on making it difficult for errors to occur either by creating forcing functions such as keyed connections (e.g., pin index safety system for tanks of medical gases) or by preventing errors from causing injury with safeguards such as the gas flow proportioning system.[15] When these 2 steps fail, then the system alarms should quickly prompt the underlying fault. However, the fact that the low O_2 alarms can be muted and the high N_2O alarms can quickly disappear are design features that may have contributed to confusion in management.

Another undesirable design feature that we uncovered is that the machine does not provide a method for monitoring the O_2 concentration of the gas being delivered from the auxiliary flowmeter. There is also no reminder that the auxiliary flowmeter has the same gas supply as the rest of the machine. In fact, the auxiliary flowmeter on most anesthesia machines usually has a green nozzle at its end for connecting to the end of the breathing circuit. The fact that the nozzle is green and set up similar to a wall O_2 outlet may have suggested to subjects that the O_2 came from a different source, confusing them.

The limitations of this study are small sample size and the use of only one type of anesthesia machine. That the overwhelming number of practitioners did not immediately diagnose the source of the equipment failure is of concern, because there was information available that clearly showed the problem. Admittedly, our subjects were preoccupied with a complex situation that rapidly deteriorated. But given the poor outcomes of respiratory and equipment malpractice cases in general, it may be useful to consider a method such as high-fidelity medical simulation to expose potential causes of these crises and possible better management strategies.

Dalley et al.[16] created a mannequin-based simulation study to examine the role of design features in causing practitioners to make errors with unfamiliar anesthetic delivery machines. They used simulation to investigate alternative methods of introducing new anesthesia equipment. This study randomized 15 trainees to receive either standard, in-service training on a Drager Fabius anesthetic machine or a combination of in-service and simulated clinical use training. The simulations involved scenarios of various types of machine malfunction. Video analysis revealed that trainees had difficulty with basic issues such as switching from manual to machine ventilation, issues that might not have been discovered during regular in-service training.

Hamman[17] found that in situ simulation (simulation scenarios performed in the real clinical environment) may unearth key system and technology issues as well as provide training. Equipment such as defibrillators or IV pumps that health care providers are expected to know and use proficiently are instead revealed as potential problems, because the equipment is too complicated or cumbersome to use easily.

Besides revealing failure modes for equipment at both system and individual practitioner levels, simulation may also generate opportunities to test how failure modes of

practitioners and equipment may be remedied.[18,19] Simulation may essentially function as a laboratory to see which of several management strategies may be optimal.

In this study, we found that participants' lack of knowledge of the anesthesia machine and gas supply, coupled with complexity and shortfalls in equipment design, particularly with regard to alarms and other safety functions, led to suboptimal management of a potentially lethal crisis. Persistence with equipment failure diagnostic strategies delayed definitive treatment. One potential option for clinicians that could then be evaluated in a simulation environment might be to determine whether the use of a generic, 1-step, precompiled response might be more easily recalled and more rapidly implemented. This option would be to quickly abandon the machine altogether and go to an external O_2 source (i.e., O_2 tank) and ventilation via a bag valve mask or other backup ventilation source.

AUTHOR CONTRIBUTIONS

SCM, RF, and SKH helped to design and conduct the study, collect and analyze the data, and write the manuscript. MFD helped to write the manuscript. DMG helped to design and conduct the study and write the manuscript.

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