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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 (O2)/nitrous oxide (N2O) 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 N2O entered through the O2 pipeline and vice versa. Because of the switched pipeline, the auxiliary O2 flowmeter delivered N2O instead of O2. 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 O2 (FIO2) alarm. Only 3 pairs recognized the high fraction of inspired N2O (FIN2O) alarm. One group failed to recognize both the low FIO2 and the high FIN2O alarms. Nine groups took 3 or more steps before instigating a definitive route of oxygenation. Seven groups used the auxiliary O2 flowmeter at some point during the management steps.

CONCLUSIONS: The fact that so many participants used the auxiliary O2 flowmeter may expose machine factors and related human-machine interactions during an equipment crisis. Use of the auxiliary O2 flowmeter as a presumed external source of O2 contributed to delays in definitive treatment. Many participants also failed to notice the presence of high N2O. This may have been, in part, attributable to 2 facts that we uncovered during our video review: (a) the transitory nature of the “high N2O” alert, and (b) the dominance of the low FIO2 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. 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.” 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. Furthermore, medical simulations afford the advantage of creating ongoing reproducible scenarios that can be recorded and of obtaining responses of practitioners studied.

Oxygen (O2) pipeline crossover with nitrous oxide (N2O) is a rare but potentially lethal event within the practice of anesthesiology. It can occur at any point from source to patient delivery, e.g., inadvertent crossing of central O2 and N2O 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,
inhaling of 100% N2O leads rapidly to hypoxia, cardiac arrest, and brain injury or death. An O2 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 O2 [Fio2]) 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 O2 supplies and an O2 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 O2 and N2O supplies, and we report on issues uncovered during residents’ responses to this event.

**METHODS**

The O2/N2O 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 O2 and N2O supplied from hose drops. An auxiliary O2 flowmeter, located on the side of the machine, normally would have received O2 from the same wall source, a standard arrangement (Fig. 1). Before the start, however, investigators switched pipeline connections “behind the wall,” so that N2O entered the O2 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% O2, 50% N2O, 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% O2, he was actually receiving 100% N2O. Shortly thereafter, first a low O2 and then a high N2O visual alarm appeared on the monitor screen. The low O2...
On observing and recording of members, articulated a statement referencing it, e.g., "The low O2 visual alarm appeared, whether or not the team recognized the low O2 alarm. The raters came together to discuss or clarify any questions that arose about subjects' comments and actions. For retrospective review of recorded performance, a picture in "picture capture subjects' comments and actions. For retrospective video analysis, each subject's response was 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 FiO2 alarm and alert. Three groups recognized the high FiN2O alert; this subset also recognized the low FiO2 alarms. One group failed to recognize both the low FiO2 and high FiN2O alarms/alerts. This group became aware of an oxygenation problem only because of a low SpO2 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 O2 flowmeter at some point during the management steps. For ventilation step 1, 6 groups used the auxiliary O2 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 O2 tanks mounted on the anesthesia machine. Two groups persisted with the crossed O2 flowmeter, attempting to somehow increase the FiO2 (but they did not increase the "N2O" flow). In ventilation step 2, 5 groups ensured adequate oxygenation either with an external O2 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 O₂ flowmeter, or mouth-to-tube ventilation before settling back to ventilation with an external O₂ tank. One group was never able to definitively provide O₂ 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 O₂ flowmeter as a presumed external source of O₂, 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% N₂O 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 O₂. Our subjects did recognize that there were problems with the O₂ 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 O₂ tanks without disconnecting wall pipeline supplies. None of our subjects attempted to turn on the N₂O flowmeter or disconnect the central O₂ pipeline supplies. The latter action would have made using the external O₂ 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 O₂ tanks can be used. Why many participants persisted with attempting to get O₂ 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 N₂O alarm. Although 9 groups noted the low O₂ alarm, only 3 groups recognized the high N₂O alarm. Possible causes uncovered were the transitory nature of the high N₂O alarm and the dominance of the O₂ alarm that can be muted. The high N₂O alarm appeared when 100% N₂O was administered but quickly disappeared from the screen despite the fact that a high concentration of N₂O persisted. This disappearance made it difficult to discern the reason for a low Fio₂. Simultaneously, the low Fio₂ 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 O₂ or the high N₂O alarm but was alerted to the presence of a problem only when made aware through a low Spo₂ 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. When these 2 steps fail, then the system alarms should quickly prompt the underlying fault. However, the fact that the low O₂ alarms can be muted and the high N₂O 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 O₂ 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 O₂ outlet may have suggested to subjects that the O₂ 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. 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 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 O2 source (i.e., O2 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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